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OPTIMISING THE ENVIRONMENTAL SUSTAINABILITY OF THE DAIRY INDUSTRY

Daniel Francisco Egas Galarza

A dissertation submitted in fulfilment of the requirements for the PhD degree in Experimental Sciences and Technology with the Mention of International Doctoral Research.

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By

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The present thesis entitled *Optimising the environmental sustainability of the dairy industry*, by Daniel Francisco Egas Galarza, was carried out at the Technological Centre for the Biodiversity, Ecology, Environmental and Agri-food Technologies (BETA Tech. Centre) at the University of Vic – Central University of Catalonia (UVic-UCC), under the supervision of Dr. Joan Colon Jorda and Dr. Sergio Ponsá Salas.

Joan Colon Jorda Sergio Ponsá Salas

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“Nothing in this world can take the place of persistence. Talent will not: nothing is more common than unsuccessful men with talent. Genius will not; unrewarded genius is almost a proverb. Education will not: the world is full of educated derelicts. Persistence and determination alone are omnipotent.”

Calvin Coolidge

To mom, dad and my family,
for all their support during this journey.

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Back then in 2017, when I started my PhD, I knew little about Life Cycle Assessment (LCA), almost nothing about the EU Product Environmental Footprint methodology (PEF); and absolutely nothing regarding the dairy production systems. However, during this journey of three and a half years, I have gained a much deeper methodological and practical experience regarding LCA and the PEF; which has allowed me to assess in deep the environmental sustainability of a very challenging agricultural sector such is dairy. So, I would like to take the chance to acknowledge and thank all the people who contributed to my work in one way or another. I am positive that this thesis would have not been the same without all of you.

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Table of contents

Acronyms and abbreviations

B_P	Background process
B-GWP	Climate change, Biogenic
F-EP	Eutrophication, freshwater
FETP	Ecotoxicity, freshwater
F-GWP	Climate change, Fossil
F-RD	Resource use, fossils
GWP	Global warming potential, Climate change
HTP-C	Human toxicity, cancer
HTP-NC	Human toxicity, non-cancer
IRP	Ionizing radiation, human health
LU	Land use
LUC-GWP	Climate change, Land use and Land use change
M-EP	Eutrophication, marine
M-RD	Resource use, minerals and metals
ODP	Ozone Depletion Potential
PMF	Particulate matter formation
POCP	Photochemical ozone formation, human health
T-EP	Eutrophication, terrestrial
W-RD	Water scarcity
AP	Acidification
Ca	Activity coefficient corresponding to the livestock feeding situation
Cf	Characterization factors
CFF	Circular footprint formula
CH_4	methane
CO_2	carbon dioxide
COD	Chemical Oxygen Demand
DE	Feed digestibility
DM	Dry Matter
DQR	Data Quality requirements
EC	European Commission
EF	Environmental footprint
EF-datasets	Environmental footprint compliant datasets
EF-LCIA methods	Environmental footprint compliant life cycle inventory assessment methods
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)
EPLCA	European Platform on Life Cycle Assessment
ESS	Environmental single score
$ESS_{WO\text{-}Toxicity}$	Environmental single score without considering the toxicity-related impacts
EU	European uniron
FAO	Food and Agriculture Organization of the United Nations
F_P	Foreground process

FPCM	Fat Protein Corrected Milk
FU	Functional unit
GE	Gross energy
GHG	Greenhouse gas emissions
GHG	Green House Gases
ILCD	International Life Cycle Data System
IPCC	The Intergovernmental Panel on Climate Change
ISO	International Standardisation Organisation
IT	Information technologies
LCA	Life cycle assessment
LCDN	The Life Cycle Data Network
LCI	Life Cycle Inventory
LCIA	Life Cycle Inventory Assessment
N	Nitrogen
N_2O	Nitrous oxide
N_{Ex}	Nitrogen excreted
Nf	Normalization factors
NH_3	Ammonia
NH_x	Imidogen compounds
NO_3^-	Nitrates
NO_x	,ono-nitrogen oxides compounds
P	Phosphorus
PEF	Product environmental footprint
PEFCR	Product environmental footprint category rules
PEFCR-D	Product environmental footprint category rules for dairy
PEF-D	Product environmental footprint of dairy products (Note: the subscripts refer to the dairy products cheese and yoghurt)
PO_4^{3-}	Phosphate
SMEs	Small and Medium-sized Enterprises
SO_x	Sulphur oxides compounds
Wf	Weighting factor

Abstract

Despite being a relevant social and economic driver, the dairy industry is well known for its high consumption of natural resources and for generating large amounts of emissions that affect the quality of the environment. To accurately identify the origin and amount of emissions that trigger environmental impacts related to the dairy industry, Life Cycle Assessment (LCA) has been widely used. However, the LCA reliability has been jeopardized by an unclear consensus regarding its many methodological choices; which generate heterogenous and incompatible results. This has created confusion among stakeholders and led to the uncontrolled proliferation of green credentials (eco-labels) for products in Europe and around the world.

As a solution to these existing LCA methodological issues for the dairy industry, the Product Environmental Footprint Category Rules for Dairy products was released as part of the European Commission Environmental Footprint initiative. The PEFCR-D aims to increase the reproducibility, consistency and comparability of the dairy products' LCA results. However, the implementation of the mandatory and specific PEFCR-D methodological requirements is a challenge since practitioners require additional no-related LCA knowledge and the support of specialized IT tools that are not currently available in the market. These challenges decrease the PEFCR-D practical application in the dairy industry; and thus, limit the dairy systems' constant environmental assessment; and do not allow the industry to satisfy the market demand for environmentally efficient dairy products.

The dairy industry should be respectful with the environment but not at any economic and social prize, economically affordable but not at any environmental and social cost and, finally, must seek for social equity, but not at any environmental and economic cost, so there are frequently conflicting objectives. Reason why, this thesis aims to optimize the environmental sustainability of the dairy industry in compliance with the European Union Product Environmental Footprint Methodology to improve its competitiveness in an everyday more exigent market for green products.

For this purpose, this thesis (i) introduces an approach to solve the mas balance conflict that arises when determining N emissions in compliance with the PEFCR-D; (ii) presents CalcPEF$_{\text{Dairy}}$ as a response to the lack of a specialized PEFCR-D compliant IT tool; and uses (iii) energy audits and (iv) circularity indicators to assess and propose custom-made optimization improvements for dairy systems; by considering its environmental and economic return benefits.

This thesis results shown that a constant environmental assessment and improvement of dairy systems is possible through the use of specialised tools such as $\text{CalcPEF}_{\text{Dairy}}$, energy audits and circular economy indicators; which together are capable to identify and propose high impact improvement measures. The results also demonstrate the feasibility of properly communicating the $\text{CalcPEF}_{\text{Dairy}}$ environmental assessment outcomes as a marketing strategy since their quality and reliability is such that they can be used in an external verification process to obtain an environmental declaration and eco-label for a market available dairy product. This verified green credentials give dairy producers the real possibility of increasing their economic returns without affecting their system and products environmental sustainability.

Resumen

A pesar de ser un relevante motor social y económico, la industria láctea es conocida por su alto consumo de recursos naturales y por generar gran cantidad de emisiones que afectan la calidad del medioambiente. Para identificar con precisión el origen y cantidad de las emisiones que desencadenan los impactos ambientales relacionados a la industria láctea, se ha utilizado ampliamente el Análisis de Ciclo de Vida (LCA por su nombre en inglés). Sin embargo, la fiabilidad del LCA se ha visto comprometida por un consenso poco claro con respecto a sus muchas opciones metodológicas; las cuales generan resultados heterogéneos e incompatibles. Esto ha creado confusión entre las partes interesadas y ha llevado a la proliferación incontrolada de credenciales medioambientales (Ecoetiquetas) para productos en Europa y en todo el mundo.

Como una solución a estos problemas metodológicos existentes durante la aplicación de LCA en la industria láctea, la Comisión Europea público las Reglas para el cálculo de la Huella Ambiental del Producto Lácteos (PEFCR-D por su nombre en inglés) como parte de la iniciativa europea para determinar Huellas Ambientales. La PEFCR-D tiene como objetivo aumentar la reproducibilidad, la coherencia y la comparabilidad de los resultados del LCA para productos lácteos. Sin embargo, la implementación de los requisitos metodológicos de la PEFCR-D es un desafío ya que los usuarios requieren conocimiento especifico adicional que no está relacionado al LCA, y también requieren del apoyo de herramientas informáticas especializadas que actualmente no están disponibles en el mercado. Estos desafíos disminuyen la aplicación práctica de la PEFCR-D en la industria láctea y, por lo tanto, limita la evaluación ambiental constante de los sistemas lácteos y no permite que la industria satisfaga la demanda del mercado por productos lácteos ambientalmente eficientes.

La industria láctea debe ser respetuosa con el medio ambiente pero no bajo ningún costo económico ni social; económicamente accesible, pero sin afectar al ambiente ni a la sociedad y, finalmente, debe buscar la equidad social, pero sin impactar al ambiente ni a la economía. Lo cual hace que estos objetivos estén frecuentemente en conflicto. Razón por la cual, esta tesis tiene como objetivo optimizar la sostenibilidad ambiental de la industria láctea en conformidad con la Metodología de la Huella Ambiental del Producto de la Unión Europea para mejorar su competitividad en un mercado cada día más exigente para productos ambientalmente amigables.

Con esta finalidad, esta tesis (i) introduce un enfoque para resolver el conflicto de balance masas que surge cuando se determinan las emisiones de N en conformidad con la PEFCR-D; (ii) presenta CalcPEF$_{\mathrm{Dairy}}$ como respuesta a la falta de una herramienta informática especializada que cumpla con los requerimientos de la PEFCR-D; y utiliza (iii) auditorías energéticas e (iv) indicadores de circularidad

para evaluar y proponer mejoras de optimización a la medida de los sistemas lácteos; ya que se consideran sus beneficios ambientales y económicos.

Los resultados de esta tesis demostraron que es posible una evaluación y mejora ambiental constante de los sistemas lácteos mediante el uso de herramientas especializadas como CalcPEF$_{\text{Dairy}}$, auditorías energéticas e indicadores de economía circular; y que juntos son capaces de identificar y proponer medidas de mejora de alto impacto. Los resultados también demuestran la viabilidad de comunicar adecuadamente los resultados medioambientales obtenidos con CalcPEF$_{\text{Dairy}}$ como una estrategia de marketing. Ya que la calidad y confiabilidad de los resultados obtenidos es tal que pueden usarse en un proceso de verificación externo para obtener una declaración ambiental y una Ecoetiqueta para un producto lácteo disponible en el mercado. Estas credenciales medioambientales verificadas brindan a los productores lácteos la posibilidad real de aumentar sus ganancias económicas sin afectar la sostenibilidad ambiental de su sistema productivo y productos.

Resum

Tot i ser un motor social i econòmic rellevant, la indústria lletera és molt coneguda pel seu elevat consum de recursos naturals i per generar grans quantitats d’emissions que afectin la qualitat del medi ambient. Per identificar amb precisió l’origen i la quantitat d’emissions que desencadenen impactes ambientals relacionats amb la indústria lletera, s’ha utilitzat àmpliament l’Avaluació del Cicle de Vida (LCA pel seu nombre en anglès). Tanmateix, la fiabilitat de l’LCA ha estat posada en perill per un consens poc clar sobre les seves moltes opcions metodològiques; que generen resultats heterogenis i incompatibles. Això ha creat confusió entre les parts interessades i ha provocat la proliferació incontrolada de les credencials verdes (Ecoetiquetes) per a productes a Europa i a tot el món.

Com una solució a aquests problemes metodològics existents durant l'aplicació de LCA en la indústria làctia, la Comissió Europea públic les Regles per al càlcul de la Petjada Ambiental de l'Producte Làctics (PEFCR-D pel seu nom en anglès) com a part de la iniciativa europea per determinar Petjades Ambientals. La PEFCR-D té com a objectiu augmentar la reproductibilitat, la coherència i la comparabilitat dels resultats de l'LCA per a productes lactis. No obstant això, la implementació dels requisits metodològics de la PEFCR-D és un desafiament ja que els usuaris requereixen coneixement específic addicional que no està relacionat a l'LCA, i també requereixen del suport d'eines informàtiques especialitzades que actualment no estan disponibles al mercat. Aquests desafiaments disminueixen l'aplicació pràctica de la PEFCR-D a la indústria làctia i, per tant, limita l'avaluació ambiental constant dels sistemes lactis i no permet que la indústria satisfaci la demanda de mercat per productes lactis ambientalment eficients.

La indústria làctia ha de ser respectuosa amb el medi ambient però no sota cap cost econòmic ni social; econòmicament accessible, però sense afectar l'ambient ni a la societat i, finalment, ha de buscar l'equitat social, però sense impactar a l'ambient ni a l'economia. La qual cosa fa que aquests objectius estiguin freqüentment en conflicte. Raó per la qual, aquesta tesi té com a objectiu optimitzar la sostenibilitat ambiental de la indústria làctia de conformitat amb la Metodologia de la Petjada Ambiental de Producte de la Unió Europea per millorar la seva competitivitat en un mercat cada dia més exigent per a productes ambientalment amigables.

Amb aquesta finalitat, aquesta tesi (i) introdueix un enfocament per a resoldre el conflicte de balanç masses que sorgeix quan es determinen les emissions de N en conformitat amb la PEFCR-D; (Ii) presenta CalcPEF$_{\text{Dairy}}$ com a resposta a la manca d'una eina informàtica especialitzada que compleixi amb els requeriments de la PEFCR-D; i utilitza (iii) auditories energètiques i (iv) indicadors de circularitat per avaluar i proposar millores d'optimització a la mesura dels sistemes lactis; ja que es consideren els seus beneficis ambientals i econòmics.

Els resultats d'aquesta tesi van demostrar que és possible una avaluació i millora ambiental constant dels sistemes lactis mitjançant l'ús d'eines especialitzades com CalcPEF$_{\text{Dairy}}$, auditories energètiques i indicadors d'economia circular; i que junts són capaços d'identificar i proposar mesures de millora d'alt impacte. Els resultats també demostren la viabilitat de comunicar adequadament els resultats mediambientals obtinguts amb CalcPEF$_{\text{Dairy}}$ com una estratègia de màrqueting. Ja que la qualitat i fiabilitat dels resultats obtinguts és tal que poden usar-se en un procés de verificació extern per obtenir una declaració ambiental i una Ecoetiqueta per a un producte lacti disponible al mercat. Aquestes credencials mediambientals verificades brinden als productors lactis la possibilitat real d'augmentar els seus guanys econòmics sense afectar la sostenibilitat ambiental del seu sistema productiu i productes.

Preface

This thesis was developed from February 2017 to July 2020 in compliance with the PhD program in Experimental Sciences and Technology of the *University of Vic – Central University of Catalunya* (UVic-UCC). The work was carried out in the for the Biodiversity, Ecology, Environmental and Agrifood Technologies Technological Centre (BETA Tech. Centre). This dissertation addressees the need of the dairy industry to produce environmentally efficient dairy products in compliance with the European Union's Product environmental Footprint methodology; It contributes to overcome the lack of specialised IT tools to facilitate the PEF implementation and to build the single European market for green products. In particular, it shows the practical implementation of different tools as part of a clear strategy for a continuous environmental assessment and optimization of dairy systems towards a more sustainable dairy industry.

This work was developed in the framework of:

- The **INNOTRANSLACT** Project (EFA005/15) under the program INTERREG POCTEFA co-financed by the European Regional Development Fund.
- A **Demonstrative** project which was co-financed by the Department of Agriculture, Livestock, Fisheries, Food and natural environment of the Government of Catalonia and by the European Agricultural Fund for Rural Development.

Moreover, in 2018, part of this research was conducted during a three-month research stay in Department of Civil & Environmental Engineering of Brunel University London in the United Kingdom. This research stay made this work eligible for the *Mention of International Doctoral Research.*

This is a paper-based thesis, which have been either published or are in preparation to be submitted in international peer-reviewed journals:

- **Egas, D.**, Vasilaki, V., Katsou, E., Stanchev, P., Ponsá, S., Colon, J., 2019. Implementation of the Product Environmental Footprint Category Rules for dairy products: An approach to assess nitrogen emissions in a mass balanced dairy farm system. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2019.01.110
- **Egas, D.**, Ponsá, S., Colon, J., 2020. CalcPEFDairy: A Product Environmental Footprint compliant tool for a tailored assessment of raw milk and dairy products. J. Environ. Manage. 260, 110049. https://doi.org/10.1016/j.jenvman.2019.110049

- Stanchev, P., Vasilaki, V., **Egas, D.**, Colon, J., Ponsá, S., Katsou, E., 2020. Multilevel environmental assessment of the anaerobic treatment of dairy processing effluents in the context of circular economy. J. Clean. Prod. 261, 121139. https://doi.org/10.1016/j.jclepro.2020.121139
- **Egas, D.**, Ponsá, S., Colon, J. Direct energy consumption of small dairy production chains: A consumption, environmental and economic assessment. *Manuscript in preparation.*

Furthermore, additional training and knowledge were obtained through other complementary scientific activities during the PhD process such as:

- Private R+D+i projects: Carbon and water Footprint ISO certification for Argal S.A pig meat products. Standards: CEN ISO/TS 14067:2015 and CEN ISO/TS 14067:2015. Certified by: AENOR IINTERNATIONAL, S.A.U. (2018)
- A one-month research stay was completed in the Danish Centre for Environmental Assessment of Aalborg University in Denmark (2019).
- **Egas, D.**, Ponsá, S., Colon, J. "Environmental Impact Assessment of Dairy Production Systems: A PEF Based Approach". 3rd International Congress of Chemical Engineering, (2019). *Oral presentation.*

This thesis is organized in six chapters with the main contents summarized below.

The introduction, background and context of this thesis are set up in **chapter 1,** stating the challenges of using the PEF methodology to environmentally assess dairy systems and how its efficient implementation together with other tools such as energy audits and circularity indicators could lead the dairy industry towards a more sustainable status. This thesis objectives are stated in **chapter 2.**

Chapter 3 presents the general over view of the methodology followed by this thesis. It summarizes the methodological requirements of the PEFCR for dairy, presents the steps taken to develop $\text{CalcPEF}_{\text{Dairy}}$ an specialized PEF IT tool for dairy products and describes the methodology followed to carry out the energy audits to dairy systems.

Then, the papers generated in the framework of this thesis are presented in **chapter 4** as part of this thesis results; so, they can be later discussed in **chapter 5** when being applied to environmentally assess real traditional dairy systems and lead them towards a more environmentally sustainable status.

Finally, the overall conclusions of this thesis along with the recommendation of future research lines are presented in **chapter 6**.

Chapter 1: Introduction

1.1 The dairy industry

Dairy products are worldwide consumed since they contribute with irreplaceable components to the human diet, dairy industry is one of the largest and most important industries in the world and in Europe. In 2019, the global dairy market reached a value of USD 673.8 billon (bn) and it is expected to reach a USD 1032.7 bn value by 2024, this is a compound annual growth rate of nearly 8% between the 2019–2024 period (IMARK, 2019). A fundamental component and also product of this industry is milk which makes this industry dependent on the agricultural livestock sector. Milk is one of the most produced and valuable agricultural commodities worldwide. According to the Food and Agriculture Organization of the United Nations (FAO), milk is not only a local commodity but also a global commodity, as milk and dairy products account for about 15% of global agricultural trade (FAO, 2016). The global dairy sector grows rapidly, as the global milk production is expected to grow at an average annual rate of 1.1% until reaching a yearly production of more than 1 bn tons by 2050 (Alexandratos and Bruinsma, 2012).

According to the latest Food Drink Europe's report (2019), the dairy industry is one of the largest and most important sub-sectors of the European Union (EU) food and beverage sector since it accounts for 13% of the sector's turnover and 8% of the employment in the sector. Within the dairy industry, milk production represents an important part of both the production and the agricultural economy of the EU. In 2018, EU-28 states produced 172.2 Mt of milk and it represented 13.2% (€ 57.33 bn) of the total EU's agricultural products value. A 97% of the total milk produced was cattle's milk while the rest is a distribution between sheep's milk, goat's milk and buffalo's milk. Most of the total produced milk (93%, 160 Mt) is delivered to the dairy industry and the rest (12.2 Mt) is used in the farm, either consumed or directly sold (Eurostat, 2019).

Regarding the production of cattle's milk, Germany (20.0%) and France (15%) were the main producers; they together with 6 other countries (United Kingdom, Holland, Poland, Italy, Turkey and Spain) generated nearly 80 % of total cattle's milk delivered to the dairy industry. On the other hand, Spain (19.6%), France (15.7%), Greece (15.7%) and Italy (13.7%) dominate the production of milk from other animals (mainly goat and sheep); the dairy industries of these countries collect more than 75% of the milk produced from these other animal species (Eurostat, 2019).

There are 10,5 million farms in Europe, of which about 25.1% are livestock specialist farms (2.64 million) and 21.1% (2.21 million) perform mixed farming activities; most of them combine cropping activities with livestock activities and the purpose of this livestock is for dairy or fattening. A 21% of the livestock specialist farms (567,000) exclusively dedicate their activities to dairy (Eurostat, 2018). It is estimated that there are 11,760 dairy processors in the EU; 30% of which are considered small dairy processors.

As shown, the dairy industry highly depends on the dairy livestock sector; which, despite being a relevant economic driver, is well known to be the biggest consumer of natural resources and releaser of emissions that affect the environmental quality. Therefore, as a consequence of the constant growth of population, the demand of dairy products will increase; leading to an increment on the release of emissions to the environment and the depletion of natural resources. It is estimated that by 2050 the world population will increase up to 9.6 bn; as result, the global dairy livestock sector faces the unprecedent challenge of increase their production by using scarce natural resources such as land, water and nutrients; and by reducing wastes and emissions to the environment (Gerber et al., 2013).

1.1.1 The dairy industry and its environmental impacts

Undoubtedly, milk and dairy products are essential in the diet of humans; especially among the most vulnerable ones (e.g. pregnant women and children) that battle against hunger and malnutrition. They provide irreplaceable nutritional benefits, supply energy and significant amounts of proteins and micronutrients, for example, calcium, magnesium, selenium, riboflavin, vitamins B5 and B12 (Duan et al., 2018). From an economic perspective, dairy products are cheaper on a per 100 kcal basis when compared to meat, poultry, fish, fruit or vegetables (Westenhöfer, 2013). Moreover, dairy livestock is a regular and fast source of food and cash for farmers. Dairy livestock provides wealth and welfare: farmers can sell livestock in time of need to generate cash, use it as collateral to obtain economic resources and transport it even for long distances, as a result livestock is an important asset for farmers if they are forced to leave their homestead (FAO, 2016).

However, due to the dairy industry supply chain dependency on livestock and the high demand of its products, this industry environmental impacts have gained attention. It has been suggested that dairy sector, alongside with meat and poultry sector, has the highest environmental footprint among the entire food industry (Munir et al., 2014; Nigri et al., 2014). Some (but not all) of the impacts associated with dairy sector are as follows: land degradation, water pollution, losses of biodiversity, deforestation and GHG emissions (Foley et al., 2011). While all of these environmental impacts are hazardous, GHG emissions receive greater attention from the global audience due to the increasing worldwide concern on climate change.

Dairy sector is a major contributor to global GHG emissions, particularly due to the large amounts of CH_4 and N_2O emissions caused by livestock farming activities (Challis et al., 2017; Gerber et al., 2013) and the high energy intensity of the dairy processing activities such as pasteurisation, evaporation or fermentation. Furthermore, the energy required for the production equipment and the cold storage of the final dairy products at the production facility, the distribution centre, the retailer store, and finally during the storage in the consumers' homes leads to other significant impacts such as photochemical ozone formation, ionizing radiation, ozone depletion, etc (Cardoso et al., 2017). The following paragraphs aim to describe the most common environmental impacts attributed to the dairy industry activities.

Climate Change:

Solar energy guides the climate and heats the surface of the earth. In turn, the earth radiates energy back into space through ultraviolet radiation. Atmospheric GHG (CH_4, N_2O and CO_2) trap part of the outgoing energy and retain heat. Without this natural greenhouse effect, the temperature of the earth would be lower than it is now, and life as we know it today would not be possible (Cubasch et al., 2013). The increase in the concentration of GHG in the atmosphere generates an increase in the greenhouse effect that modifies the different climates of the planet. This phenomenon, called climate change, is not a natural change but a climate change linked to human activity.

However, climate change is not just an increase in the global average temperature of the earth's surface, or an increase in the level of the sea and oceans, or a reduction in the areas covered by snow. The IPCC (2014) reports also warn about the increase in the frequency of extreme weather events, the severe alteration of hydrological regimes, effects on human health, animals and ecosystems, as well as various social and economic problems (e.g. expansion of pandemics).

The global livestock supply chain is one of the main drivers for global warming in the world since it releases around 14.5% (7.1 Gt CO_{2eq}/year) of the total human-induced (anthropogenic) GHG emissions; from which about 20% (1.4 Gt CO_{2eq}/year) is specifically attributed to dairy livestock supply chains. Due to these global GHG fluxes, it is projected that about 2.8 kg of CO_{2eq} are released per one kilogram of fat protein corrected milk (FPCM) (Gerber et al., 2013). In Europe, raw milk production, dominated by cattle, accounts for 29% (661 Mt CO_{2eq}) of the total GHG fluxes of the European livestock production including land use and land use change emissions (JRC, 2010).

Within the livestock supply chain, it is estimated that the livestock farming stage is responsible for most (49%) of the anthropogenic GHG emissions followed by the animal feed production and post farming stages (47% and 3% respectively) (Gerber et al., 2013). The livestock farming stage involves many different activities (e.g. animal housing, yards, manure storage and treatment and land application) from which GHG emission arise. CH_4 is attributed to the livestock's enteric fermentation and manure decomposition processes and represents around 44% of the GHG emissions generated in the livestock farming. About 27% of the GHG emissions are CO_2 which is mainly released during the production and transport of animal products and feed; and finally, approximately 29% of the GHG emissions are N_2O that is released from the manure and fertilizers (Shields and Orme-Evans, 2015).

Water consumption:

During the twentieth century, the world population has tripled, however, the use of water resources has multiplied by six in the same period. It is estimated that, within the next fifty years, the world population will increase by another 50% (Roser, 2019). This population growth, together with industrialization and urbanization, will lead to an increasing demand of water and will have serious consequences on the environment. In many regions of the world, and although water is abundant globally, human well-being and the health of ecosystems are being seriously affected by changes in the global water cycle caused to a large extent by human activities (WWAP, 2009) .

As a consequence, water has become a strategic resource for the economic development and survival of countries, the water problem is associated with two factors, (i) in the first place, water scarcity (lack of water to meet water human needs and maintain the quality of ecosystems) and (ii) secondly to the decrease in water quality (contamination of water bodies such as freshwater eutrophication, freshwater ecotoxicity or freshwater acidification) (Cosgrove and Loucks, 2015).

The depletion of water resources in the framework of an environmental impact assessment is represented by the consumption of "blue water" defined as the abstraction of fresh water that is evaporated, incorporated into products and waste, transferred to different basins or they discharge at sea, depriving its use to another user (human or ecosystem) when it is consumed in a determined area (Mekonnen and Hoekstra, 2010). “Blue water consumption” refers to the fraction of water withdrawal that has been taken out from the originating river basins and, therefore, it is unavailable for users because it has not returned to the original water basing due to evaporation, transpiration, product integration or because it has been discharged into other basing or into sea (Boulay et al., 2018; Hoekstra et al., 2012). It is suggested that the production of animal feed consumes 20% of the global blue water (FAO, 2019)

The water footprint of ruminants consists mainly of indirect consumption of food production (fodder, feed, etc.) and direct consumption associated with drinking water (e.g. livestock consumption needs) and process water (e.g. cleaning) (Chapagain and Hoekstra, 2003). For instance, the 95% and 96% of the water shortage when producing conventional and organic milk respectively is caused by the irrigation of the crops used for feed purposes (Palhares and Pezzopane, 2015), on the contrary, the water used in the farms and the processed milk products represents a small proportion to the contribution of the total water shortage (Vasilaki et al., 2016).

Nitrogen eutrophication (marine and terrestrial)

Nitrogen eutrophication affects soils and mostly marine water since N is the limiting component in the eutrophication of marine ecosystems. Within the livestock supply chain, soil N eutrophication is mainly caused by reactive volatile N (mostly NO_x and NH_3) arising from the management of livestock manure (Webb et al., 2005). N eutrophication is tribute to the NH_4^+, NH_3 NO_3^- , released by manure deposition and the application of manged manure and fertilizers, that reach coastal areas through water streams or erosion.

Soil N eutrophication is a consequence of the increment on the budget of reactive volatile N and therefore, leads to changes on the composition of vegetation; creating more nitrophilous species and replacing other species in the ecosystem. Moreover, it alters the balance of nutrients in the soil which results in an increased risk of vegetation damage. Among other emissions, the Air Quality Directive sets limits for these reactive volatile N atmospheric emissions (NH_3 and NO_x). The directive sets reduction targets for NH_3 between 0 to 43% depending on the member states.

Marine water N eutrophication results in biomass booms which lead to toxic and harmful impacts on marine ecosystems and human health. It generates coastal dead zones since the lack of oxygen in marine water results in death of fish and other marine fauna. Despite not being the limiting factor to cause freshwater eutrophication , the high level of NO_3^- limits the use of fresh water for irrigation and drinking purposes (Ansari et al., 2011).

The application of livestock manure is a relevant variable when talking about any kind of eutrophication caused by either N or P since it contains an excess of these nutrients due to the livestock's low nutrient absorption capacity. Thus, a nutrient surplus is created when it is later applied, together with other mineral fertilizers, to the animal producers' small areas of agricultural land. This causes an excess of nutrients which increases the net accumulation of P in soil, NH_3 emissions to the atmosphere and nitrates (NO_3^-) and phosphates (PO_4^{3-}) to water bodies. Reason why, regarding N eutrophication, the EU Nitrates Directive (EC, 1991) sets the amount of 170 kg N/ha·year as maximum application rate of N from agricultural sources such as manure.

Phosphorus eutrophication (freshwater)

Phosphorus (as mainly PO_4^{3-}) is the limiting factor that causes the eutrophication of freshwater ecosystems. The excessive amount of P results in the proliferation of algae and other fresh water plants. When this excess of algae/plants die, their microbial degradation consumes most of the oxygen dissolved in the freshwater bodies (e.g. rivers), reducing the capacity of the water to support life.

Due to its surplus of nutrients, the application of livestock manure to soil, for agricultural purposes, is the main source of P in the livestock supply chain. Due to this, the EU Water Framework Directive (EC, 2000) sets demanding objectives for PO_4^{3-} concentrations in surface waters and it is estimated to have an even greater impact on agricultural activities than the nitrate directive.

the manure applied to soil together with other mineral fertilizers are main source of P since they are used as fertilizers to produce crops and animal feed. Hence, a proper management of these P fluxes, from ingestion to manure management, is also an important lever for milk producers to improve their sustainability record (Ansari et al., 2011).

Acidification

Acidifying pollutants have a wide variety of impacts on soil, groundwater, surface water, biological organisms, ecosystems and materials (e.g. buildings). Some examples are the mortality of fish in lakes, the decline of forests and the deterioration of construction materials. The main acidifying compounds are SO_x, NO_x, HCl, and NH_x emitted into the air which, when combined with other molecules in the atmosphere, result in the acidification of ecosystems. For example, NH_3 neutralizes atmospheric nitric or sulfuric acid and, when transformed into NH_4^+, is deposited in the soil. During nitrification, NH_4^+ is transformed to NO_3^-, releasing H^+. In a surplus N situation, this release of H^+ will cause acidification of the soil. Acidification can result in a greater mobilization of heavy metals such as aluminium, causing an increase of this element in groundwater, affecting the growth of plants and roots, increasing the risk of vegetation damage and being toxic both for animals and for humans (Lekkerkerk et al., 1995).

Nutrients in manure or mineral fertilizers (mainly N) used to produce feed can emit NO_x, NH_3 and SO_x. These emissions contribute to the acidification of soils and water when they are released in areas where buffer capacity is low, which leads to acidification of soil and water (Pawłowski, 1997).

Soil use

The degradation of soil quality is a major concern due to the scarcity of fertile soil, and should be adequately addressed in an evaluation of agroforestry systems (Milà I Canals et al., 2007). The fertile soil is possibly the most relevant type of soil from the perspective of scarce resources, and has been defined as the most limiting resource in the near future before the energy shortage or the scarcity of other mineral resources (Weidema and Meeusen, 2000). Therefore, apart from the amount of soil used, changes in the quality of said soil should also be evaluated. According to Pimentel et al.(1995), 0.5 ha of arable land per capita is needed to adequately feed people. On the other hand, according to Food and Agriculture Organization (FAO, 2011) the arable land per person will decrease from 0.45 ha/person needed in the sixties (0.7 in developed countries and 0.35 in developing countries) to approximately 0.20 ha/person in year 2050 (0.45 in developed countries and 0.20 in developing countries).

Dairy products that are at the top of the food pyramid since they play an important role in the competition for arable land, through the production of feed and grazing areas. Currently, 70% of the global agricultural land is used for livestock grazing or for animal feed (FAO, 2019)

Other environmental impacts

In addition to the previously mentioned environmental impacts, the dairy industry also influences the biodiversity loss, ozone depletion, ecotoxicity, formation of particulate matter/respiratory inorganics and photochemical ozone formation.

The *Biodiversity loss* is mainly caused by the many activities related to the dairy industry that lead to the habitat loss of animal and vegetal species. For instance, extensive dairy livestock farming, converts natural habitats on grazing fields and leads to the displacement of native animal and vegetal species. Also, due to the production of animal feed, no native vegetal species could be introduced to new habitats and this could put under danger native vegetal species. For this reason, the change on the land use for livestock activities is more likely to generate biodiversity loss.

Ozone depletion is mainly caused by the man-made emissions of halocarbons such as CFCs and HCFCs, halons and gases containing chloride and bromine. In the dairy industry these gases are commonly released due to the leakage of cooling compounds needed for refrigeration of materials and final dairy products until its consumption. These gases have a high energetic radiation, when reaching the stratosphere, they break down releasing free radicals that destroy the ozone molecule. Due to the increment of these gases in the stratosphere since 1985 it has been evidenced a reduction of the earth's ozone layer. As a consequence, there is an increment of the hazardous ultra violet radiation that reaches the earth's surface; this increases the risk of skin cancer in humans and damages plants (Stranddorf et al., 2005).

Ecotoxicity this impact covers a wide range of acute and chronic toxicity effects in different species of soil and water. The substance that contribute to this category are numerous and cannot be easily arranged in a finite number of groups. However, in the dairy industry, ecotoxicity is attributed to the application of pesticides, fertilizers and other persistent organic pollutants (POP). Any substance that affects the function and structure of the ecosystem by exerting toxic effects on the organisms which live in it can be considered as an ecotoxicity contributing substance (Frischknecht and Joliet, 2019).

Particulate matter/respiratory inorganics is attributed to ambient concentrations of fine particulate matter ($PM_{2.5}$) in the air that are directly arising from indoor and outdoor activities. However, these particles can also be indirectly created from SO_2 and NO_x emissions that create sulphate and nitrate aerosols. In the dairy supply the release of particulate matter mainly originates from the livestock feed and from the livestock housing and holding areas (EMEP/EEA, 2016a). The formation of particulate matter mainly affects human health (Frischknecht and Joliet, 2016).

Photochemical ozone formation is a consequence of releasing solvents, volatile organic compounds (VOCs) to the atmosphere; which under the influence of the sun's light are oxidized and form ozone.

These solvent and VOCs are mainly released by combustion processes however, in the dairy supply chain VOCs emissions arise from livestock buildings, yards, manure management and application, and even from livestock feeding with silage (EMEP/EEA, 2016a). The generated ozone stays in the earth's troposphere thus cannot rise to the stratosphere and reduce the depletion of the ozone layer. Hence, the ozone is trapped in the troposphere and attacks organic compounds in any material, animal or plant that is exposed to air. Moreover, it causes respiratory problems to humans due to the generation of photochemical smog in cities (Stranddorf et al., 2005).

1.2 Life Cycle Assessment in de dairy industry

The dairy industry, like any other industry in the world, has also certain environmental drawbacks despite its several economic, social and nutritional benefits. Environmental impacts associated with dairy product supply cannot be avoided, but can only be assessed, identified and reduced. Hence, to identify the quantities and the source of these impacts accurately, an environmental life cycle assessment (LCA) is essential.

LCA methodology

Life cycle assessment (LCA) is a standardized methodology to assess the potential released emissions and consumed resources through a product life cycle (Finnveden et al., 2009; ISO 14040, 2006). Currently it is a widely used tool for environmental management and is normalized by the ISO 14040 (2006) for environmental management systems. A complete LCA has a "cradle-to-grave" approach which includes each stage of the product's life cycle; from the exploitation of raw materials, through the stages of production and use, until the waste management stage. The LCA methodology follows four well defined steps as shown in Figure 1.1.

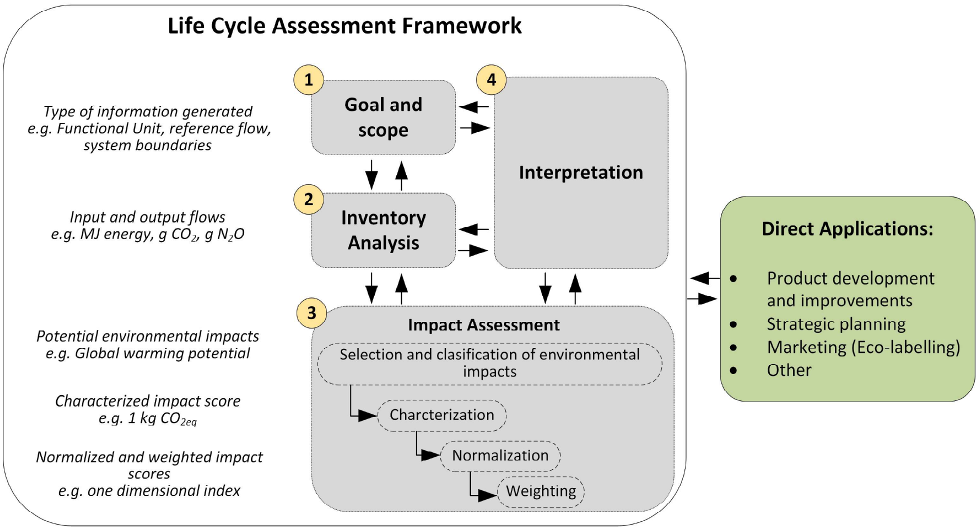

Figure 1.1 Framework of the Life Cycle Assessment methodology. Adapted from Hauschild et al. (2018)

The first step is the goal and scope definition where a precise and measurable functional unit (FU) is defined together with the study's reference flow and system boundaries. The system boundary represents all the life cycle stages of the studied system with their respective process and sub-process that use resources (input flows) to produce the desired products, co-product and unwanted outputs such as wastes and emissions (output flows). The second step is the inventory analysis; here the types and quantities of the smallest elements of the system's input and output flows (elementary flows) are listed to create a life cycle inventory (LCI). The LCI reflects the input and output flows needed to or generated from the production of one FU from the assessed system.

The third step is the life cycle impact assessment (LCIA) where the LCI flows are converted into characterized midpoint or endpoint environmental impacts through characterization factors; and optionally afterwards these characterised scores can be normalized and weighted to generate a unique environmental single score. The last step is the interpretation of the LCIA results; here the system's environmental impact drivers "hot-spots" are identified and assessed; this allows the formulation of conclusions and recommendations to enhance the product system's environmental performance. Finally, the LCA results can be used to environmentally manage the production systems, to ensure that the industries are resource efficient and as marketing strategies through the generation of green credentials.

LCA applied to assess the dairy industry's environmental impacts

The use of LCA methodology is well stablished in industrial production systems since it was primarily developed to assess the environmental performance of its products (Mourad et al., 2007). However, because of its accuracy, objectiveness and transparency, LCA is also applied to environmentally assess different types of food production systems such as dairy (Notarnicola et al., 2017; Roy et al., 2009).

LCA to study of the environmental impacts related to the dairy industry's supply chain gained momentum in the last two decades (Figure 1.2). According to Scopus database since the year 2000, and until April 6th 2020, there are over 272 research studies related to the key words "dairy LCA" and "life cycle assessment dairy products" or "life cycle assessment dairy farms". The use of LCA in the dairy industry has drastically increased in the last decade passing from an average publication of 3 documents per year (from 2000 to 2009 inclusive) to 23 documents per year (from 2010 to 2019 inclusive). So far in 2020, there are 15 documents published; this represents a 40% of the total documents (38) published in 2019 and 65% of the average yearly documents published in the last decade.

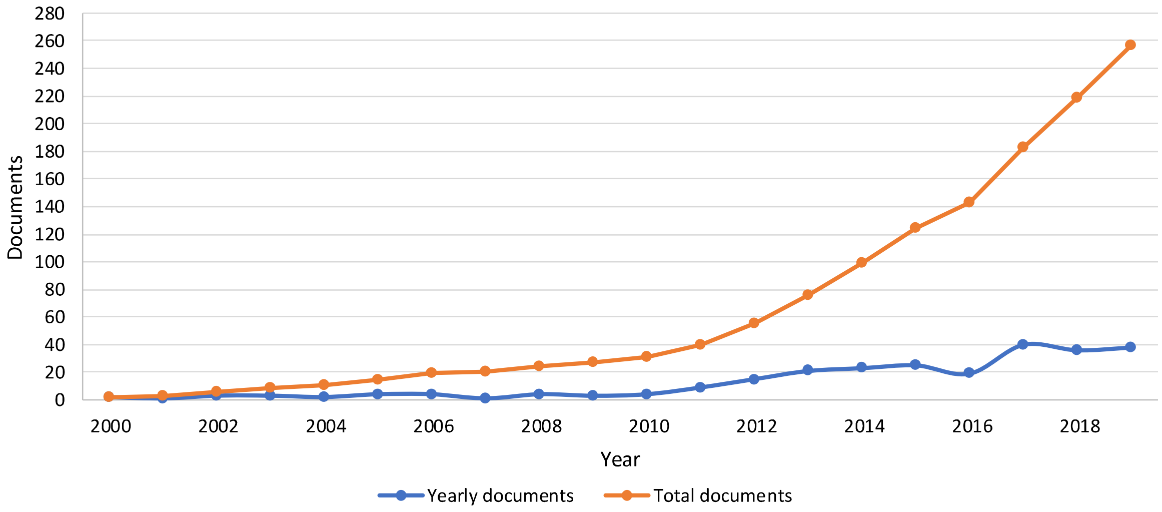

Figure 1.2: Documented dairy LCA studies reported by Scopus from 2000 to 2019 inclusive.

These documented dairy LCA studies involve the assessment of raw milk production systems and dairy processing systems; most of them focus on the assessment of cattle production systems and on determining global warming potential or carbon footprint. There is minimum information regarding raw milk and dairy products obtained from small livestock such as sheep and goat; and also, from other environmental impacts directly related to the dairy industry such as eutrophication, land use or acidification.

The practice of only focus dairy LCA studies on one environmental impact, such as global warming potential, does not complies with the LCA principles stated in the ISO 14040 (2006) which aim to avoid the shifting of a potential environmental problem to another when performing an LCA. Reason why several authors (Arvanitoyannis et al., 2014; Baldini et al., 2017; Üçtuğ, 2019; Yan et al., 2010) have not included these single environmental impact studies in their work when reviewing the existing dairy LCA studies. These review works analysed a total of 62 documented studies that were published between 2000 and 2018. Further information regarding these reviewed studies can be found in Table A 1 and Table A 2 of the Annex A-1.

Among this total of reviewed studies, 29 evaluate raw milk production systems while the remaining 33 focus on dairy processing systems. All these studies have assessed global warming potential among other 29 different midpoint environmental impacts as shown in Table 1.1

Table 1.1: Environmental impact coverage of dairy LCA studies. Adapted from Baldini et al. (2017), Üçtuğ (2019) and Yan et al. (2010)

Environmental impact (midpoint)	**Number of studies**		
	Raw milk production	**Dairy processing**	**Total**
Global Warming	29	33	62
Acidification			
Acidification (undefined)	23	18	41
Terrestrial acidification	-	7	7
Biodiversity	1		1
Organic and inorganic particles	-	1	1
Energy use	14	18	32
Ecotoxicity			
Ecotoxicity (undefined)	-	5	5
Freshwater Ecotoxicity	3	8	11
Marine Ecotoxicity	2	5	7
Terrestrial Ecotoxicity	4	6	10
Eutrophication			
Eutrophication (not specified)	20	15	35
Freshwater Eutrophication	2	12	14
Marine Eutrophication	2	9	11
Terrestrial eutrophication	-	3	3
Human Toxicity			
Human Toxicity (undefined)	3	11	14
Human toxicity, cancer	-	2	2
Human toxicity, non-cancer	-	1	1
Ionising radiation	-	4	4
Land Use	24	12	36
Land Use Change	6	2	8
Ozone Depletion	3	19	22
Particulate matter formation	1	6	7
Photochemical Oxidants Formation	5	22	27
Resource depletion			
Abiotic resource depletion	7	10	17
Mineral resource depletion	-	5	5
Fossil resource depletion	-	4	4
Mineral, fossil and renewable resource depletion	-	1	1
Water resource depletion	-	11	11
Toxicity (undefined)	-	1	1
Waste produced	-	1	1

On one hand, the identified raw milk production LCA studies analyse cradle to farm gate systems and report the environmental impacts related to raw milk at the farm (Annex A, Table A 1). The studies evaluate a total of 17 different impact categories, from which global warming, acidification and land use are assessed the most. Despite having the same system boundaries, a direct comparation of the characterized environmental impact scores of all these studies is not possible since they have followed different LCA methodological choices regarding the FU, developing the LCI and defining the allocation criteria and the LCIA method to be used.

For instance, some of the raw milk prodcution studies use FU like litters or kilograms of raw milk while others use kilograms of fat protein corrected milk (FPCM) or kilograms of energy corrected milk (ECM). Some studies avoid allocation and apply system expansion while others apply a biological, fat and protein content, economic or mass criteria to allocate the environmental impacts to the produced raw milk and to the other farm coproducts (manure, meat and crops). Finally, diverse LCIA methods such as CML, ReCiPe and ILCD are used by the different studies (Baldini et al., 2017).

By taking into consideration the many LCA methodological choices that influence the LCIA results, Table 1.2 presents a summary of the global warming, acidification, eutrophication, energy use and land use characterised results of 10 “similar” studies that have adopted FPCM as FU. As shown despite following similar FU, the studies’ results for these impact categories have a wide range of variation; mainly due to the different LCA methodological choices that these studies have followed.

Table 1.2: Global warming, acidification, eutrophication, energy use and land use environmental impact results summary per kg FPCM

Source	**Environmental impact**				
	Global warming (kg CO_{2eq})	**Acidification (g SO_{2eq})**	**Energy use (MJ_{Eq})**	**Eutrophication (g PO_{4eq})**	**Land use (m^2)**
Meul et al. (2014a)	1.04	13.57	3.41	3.78	0.88
Nguyen et al. (2013)	1.28	0.00	-	0.00	1.32
O'Brien et al. (2012)	0.95	10.50	3.10	4.75	0.83
Penati et al. (2013)	1.15	9.40	5.39	4.00	-
Thomassen et al. (2009)	1.36	22.00	5.30	7.10	1.28
Van der Werf et al. (2009a)	1.06	11.20	2.70	11.40	-
Basset-Mens et al. (2008)	0.93	7.20	1.51	6.05	1.15
Zehetmeier et al. (2014)	1.02	8.12	-	2.93	1.07
Battini et al. (2014)	1.18	0.00	3.59	0.00	0.98
Bava et al. (2014a)	1.26	12.80	5.46	0.37	0.96
Chen and Corson (2014)	1.06	15.37	-	7.39	-
Average	1.12	7.20	3.81	6.05	1.06
Maximum	1.36	11.74	5.46	5.38	1.32
Minimum	0.93	22.00	1.51	11.40	0.83

Nonetheless, the reviewed literature identifies the dairy farm activities as the principal source of emissions affecting the environmental performance of the produced raw milk. Moreover, farm activities such as livestock feed production, livestock enteric fermentation, and the livestock manure management/storage and the farm’s consumption and production of energy (electric and thermal) are identified as main sources of pollutant emissions that cause environmental impacts (Meul et al., 2014a).

Turning now to the dairy processing LCA studies (Annex A, Table A 2), the identified documents commonly produce more than one dairy product (multiproduct systems) at the time since they use dairy coproducts such as fat from milk skimming to produce other final dairy products like yogurt. Cheese, pasteurized milk and yoghurt are the dairy products that have been assessed the most; 17, 11 and 6 studies analyse their production systems respectively (Figure 1.3).

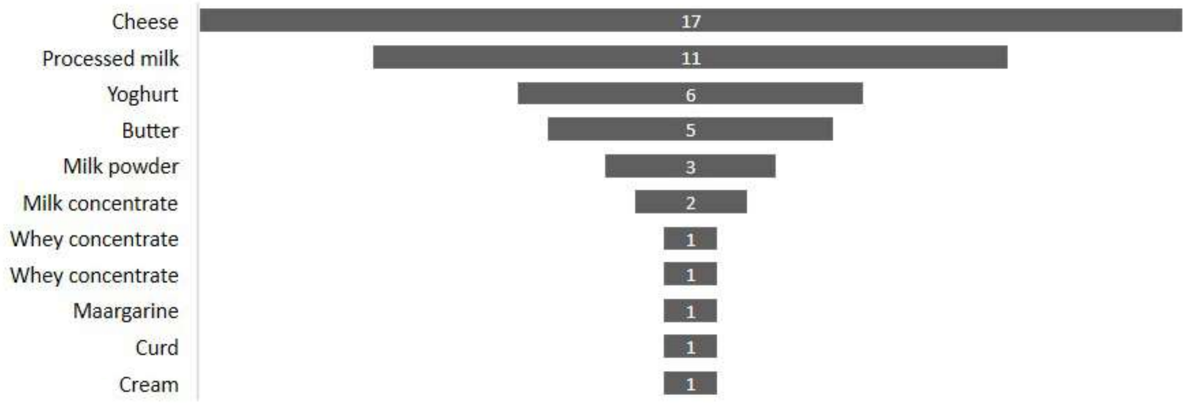

Figure 1.3: Dairy products coverage of dairy LCA studies. Adapted from Baldini et al. (2017), Üçtuğ (2019) and Yan et al. (2010)

Within the 33 identified dairy LCA studies, a total of 29 different environmental impacts where evaluated (Table 1.1). Environmental impacts such as global warming (33 studies), photochemical ozone formation (22 studies), ozone depletion (19 studies) and acidification (18 studies) are highly assessed. It is worth mentioning that only 10 studies have assessed water resource depletion.

As well as in the raw milk production LCA studies, these dairy processing studies are also influenced by the many available LCA methodological choices. Hence, in addition to the previous mentioned LCA methodological choices (FU, allocation, LCI, LCIA methods, etc) that affect the assessment of raw milk production systems, the dairy processing LCA studies are influenced by the different systems boundaries used to assess similar products; some of these studies, perform full LCA studies with cradle-to-grave boundaries while others perform partial LCA studies.

These partial studies don't include all the product's life cycle stages in their systems boundaries. For example, some studies set cradle-to-gate boundaries which include environmental emissions until the dairy processing stage; and a few other studies set gate-to-gate boundaries that only focus on the processing facility environmental impacts. Due the different LCA methodological choices followed by the studies' authors, a direct comparation of the characterized impact scores of the different dairy products is not an effective approach. Instead, for cheese, processed milk, yogurt and butter, Table 1.3 presents the average contribution of different dairy processing stages to different environmental impact categories (Üçtuğ, 2019).

Table 1.3: Average contribution percentage (%) of different dairy production stages to different environmental impact categories for cheese, processed milk, yoghurt and butter. Minimum and maximum percentages written in parentheses where applicable. Adapted from Üçtuğ, (2019).

Impact category	**Dairy product**														
	Cheese					**Processed milk**			**Yoghurt**				**Butter**		
	Raw milk production	**Processing**	**Transport**	**Storage and use**	**Waste treatment**	**Raw milk production**	**Processing**	**Transport**	**Raw milk production**	**Processing**	**Transport**	**Storage and use**	**Raw milk production**	**Processing**	**Transport**
Abiotic resource depletion	59 (43–74)	38 (22–57)	6 (4–10)	-*	5	28 (15–40)	72 (60–85)	-*	23 (18–26)	71 (63–75)	10	9	66	34	-*
Acidification	92 (88–95)	7 (2–10)	2 (1–3)	-*	2	81 (58–93)	21 (5–39)	3 (3–3)	69 (54–84)	36 (30–41)	3	2	98 (96–99)	4	1
Ecotoxicity	75 (55–95)	9	-*	3	3	60	40	-*	60	38	-*	10	87	13	-*
Energy use	60 (44–83)	26 (11–56)	11	6	4	31 (22–40)	69 (60–78)	-*	18	65	8	5			
Eutrophication	88 (66–96)	10 (3–20)	2 (1–3)	1	5 (3–8)	88 (74–97)	14 (2–25)	1	77 (55–93)	29 (17–41)	1	3	97 (95–99)	4	1 (1–1)
Global warming	82 (71–98)	12 (7–18)	3 (1–5)	1	2 (2–2)	70 (55–85)	25 (11–45)	3 (2–4)	47 (34–58)	51 (50–51)	5	7	90 (84–95)	11 (8–14)	2 (1–2)
Human toxicity	47 (21–60)	22 (5–40)	16 (12–20)	3	4 (1–6)	37	63	-*	-	-	-	-	88	12	-*
Land use	98 (96–99)	2 (2–2)	1	-*	-*	95	-*	-*	95	5	-*	-*	99	1	-*
Ozone layer depletion	39 (7–71)	38 (10–80)	21 (2–55)	2	4	43 (22–62)	37 (27–50)	20 (11–29)	20	63	7	8	-	-	-
Photochemical ozone formation	77 (55–98)	16 (3–32)	12 (6–18)	1	2 (1–2)	51 (37–81)	48 (12–68)	2 (1–4)	40	49	7	3	-	-	-
Water depletion	96 (93–98)	4	-*	-*	3	-	-	-	48	52	-*	-*	85	13	2

* no specific data available

As shown, the raw milk production stage is the dairy processing stage that contributes the most to the different environmental impacts; specially regarding the global warming, acidification, eutrophication and land use impact categories. The dairy processing stage is the life-cycle stage that has the second larger contributions to the assessed category impacts; specially regarding ozone depletion, abiotic resource depletion and energy use. For instance, processed milk is the dairy product that uses the most amount of energy and abiotic resources; this is because its production involves pasteurization and skimming activities which consume a big amount of energy. Djekic et al. (2014) also shows the reliance and high consumption of energy of the butter production system since this product is very sensitive to changes in temperature and it requires constant refrigeration. The main drivers and emission flows that contribute to each impact category are summarized in Table 1.4.

Table 1.4:Main environmental impact drivers and key flows for dairy products. Adapted from Üçtuğ, (2019).

Impact drivers and key flows	**Impact categories**											
Impact drivers	**A-RD**	**AP**	**C**	**ETP**	**EnU**	**EP**	**GWP**	**HTP**	**LU**	**ODP**	**POCP**	**W-RD**
Agricultural equipment manufacture	✓	✓	✓	✓	✓	-	✓	✓	-	-	✓	✓
Combustion of fossil fuels for energy supply and equipment	✓	✓	✓	✓	✓	-	✓	✓	-	-	✓	✓
Cultivated area	-	-	-	-	-	-	-	-	✓	-	-	-
Fertilizers and phytosanitary compounds application	✓	✓	✓	✓	✓	✓	✓	✓	-	-	-	✓
Fertilizers and phytosanitary compounds production	✓	✓	✓	✓	✓	-	✓	✓	-	-	-	✓
Fuel production	✓	-	-	-	-	-	-	-	-	-	-	-
Livestock enteric fermentation	-	-	-	-	-	-	✓	-	-	-	-	-
Manure application	-	-	-	-	-	✓	-	-	-	-	-	-
On-site farm emissions	-	-	-	-	-	✓	✓	-	-	-	-	-
Refrigerant gases at storage	-	-	-	-	-	-	-	-	-	✓	-	-
Transportation	-	-	-	-	-	-	-	-	-	✓	✓	-
Key flows	-	-	-	-	-	-	-	-	-	-	-	-
Ammonia (NH3)	-	-	-	-	-	✓	-	-	-	-	-	-
Arsenic (As)	-	-	-	-	-	-	-	✓	-	-	-	-
Benzene (C6H6)	-	-	✓	-	-	-	-	-	-	-	-	-
Carbon dioxide (CO2)	-	-	-	-	-	-	✓	-	-	-	-	-
Chlorofluorocarbons (CFC)	-	-	-	-	-	-	-	-	-	✓	-	-
Chromium (Cr)	-	-	✓	✓	-	-	-	-	-	-	-	-
Coal	✓	-	-	-	-	-	-	-	-	-	-	-
Crude oil	✓	-	-	-	-	-	-	-	-	-	-	-
Fossil fuels	-	-	-	-	✓	-	-	-	-	-	-	-
Land	-	-	-	-	-	-	-	-	✓	-	-	-
Methane (CH4)	-	-	-	-	-	-	✓	-	-	-	-	-
Natural gas	✓	-	-	-	-	-	-	-	-	-	-	-
Nitrates (NO_3^-)	-	-	-	-	-	✓	-	-	-	-	-	-
Nitrogen oxides (Nox)	-	✓	-	-	-	✓	-	-	-	-	✓	-
Nitrous oxide (N2O)	-	-	-	-	-	-	✓	-	-	-	-	-
Phosphates (PO_4^{3-})	-	-	-	-	-	✓	-	-	-	-	-	-
Sulphur (S)	-	✓	-	-	-	-	-	-	-	-	-	-
Volatile organic compounds (VOC)	-	-	-	-	-	-	-	-	-	-	✓	-
Water	-	-	-	-	-	-	-	-	-	-	-	-
Zinc (Zn)	-	-	-	✓	-	-	-	✓	-	-	-	-

✓= Driver or flow affecting an impact category

Impact categories: A-RD= Abiotic resource depletion, AP= Acidification, C= Carcinogens, ETP=Ecotoxicity, EnU= Energy use, EP= Eutrophication, GWP= Global warming potential, HTP= Human toxicity, LU= Land use, ODP= Ozone depletion, POCP=Photochemical ozone formation-RD=Water depletion

Finally, yet important, the dairy processing LCA results of the reviewed studies have led the authors to suggest recommendations regarding the reduction of the identified environmental impacts. Up to 10 reviewed studies suggest the application of different improvement measures to achieve more energy efficient dairy processing systems such as the use of more energy-efficient processing equipment or the reducing heat losses by the implementation of insulation. Between 2 to 5 studies suggest the use of renewable energy sources such as photovoltaic or by the use of anaerobic digestion of slurry to recover biogas.

Despite acknowledging the low contribution of transport to the dairy product environmental footprint, it is curious that between 7 to 9 authors suggest improvements to it like the optimization of the routes. As previously stated, the farming stage contributes the most to the dairy product's environmental footprint therefore, up to 8 authors suggest improvements mainly focused on the quality enhancement of the livestock diets.

The outcomes of any of the reviewed LCA studies evidence that there is room for enhancing the environmental performance of dairy products in the two key life cycle stages (raw milk production and dairy processing). However, this requires the particular evaluation of each dairy system in the dairy industry through LCA. The suggested improvements shall cover the particular necessities of each assessed system; based on its specific environmental impact drivers and characteristics.

1.3 Ecolabeling and the Product Environmental Footprint method.

Currently, there is great interest to demonstrate the products' environmental friendliness by the different industries and LCA has been used to generate this detailed environmental information. LCA results allow industries to environmentally manage their production systems and ensure their resource efficiency. Moreover, LCA results are used to communicate consumers how "green" a product is trough green credentials (Eco-labelling).

However, the reliability of their LCA results is jeopardized by an unclear consensus regarding the LCA methodological choices that generate heterogenous and incompatible LCA results among common production systems. This is affecting the communication, reliability and interpretation of the LCA results through the product's green credentials and therefore it has become an issue for stakeholders.

This issue is clear in the European market where there is an 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). These conditions have led to an uncontrolled proliferation of eco-labels for products which results cannot be directly compared because of the unclear LCA methodological choices used to obtain the green credentials.

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, the European market is saturated of products with a diverse amount of green credentials; which are communicating LCA results obtained from studies that have followed many different initiatives and methodological choices.

To create a consensus when implementing the LCA methodology, reduce the confusion among stakeholders and to face the uncontrolled 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 Environmental Footprint methods to assess products (PEF) and Organizations (OEF) (EU, 2013).

The PEF Guide (Manfredi et al., 2012; Zampori and Pant, 2019) provides a general framework for measuring the environmental performance of a product or service through its lifetime based on LCA. The PEF primary goal is to harmonise the existing LCA methodological choices and to provide objective criteria for comparing the environmental performance of products. It defines requirements for some of the methodological aspects and provides guidelines for conducting the environmental assessment.

However, each of the existing products' groups in the market have specific product and production characteristics and each of these product groups require a bespoke environmental assessment guideline to reach the PEF goals. 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, 2018a). The PEFCR must be used to generate a fully PEF compliant study and its aim is increase reproducibility, consistency and comparability among the results of the same products in each category (EU, 2017).

In this context, a three-year environmental footprint (EF) pilot phase started in 2013 with the aim of testing the development processes of PEFCRs. In 2016, the pilot phase carried out by the European Commission (EC) ended, in which the current and future relevance of the PEF in a European and international level was clearly highlighted. The pilot phase was the starting point for the consolidation of the PEF as the official European method to measure and communicate the environmental performance of the products traded in the European market. The main results of the EF pilot phase are the development and validation of 22 PEFCRs (EC, 2019a) for different products and also, the development and validation of EF compliant database (EF-database). One of the PEFCR's developed in the pilot phase is the one to assess dairy products (PEFCR-D) due to the economic, social and environmental relevance of this industry; and also, because the dairy system is one of the most challenging food production systems where to apply the LCA methodology (Mourad et al., 2007; Notarnicola et al., 2017).

As mentioned above, during the EF pilot phase, the development of the EF-database started; and since then, it has been constantly updated and released as part of a group of specific EF compliant data known as the EF reference package. The EF- database follows the International Life Cycle Data System (ILCD) format and consists on several documents, tools and data to help LCA practitioners develop EF compliant LCA models. For instance, the EF-database contains compliant EF datasets (EF-datasets) and LCIA methods (EF-LCIA methods) (EC, 2018b; EPLCA, 2018).

Additionally, another objective of the EF pilot phase was to start the development of PEF compliant open-source IT tools for Small and Medium-sized Enterprises (SMEs). Its development is an important step to reach the EU Single Market for Green Products objectives since their goal is to expand and simplify the use of the PEF methods (EC, 2013). Hence, by taking as starting point the PEFCRs for beer, leather, olive oil and T-shirts, this phase started the conceptualization and development of tools to perform PEF calculations for these products. The tools were expected to be ready during the first half of 2018 (EC, 2019a) however, to the best of our knowledge these official IT tools have not been released yet.

Currently and until 2021 the PEF methods are in a transition phase; during this time the implementation of the existing PEFCRs is being monitored and also new ones are being developed. Furthermore, this phase is allowing new methodological developments (EC, 2019b). From 2021 onwards, an implementation and communication phase will start. In this phase, a decision will be taken regarding when and where the application of the PEF and the communication of its results (eco-labelling) is required by law (Nissinen et al., 2019).

1.4 Challenges of assessing the environmental impacts of the dairy industry

Methodological challenges

LCA to study the environmental performance of dairy systems has been widely used despite being one of the most challenging food production systems where to apply this methodology. The challenges are due to the different LCA methodological choices that practitioners must take, the system's multifunctional role and because of its dependence on environmental systems that are only partly understood

The different LCA methodological choices start from the definition of the study's goal and scope and generate a domino effect through all the other LCA steps. As shown by the reviewed literature, LCA studies for common dairy products have been performed by using different FU and system boundaries. Which has led to the consideration of different processes and flows when developing the LCI. Moreover, during the development of the LCI, the practitioners also have diverse models or techniques options to quantify the emissions arising from the foreground processes and LCA databases from which obtain LCI data for background processes. Finally, the developed LCI could be characterized, normalized and weighted by any of the many factors available in the LCIA methods.

This overwhelming amount of methodological choices do not allow LCA practitioners to develop homogeneous dairy LCA studies with compatible results that can be directly compared. To solve this issue the PEFCR-D was developed but, despite reducing the range of the methodological choices, the PEFCR-D practitioner still faces implementation challenges; and also, has to take care of some remaining methodological choices.

For instance, the generation of a PEFCR-D compliant LCI is not trivial since its data must be obtained as result of applying specific emission models (Table 1.5), allocation rules, specific calculation parameters and formulas (Circular Footprint Formula and Data Quality Requirements Formula). Hence, in addition to a good pre-knowledge of the LCA methodology, the PEFCR-D practitioner shall have additional no-related LCA knowledge.

Table 1.5: PEFCR-D compliant calculation emission models for different on-site dairy farm emissions. Adapted from EDA (2018).

Emission	**Calculation model**
Direct and indirect nitrous oxide (N_2O), emitted to air	IPCC[a] and EMEP/EEA[b]
Ammonia (NH_3), emitted to air	
Nitric oxides (NO_X), emitted to air	
Nitrate (NO_3), emitted to ground water	
Methane (CH4), emitted to air	IPCC[a]
Phosphate (PO_4^-), emitted to ground and surface water	-*
Phosphorus (P), emitted to surface water	
Particulate matter (PM2.5), emitted to air	EMEP/EEA[b]
Non-methane volatile solids (NMVOC), emitted to air	EMEP/EEA[b]
Carbon dioxide (CO_2), emitted to air	IPCC[a]
Heavy metals emitted to groundwater and soil	Freiermuth (2006)

*= Calculation model not defined in the PEFCR-D

[a] IPCC chapter 10 (2006a) and chapter 11(2006b)

[b] EMEP/EEA section 3.B (2016a) and 3.D (2016b)

The statement of PEFCR-D compliant on-farm emission models reduces until some degree the LCA methodological choices that the practitioner faces. However, it constitutes a special challenge for any PEFCR-D practitioner despite its previous expertise and knowledge regarding the LCA since it must still dominate the content of these different emissions guidelines and be aware of their respective gaps.

As shown in Table 1.5, for most of the cases, the PEFCR-D states one emission model per emission however, two mandatory models to determine on-site farm N emissions are given. These models were developed by the Intergovernmental Panel on Climate Change (IPCC) and the European Monitoring and evaluation programme in association with the European Environmental Agency (EMEP/EEA). Each of these models provide different equations, emission factors and default values to determine on-site N dairy farm emission from different sources (e.g. managed manure, inorganic and organic fertilisers). These different methodological approaches create two different N flows in the same dairy farm system which creates a mass balance conflict that must be addressed.

The assurance of a balanced N flow system when simultaneously applying the IPCC and the EMEP/EEA is necessary for validating the process definition and associated data, to check the quality of data (Guinée, 2002; ISO 14044, 2006) and to ensure the comparability between different dairy products and systems in accordance to PEFCR-D aims. However, neither the PEFCR-D, IPCC nor EMEP/EEA state how the outcomes from the EMEP/EEA should be integrated into the IPCC and vice versa from a mass balance perspective to achieve a unique N flow. Therefore, there is a clear need of an approach to link both IPCC and EMEP/EEA methodologies in order to obtain credible N balanced results and comply with the PEFCR-D requirements.

Lack of specialized tool for PEF implementation

Another significant challenge is the technological one; since the correct implementation of the PEFCR-D depends on not specialized LCA software. The currently available LCA software (SimaPro, GaBi, bright-way or Open LCA) is generalist; it overlooks the LCI development step and mainly focusses on executing the LCIA.

This generalist software is not able to easily cover the specific PEFCR-D methodological demands to develop a compliant LCI for the full dairy system, such as the execution of the mandatory emission models, formulas and other specific calculations needed. This technological gap increases the complexity of the practical application of the PEFCR-D since, to achieve the methodological demands, the practitioner should first execute all the mandatory calculations out of the available LCA software and use different tools. Only then, the practitioner can open the generalist LCA software, import and manage the LCI data to continue the analysis.

Finally, yet important, the proper execution of the LCIA step in the PEFCR-D framework highly depends on this not specialized software; since it is needed to view and use the data in the EF reference packages, the EF-datasets and EF-LCIA methods; data that is essential to obtain LCIA results that are fully compliant with the PEFCR-D.

Overcoming these technological challenges is important to reach the EU Single Market for Green Products goals (EC, 2013). Reason why one of the goals of the EF pilot phase was to start the development of specialized PEF IT tools for beer, leather, olive oil and T-shirts; which will simplify the implementation of the PEF methodology by allowing SMEs to assess their production systems without depending on external parties. However, until the publication of this work, none of them is available.

Developing specialized PEF IT tools is challenging for even LCA practitioners with a high expertise level since they must also have good computing and coding skills. These profile requirements reduce the amount of LCA practitioners that could be capable to develop specialized IT tools by their own as part of their academic, research or professional work. Therefore, the existence of specialised PEF IT tool mainly depends on the few LCA software developing companies that exists since they have the resources to carry out their development. These conditions highly conditionate the implementation and expansion of the European market for green products since the development of specialized PEF IT tools depends on the will of the LCA software developing companies.

Regarding dairy products and to the author knowledge, there has been only one 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 does not use the official EF-datasets and 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.

Therefore, the PMT_01 tool does not incorporate the 2018 changes on the EF-LCIA methods to determine the required environmental impact categories (EC, 2018b). To give an example, it reports Water Resource Depletion impact category results by using the Swiss Ecoscarsity model when, due to the changes, the Water Use impact category results shall be reported through the implementation of the AWARE model. Because of these and other reasons, the presented tool and its results are not fully PEFCR-D compliant.

In summary, there is the need to develop a fully PEFCR-D compliant specialised IT tool to assess dairy products while overcoming the existing challenges. This specialized IT tool shall increase the practical use of the PEFCR-D by simplifying the implementation of its methodological requirements and by also generating and executing PEFCR-D compliant LCI and LCIA results respectively.

1.5 Strategy towards a sustainable dairy industry

The dairy industry should be respectful with the environment but not at any economic and social prize, economically affordable but not at any environmental and social cost and, finally, must seek for social equity, but not at any environmental and economic cost, so there are frequently conflicting objectives. Therefore, the delay on overcoming the discussed challenges and developing fully compliant PEFCR-D IT tools threats the environmental sustainability of this industry and limits its positive effects in the economy and society.

To achieve an environmentally sustainable state and, therefore, enjoy of its collateral economic and social benefits, the dairy industry requires to be environmentally optimized. Therefore, each of the dairy systems in this industry shall be involved in a constant environmental evaluation and optimization process (Figure 1.4). This continuous process has five stages which are (i) environmental assessment, (ii) identification and analysis of hot-spots, (iii) suggestion of improvements, (iv) implementation of improvements and (v) environmental communication. By following this path, each dairy system can reach an optimal environmental performance which outcome can be used as marketing strategies to enhance product’s competitivity in an everyday more exigent European market for green products.

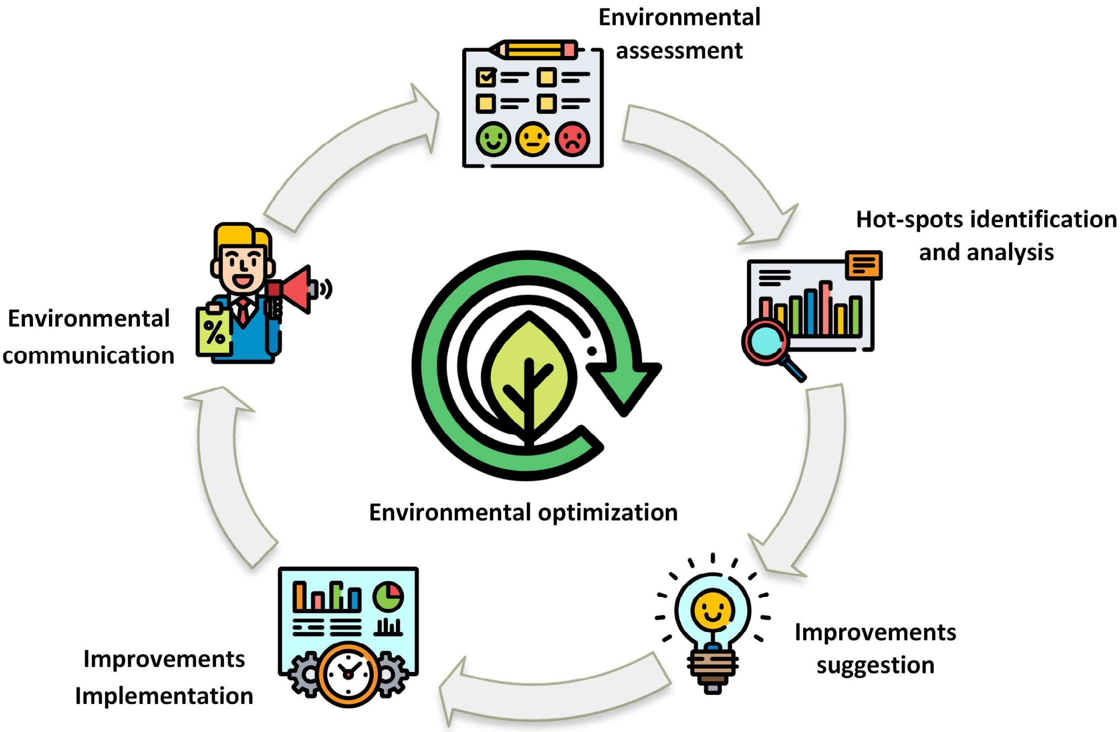

Figure 1.4: Continuous process for an environmental optimization[1]

Environmental assessment

The environmental assessment of dairy systems can be done by the required specialised tools; which allow the practical implementation of the LCA methodology in harmony with the specific PEFCR-D requirements. Through the dissemination and use of these tools, a larger number of dairy farmers and producers could be able to assess their particular system and complete this first optimisation stage and. As outcome of this stage, dairy producers will determine their system and products' current (baseline) environmental performance and be able to directly compare the results of similar products among them.

Hot-spots identification and analysis

From the systems baseline outcomes, each producer can identify which dairy processes or activities contribute the most to each of the different assessed environmental impacts (environmental hot-spots). And then, an analysis of the hot-spots can be carried out to determine the flows (supplies or emissions) that contribute the most to each of their environmental impacts. For example, a hot-spots could be the manure management activities at the farming stage since the livestock manure is collected in an open slurry tank and an important amount of emissions arise from it.

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[1] Icons made by Freepil and Surang from www.flaticon.com

Suggestion of improvements

LCA is a useful tool to identify environmental hot-spots and tells the decision-maker where to focus its attention and efforts on the environmental optimization process. However, LCA, as it self, it is not a tool capable to provide specific solutions to the decision-maker. Thus, once the hot-spots are identified, the decision-maker requires the support of other tools and techniques (energy audits, circular economy/resource efficiency studies, nutritional studies for animal diets, etc) that are capable to assess and propose custom-made optimization improvements for the system; by considering the improvements' environmental and economic return benefits.

For example, energy audits are valid tools to generate specific data regarding the system energy efficiency and energy related costs and emissions so, they are capable to suggest high impact energy related improvements. The audits' outcomes are useful to further evaluate a previously thought energy related measure and to explore new improvements based on the audited system energy needs; such is the case of the feasibility of implementing a photovoltaic installation for electricity production. While, circularity indicators are effective tools to determine how much a measure contributes to the closure of the circular economy loops of the system. Thus, it allows a deeper analysis of the systems resource efficiency and the suggestion of improvements to reduce the consumption of resources, benefit the environment and reduce operational costs.

Improvements implementation

In this fourth optimization stage, the producer can take an informed decision regarding which improvements implement in their system. In addition to the environmental and circular economy benefits, this informed decision will be affected by the economic costs and benefits of implementing any of the improvements, such improvements cannot put under risk the system's finances. Thus, the calculation of economic ratios such as the Net Present Value (NPV) or the Internal Rate of Return (IRR) for each proposed improvement will help the final decision-making process.

The process of (i) assessment, (ii) hot-spot identification, (iii) suggestion of improvements and (iv) implementation of corrective measures has to be done in a continuous basis over the years moving, in the end, each individual farm and the whole sector towards a more sustainable production of milk and dairy products.

Environmental communication

Finally, yet important, it is estimated that 47% the EU citizens do not trust the claims made by the producers regarding their products and 77% of the citizens are willing to pay more for products if they are confident on their environmental friendliness (Eurobarometer, 2013). Hence, to catch this share of the market and to satisfy consumers demand on reliable green credentials, the optimization results can be used by the producer for environmental communication as part of the last optimization stage.

Communicating the results thorough a specific PEF compliant green credentials (eco-label) is a valid marketing strategy to increase sales, consolidate the dairy products in the market and cover the consumer demands; due to its consistency, replicability and comparability among similar dairy products.

Therefore, the use of PEF compliant eco-labels gives dairy producers the real possibility of increasing their economic returns. Which may be the final motivation that producers need to start the environmental optimization of their systems; and thus, guide the dairy industry towards a more sustainable production path.

The generation of this unique Type III (ISO 14025, 2010) PEF eco-label in the EU market is the ultimate goal of the Single Market for Green Products and the Road Map to a Resource Efficient Europe initiative and it is still in progress. However, until the European commission releases this eco-label, the PEF methodology can be used to generate other environmental declarations as carbon footprint (ISO 14067, 2018) or water footprint (ISO 14046, 2016).

Chapter 2: Objectives

The main goal of this thesis is to optimize the environmental sustainability of the dairy industry in compliance with the European Union *Product Environmental Footprint Methodology* to improve its competitiveness in an everyday more exigent market for green products This, through the use of tools capable of (i) environmentally asses dairy systems (production or processing of raw milk), (ii) identify their environmental impact drivers (hot spots); and (iii) whose results support the suggestion of measures that would not only improve the systems' environmental performance, but would also lead them towards a circular economy model. Environmental results that are capable of enhancing the economic and social benefits of the dairy industry when communicated through environmental declarations and green-credentials (eco-labels) as a clear marketing strategy to consolidate certified green dairy products in the market.

In order to achieve these main goals, it has been necessary to:

- Propose a comprehensive approach to calculate N emissions from a dairy farm balanced system to solve the mas balance conflict that arises when simultaneously implementing the IPCC and EMEP/EEA models as required in the European Union *Product Environmental Footprint Category Rules* for dairy products (PEFCR-D).
- Develop a specialised IT tool (*CalcPEF$_{Dairy}$ tool*) compliant with the *PEFCR-D* to cover the methodological and technological challenges for its implementation; and therefore, determine the environmental and sustainable status of raw milk production (cradle-to-farm gate) and dairy processing systems (cradle-to-grave), identify their environmental hot-spots and assess the effect of potential changes on these systems' environmental performance.
- Carry out energy audits of dairy facilities, producers of raw milk and dairy processors, to determine their current energy performance and generate relevant information on the costs and environmental impacts related to energy consumption. The aforementioned to identify specific hot-spots and propose feasible energy improvements; in order to achieve more energy efficient dairy facilities with also environmental and economic benefits.
- Evaluate the performance of an anaerobic digestor to treat dairy effluents as a possible improvement towards more environmentally friendly and energy efficient dairy facilities. To discuss the anaerobic digestor potential in closing the circular economy loops of water, energy and nutrients at different levels of the dairy production system.
- Externally audit the developed IT tool compliance with the *PEFCR-D*, so a validated tool can be put in the market. Then, use it to assess and externally audit a real dairy facility to obtain an environmental declaration and green credential (eco-label) for one of its dairy products.

Chapter 3: Materials and methods

3.1 Product Environmental Footprint Guidance and Product Environmental Footprint Category Rules for dairy products

The PEFCR-D, supported by the PEFCR guidance v6.3, set a specific framework for the environmental assessment of dairy systems and its products. Therefore, the following is a brief description of these document's main content by following the LCA steps (i) goal and scope definition, (ii) inventory analysis, (iii) impact assessment and (iv) interpretation. Further and detailed information can be find in the full PEFCR-D (EDA, 2018) and PEFCR guidance v6.3 (EC, 2018a)documents.

As previously stated, the PEFCR-D provides a clear consensus to LCA practitioners in the dairy industry regarding the methodological choices needed to perform a PEF compliant LCA study. Its increases the reproducibility of the studies and reduces its results' methodological heterogeneity; which allows a direct comparation of the PEF results among similar dairy products (EDA, 2018). The environmental evaluation of dairy systems under a common framework, the PEFCR-D, increases the communication potential of the product's results among producers, business and consumers and therefore, these last ones, can include an environmental factor when taking the decision of purchasing or not a specific dairy product.

3.1.1 Goal and scope definition:

The PEFCR-D assessment scope includes five sub-categories of products and covers a wide range of typical dairy products as presented in Table 3.1 However, this thesis focuses on the assessment of liquid milk, cheeses and fermented milk products reason why only information about these three product sub-categories will be given from now on.

Table 3.1: PEFCR-D: Sub-categories for dairy products. Adapted from EDA (2018)

Sub-category	Type	Typical products
Liquid milk	F	Standardised milk (skimmed, semi-skimmed, whole milk) Whey
Dried whey products	I	Whey powder, whey protein powder, lactose powder
Cheeses	F	Ripened cheese (soft and hard), unripened cheese (spoonable, spreadable, solid)
Fermented milk products	F	Spoonable yoghurt (set, stirred), fermented milk drinks (liquid yoghurt, kefir)
Butterfat products	F	Butter (salted, unsalted), spreadable dairy fats

I= Intermediate product, F= Final product

There are many other dairy products that are not in the scope of this PEFCR-D; however, a PEF study can be carried out following this PEFCR-D guideline but its results cannot be claimed to be compliant with it. The guidelines provided in this PEFCR-D generate PEF compliant results for cattle's raw milk (cradle to fam gate) and the cattle`s raw milk its derived products through their full life cycle (cradle to grave). The PEFCR-D could however be used for determining the PEF of non-cattle (e.g. sheep or goat) raw milk and its derived products but the results cannot be declared in compliance with the PEFCR-D.

Additionally, this PEFCR-D provides detailed information and benchmark results for dairy representative products, one per product sub-category (Table 3.2). These representative products are virtual products; hence they characterize what is potentially sold in the European market and not wat is produced in the European union.

Table 3.2: PEFCR-D representative virtual products for each product sub-category. Adapted from EDA (2018)

Sub-category	Representative virtual product
Liquid milk	Liquid milk, standardized to specific fat content, and thermally treated, homogenized, unsweetened and unflavoured, packaged and conditioned.
Cheeses	Average of unripened and ripened (soft, semi-hard, hard) cheese, standardised protein and fat, packaged and conditioned
Fermented milk products	Fermented milk, standardised, cultured, average of skimmed/plain, spoonable/liquid, plain/flavoured/fruited (strawberry), packaged and conditioned

Functional unit and reference flows

A FU is a precise and quantifiable description of the service or product for which the assessment is carried out and it is important in LCA since it defines the reference flow of product which scales the collected data. The reference flow is the amount of service or product needed to fulfil the defined function and shall be quantified in specific units.

The PEFCR-D provides default functional units and its respective reference flow as presented in Table 3.3.

Table 3.3: PEFCR-D default functional unit and reference flow for each product sub-category. Adapted from EDA (2018)

Sub-category	Functional unit	Reference flow
Liquid milk	Liquid milk, consumed at home as final product without heating, cooking or further transformation	1000 ml
Cheeses	Cheese, consumed at home as final product without cooking or further transformation	10 g dry matter equivalent
Fermented milk products	Fermented milk or yoghurt, consumed at home as final product without cooking or further transformation	125 g

System boundary:

The system boundary defines the product's life cycle stages that will be assessed and within each stage identifies the respective foreground (core) and background processes. In the system boundaries the main flows (inputs/outputs) that connect the different processes along the life cycle stages are also identified. The Foreground or core processes are the ones under the control of the decision-maker for which the study is carried out; while the processes for which the decision-maker has none or, at best, indirect influence are known as background processes.

The PEFCR-D considers seven *life cycle stages* (from cradle to grave) and defines the activities in each of them. These life cycle stages are: 1) "Raw milk supply", 2) "Dairy processing", 3) “Non-dairy ingredients supply”, 4) "Packaging”, 5) “Distribution”, 6) “Use” and 7) “End-of-life”.

Figure 3.1 illustrates the system boundaries for dairy products in the view of a traditional LCA with its respective life cycle stages. Also, it shows the foreground system in a different colour than the background (upstream and downstream) systems. The PEFCR-D has made this distinction from the perspective of dairy processors, but when the PEFCR-D is used from the perspective of other stakeholders (e.g. dairy farmers, retailers, restaurants, food processors), the foreground and background systems presented in the figure may differ.

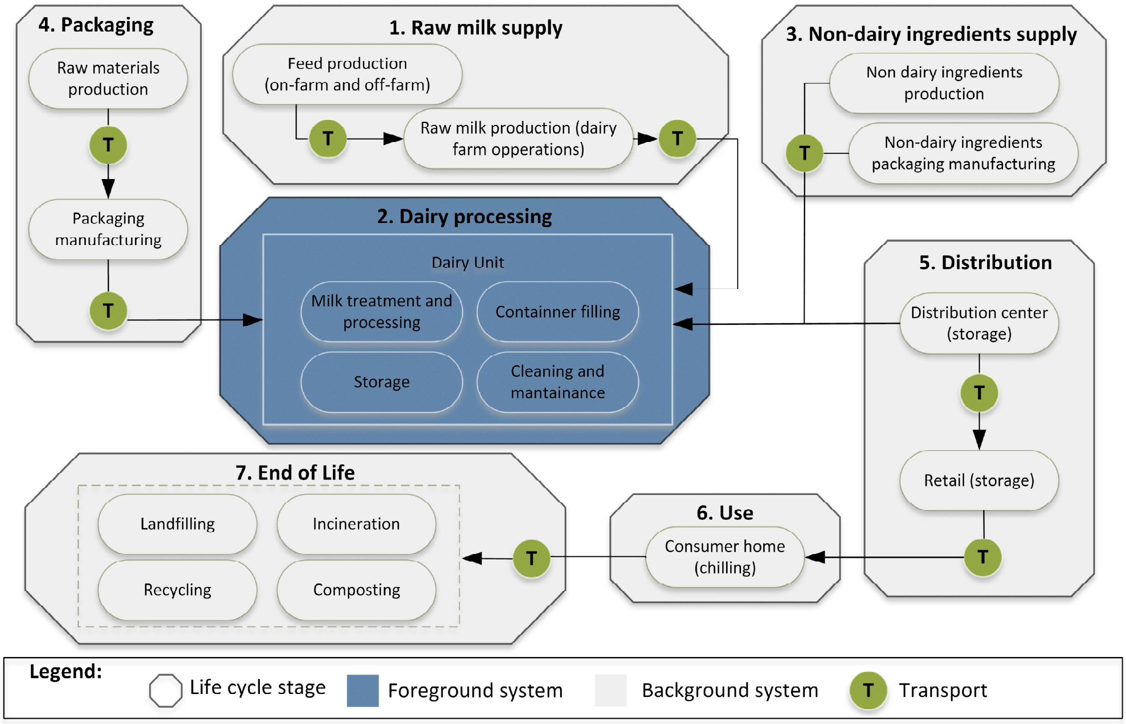


Figure 3.1:PEFCR-D dairy system boundaries in a traditional LCA view. Adapted from EDA (2018)

3.1.2 Inventory analysis

This step lists and quantifies all the input and output flows (elementary flows) of the different processes involved in the products life cycle (cradle-to-grave). This information is presented in the Life Cycle Inventory (LCI) of the assessed system which is the main outcome of this step. The input flows to any of the processes in the system’s life cycle stages can be from the technosphere (materials fuels, energy, transport, etc.) or from the nature (land, water, minerals, metals, etc.). While, the outputs could be the system’s product, coproducts, wastes and emissions to the air, water and land (Figure 3.2).

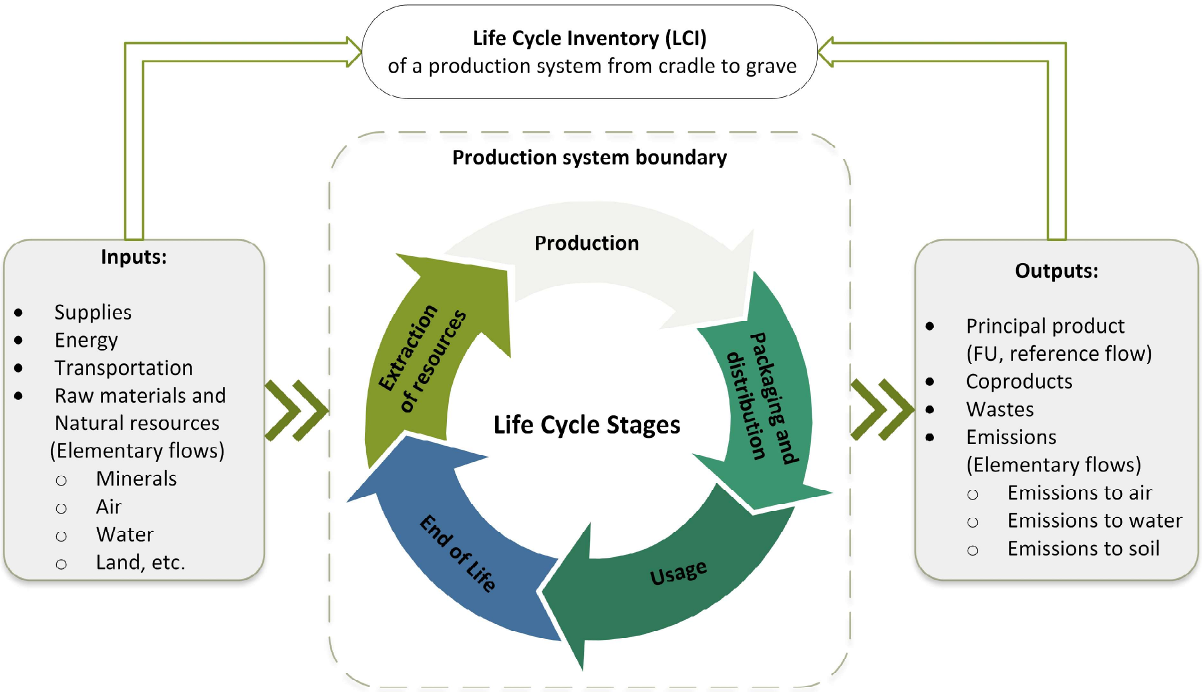


Figure 3.2:Schematic representation for the development of a Life cycle inventory (LCI).

A robust PEFCR-D compliant LCI shall contain company specific LCI data (output and input flows) for the foreground processes but, often, it also relies on LCI data from EF-datasets for background processes. These EF-datasets are part of the EF-database which provides official PEF compliant data that shall be used in any PEF compliant study. For instance, these EF-datasets are commonly used to obtain LCI data of from processes such as production of materials, generation of energy, transportation or waste management (EPLCA, 2018). What follows is a general view of the LCI data (input and output flows) required by the PEFCR-D to develop a PEF compliant LCI.

Farming stage

The processes included in this life cycle stage are considered foreground processes for which primary and company specific data shall be collected (i.e. amount of consumed inputs and generated outputs). Table 3.4 presents the LCI data flows from the activities and processes of this stage; while the calculation models to determine the on-site emissions from each of the farm activities are presented in Section 3.2.2.

Table 3.4: PEFCR-D input and outputs flows of the farming life cycle stage. Adapted from EDA (2018)

Life cycle stage	Flows	
	Inputs	**Outputs**
Farming	Feed (grass, fodder, concentrate)	Raw milk
	Mineral fertilisers and pesticides for feed production	"Meat", or live animals for slaughter or further fattening (cull cows and calves)
	Animals for milk production	Manure
	Bed materials (straw, paper, sand)	Renewable energy
	Manure	Emissions from combustion of fossil fuels
	Fuel for machinery	Wastewater and other wastes
	Energy used at the farm	Emissions from farm activities
	Refrigerants used at farm	• from enteric fermentation
	Farming equipment (capital goods) & barn	• from manure storage
	Water used in farm	• from manure application
	-	• from mineral fertilisers and pesticides application
	-	• from mineral and organic soils

Packaging and non-dairy ingredient supply stages

The LCI data for the packaging and non-dairy ingredients supply stages could be obtained from default PEFCR-D parameters if specific company data is not available. The processes included in these life cycle stages are commonly out of the influence of the decision-maker, thus they are background processes and its data often rely on EF-datasets available in the EF-database.

Dairy processing stage

Primary and company specific data shall be collected (i.e. amount of consumed inputs and generated outputs) from the foreground processes included in this life cycle stage. Table 3.5 presents the LCI data flows from the activities and processes of the dairy processing stage.

Table 3.5: PEFCR-D: Inputs and Outputs flows of the dairy processing life-cycle stage. Adapted from EDA (2018)

Life cycle stage	Flows	
	Inputs	**Outputs**
Dairy processing	Raw milk	Dairy products
	Dairy ingredients (i.e. intermediate dairy products)	Wastewater
	Non-dairy ingredients	Waste materials (to recycling or disposal)
	Cleaning agents	Emissions to air and water
	Packaging (treated in life cycle stage "packaging")	-
	Energy (i.e. heat and electricity)	-
	Water	-
	Refrigerant gases	-

Special attention is given to the emissions arising from the wastewater management process of this life cycle stage to generate the LCI. If no company specific data is available, the PEFCR-D states that emissions from the municipal wastewater treatment plant must be obtained from a specific EF-datasets and then re-estimated according to the Chemical Oxygen Demand (COD) content of the dairy facility effluents.

Distribution and Use stages

The process included in these stages are regularly background processes and its data also rely in the EF-datasets. However, the LCI data from the distribution and use stages is closely related to transportation and to the energy consumed during storage and chilling at the distribution and retail centres and at the consumer's home. Therefore, the most accurate amount of the transported distances and consumed energy shall be estimated at each stage; to then be related to the respective EF-dataset. 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. The PEFCR-D provides default values for these and other parameters if required.

End of Life stage

For this stage the PEFCR-D requires the application of the Circular Footprint Formula (CFF). Hence, the data required from this stage is the one to fulfil the CFF formula variables. The variables are mainly related to packaging, energy and waste management processes and other country and non-country dependent parameters. The CFF is presented in Equation 3.1 and fully detailed in the PEFCR guide (EC, 2018a).

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

(Equation 3.1. EC, 2018)

Where *E* are the emissions attributed to packaging related processes such as packaging production (cradle to gate), energy recovery, landfilling and recycling. The country dependent parameters are: *A* as the allocation factor for burdens and credits, *B* as the allocation factor for energy recovery process, R_2 as the product's material proportion that will be recycled and R_3 as the product's material proportion that is used for energy recovery. While the non-country dependent parameters are: *Qs/ QP* as the quality proportion between secondary and primary materials, *LHV* as the material's low heating value, $X_{ER,heat}$ and $\mathrm{X}_{\mathrm{ER,elec}}$ as the efficiency of electric and heat recovery processes respectively and R_1 as the material's proportion input recycled from a previous system. The PEFCR-D provides default values for these and other parameters if required.

Transport

Transport is the link among the dairy product's life-cycle stages and among processes. Hence, data regarding it shall be also considered in the LCI. The transport LCI data is commonly related to the type of transport (passenger car, lorry, plane, train or boat), the transport utilization ratio and the good's transported distance. The LCI data regarding the type of transport is obtained from EF-datasets. While, the transported distance and the transport utilization ratio shall be company specific LCI data when possible. If it is not possible to obtain this company specific data, the PEFCR-D provides default distances and utilization ratios depending on the transport type.

3.1.3 Impact Assessment

This step transforms the LCI flows into environmental impacts and it is known as Life Cycle Impact Assessment (LCIA). LCIA has four phases which are selection and classification of impact categories, characterisation, normalization and weighting

The first phase, the selection of the environmental impact categories and the classification of the LCI results is given by the PEF methodology since it sets the mandatory use of the EF-LCIA methods that take care of this LCIA phase. The EF-LCIA methods were released by the European Platform on Life Cycle Assessment (EPLCA) in the EF 2.0 reference package (EDA, 2018; EPLCA, 2019).

An EF-LCIA method refers to an individual characterization model used to derive specific EF compliant characterization factors (Cf_{EF}); which, during the LCIA characterization phase, are applied to convert the assigned LCI results to the common unit of a specific environmental impact category indicator (e.g. kg $CO_{2\ eq}$ for global warming potential or climate change). Thus, the EF-LCIA methods are a group of 16 different models needed to characterize the environmental impact categories considered in the PEF methodology (Table 3.6). As result of applying the EF-LCIA methods 16 characterized category impact scores are obtained which together are known as the characterized PEF profile.

According to the ISO 14040 (2006), the normalization and weighting phases are optional in an LCA study however, in the PEF framework this phases are mandatory and therefore, the methodology provides specific EF normalization and weighting factors (Table 3.7). The normalization phase determines the magnitude of each characterized impact category score relative to a common reference impact. The normalization phase is carried out by the use of the EF compliant normalization factors (Nf_{EF}) and its outcome is a normalized PEF profile where all the 16 normalized scores are unitless.

The last phase, weighting, converts the normalized impact scores in to weighed impact scores by the application of the EF compliant weighting factors (Wf$_{EF}$) and, another unitless weighted PEF profile is obtained. Finally, each of the 16 scores in the weighted PEF impact profile are added together to obtain the PEF compliant environmental single score (ESS) (EC, 2017b).

Table 3.6: PEF compliant impact categories and their calculation LCIA methods. Adapted from EDA (2018)

Environmental impact category indicator	Unit	EF-LCIA method
Climate change (GWP) • Climate change, Biogenic (B-GWP) • Climate change, Fossil (F-GWP) • Climate change, Land use and Land use change (LUC-GWP)	kg $CO_{2\ eq}$	Baseline model of 100 years of the IPCC 2013 (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 as developed by D reicer et al. 1995 (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 (LU)	pt	Soil quality index based on LANCA (Bos et al., 2016)
Water scarcity (W-RD)	m^3 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 (Guinée, 2002; Van Oers et al., 2002)

* DI= Disease incidence

Table 3.7:PEFCR-D:Normalization and weighting factors (EF 2.0 reference package). Adapted from EDA (2018)

Impact category	Unit	Normalization factors (Unit)	Weighting factors (%)
Climate change (GWP)	kg $CO_{2\ eq}$	7.76E+03	22.19
Ozone Depletion Potential (ODP)	kg CFC-11$_{eq}$	2.34E-02	6.75
Human toxicity, cancer (HTP-C)	CTUh	3.85E-05	-
Human toxicity, non-cancer (HTP-NC)	CTUh	4.75E-04	-
Particulate matter formation (PMF)	DI	6.37E-04	9.54
Ionizing radiation, human health (IRP)	kg U235 $_{eq}$	4.22E-03	5.37
Photochemical ozone formation, human health (POCP)	kg NMVOC $_{eq}$	4.06E+01	5.1
Acidification (AP)	mol H+ $_{eq}$	5.55E+01	6.64
Eutrophication, terrestrial (T-EP)	mol N $_{eq}$	1.77E+02	3.91
Eutrophication, freshwater (F-EP)	kg P $_{eq}$	2.55E+00	2.95
Eutrophication, marine (M-EP)	kg N $_{eq}$	2.83E+01	3.12
Ecotoxicity, freshwater (FETP)	CTUe	1.33E+06	-
Land use (LU)	pts	1.18E+04	8.42
Water scarcity (W-RD)	m^3 world $_{eq}$	1.15E+04	9.03
Resource use, minerals and metals (M-RD)	kg Sb $_{eq}$	6.53E+04	8.08
Resource use, fossils (F-RD)	MJ	5.79E-02	8.92

DI= Disease incidence

Allocation rules

The dairy system is a multifunctional system which outputs have economic value (products and co-products) and non-economic value (wastes). Hence, the upstream environmental impact burdens shall be assigned to each of the products and co-products at (i) the dairy farm gate and (ii) at the processing facility gate.

The PEFCR-D follows the next decision hierarchy cases to suggest allocation rules for multifunctional systems:

- *The first case* is to avoid allocation whenever possible by dividing the process into two or more processes.
- When allocation cannot be avoided, the *second case* suggest the partition of the system's input and output flows between its products; the partitioning shall reflect the underlying physical relationship between the system's products.
- If neither the first or second cases could have been done, the *third case* in the hierarchy is to allocate the inputs between the products and function in a way that reflects the relationships between them. Such as an allocation of the input and output data based on the proportion of the economic value of the products and co-products (i.e. economic allocation)

Takin as basis the hierarchy cases presented above, the PEFCR-D suggest the following allocation rules at the dairy farm for its products (raw milk) and coproducts (live animals, manure and crops) and at the processing facility for its dairy products (processed milk, cheese and yoghurt) and coproducts (cheese whey and cream).

On one hand, to assign the farm's environmental burdens between raw milk and live animals, the PEFCR-D suggest to follow biophysical allocation criterion (*second hierarchy case*). Therefore, it suggests the use Equation 3.2 to allocate the farm's impacts to the produced raw milk. Where $AF_{RAW\ MILK}$ is the allocation factor for the produces raw milk, 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 3.3, correcting the produced farm's milk to 4% of fat and 3.3% of protein.

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

(Equation 3.2. EDA, 2018)

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

(Equation 3.3. EDA, 2018)

However, if the dairy farm exports manure as a coproduct with economic value, an economic allocation criterion shall be used to assign the upstream environmental burdens to the manure according to the PEFCR-D (*third hierarchy case*). This criterion uses the relative economic value of the manure compared to the milk and live animals at the farm gate.

And finally, if the dairy farm exports non-dairy products such as animal feed, crops or any other non-dairy animal or product, the dairy farm system shall be subdivided (*first hierarchy case*)for non-dairy farm activities to assign environmental burdens to these non-dairy related products.

On the other hand, at the dairy processing facility, the PEFCR-D suggests to allocate the total processing impacts to each of the final products (cheese, yoghurt, processed milk, cream, etc) by using a dry matter criteria (DM) presented in Equation 3.4. 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*.

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

(Equation 3.4. EDA, 2018)

3.1.4 Interpretation

In this last step, the LCI and LCIA results are quantitative and qualitative interpreted in order to reach the study's goal. The interpretation is an iterative interaction among the three previous steps, and it must be carried out until reaching the study's goal and cover its scope. This transversal step allows, the identification of environmental "hot-spots" of the assessed system and allows the formulation of conclusions and recommendations to enhance the product system's performance.

One of the important achievements of the PEFCR-D is the development of quantitative benchmark results which allow the interpretation of the results obtained from its application at an EU level. Since no detailed market study on dairy products exists at the EU level, the PEF profiles presented in the PEFCR-D should be seen as a first attempt to provide sectorial and sub-sectorial benchmark results for its different representative dairy. These PEFCR-D benchmarks allow dairy producers to compare their environmental status with the PEFCR-D results for the virtual representative products. Therefore, they will be comparing their products' environmental performance with products that are potentially sold in the European market.

The PEFCR-D provides the benchmark PEF profiles (characterised, normalised and weighted) and environmental single score results for each of the representative products as requested in the PEFCR Guidance v6.3 (EC, 2018a). Table 3.8 shows the benchmark characterized impact category scores and environmental single score for the PEFCR-D representative products.

Another strength of the PEFCR-D is that it provides specific guidelines for the semi-quantitative quality assessment of the LCI and the LCIA results. This assessment is done by the application of the Data Quality Requirements (DQR) formula; Equation 3.5 presents the general DQR formula. The DQR assessment is carried out by the quality criteria of the data based on Technological representativeness (TeR), Geographical representativeness (GR), Time-related representativeness (TiR), and Precision (P). The application of the DQR formula and its special considerations when assessing the LCI data or the LCIA results is explained in detail in the PEFCR-D (EDA, 2018) and the PEFCR guidelines (EC, 2018a).

$$DQR = \frac{\mathrm{TeR} + \mathrm{GR} + \mathrm{TIR} + \mathrm{P}}{4}$$

(Equation 3.5. EDA, 2018)

Table 3.8:PEFCR-D: Benchmark characterized impact category scores and environmental single score for representative products. Adapted from EDA (2018)

Benchmark results	Impact category	Unit	PEFCR-D representative products		
			Liquid milk (1000 mL)	Cheeses (10 g dry matter)	Fermented milk products (125 g) *
Characterized impact category scores	Climate change (GWP)	kg CO_2 $_{eq}$	1,61E+00	1,22E-01	1,94E-01
	Biogenic (B-GWP)		7.38E-01	6.38E-02	6.61 E+02
	Fossil (F-GWP)		6.81E-01	4.18E-02	1.10 E+01
	Land use and Land use change (LUC-GWP)		1.92E-01	1.66E-02	1.73 E+02
	Ozone Depletion Potential (ODP)	kg CFC-11_{eq}	5,02E-09	2,39E-09	1,27E-09
	Human toxicity, cancer (HTP-C)	CTUh	1.99E-08	1.70E-09	2.42E-09
	Human toxicity, non-cancer (HTP-NC)	CTUh	1.32E-06	1.25E-07	1.86E-07
	Particulate matter formation (PMF)	DI *	1,06E-07	8,05E-09	1,10E-08
	Ionizing radiation, human health (IRP)	kg U235 $_{eq}$	8,86E-02	3,29E-03	1,49E-02
	Photochemical ozone formation, human health (POCP)	kg NMVOC $_{eq}$	3,87E-03	2,61E-04	4,11E-04
	Acidification (AP)	mol H+ $_{eq}$	1,28E-02	1,06E-03	1,38E-03
	Eutrophication, terrestrial (T-EP)	mol N $_{eq}$	5,39E-02	4,55E-03	5,70E-03
	Eutrophication, freshwater (F-EP)	kg P $_{eq}$	1,14E-04	9,46E-06	1,33E-05
	Eutrophication, marine (M-EP)	kg N $_{eq}$	3,83E-03	3,21E-04	4,79E-04
	Ecotoxicity, freshwater (FETP)	CTUe	3.45E+00	5.97E-01	1.99E+00
	Land use (LU)	pts	1,52E+02	1,18E+01	1,49E+01
	Water scarcity (W-RD)	m3 world $_{eq}$	3,82E-01	2,21E-02	9,49E-02
	Resource use, minerals and metals (M-RD)	kg Sb $_{eq}$	1,35E-06	1,23E-07	4,25E-07
	Resource use, fossils (F-RD)	MJ	8,15E+00	4,22E-01	1,43E+00
Environmental single score	-	pts	1.25E-04	9.48E-06	1.57E-05

* yogurt, DI= Disease incidence

3.2 Development of CalcPEF$_{\text{Dairy}}$ an specialized PEF IT tool for dairy products

The development of the proposed specialized PEF IT tool (CalcPEF$_{\text{Dairy}}$) for dairy products is done through three main tasks which are (i) transformation of the EF reference package to user meaningful data (ii) development of models for direct on-farm emissions and (iii) the deployment of the tool as illustrated in Figure 3.3.

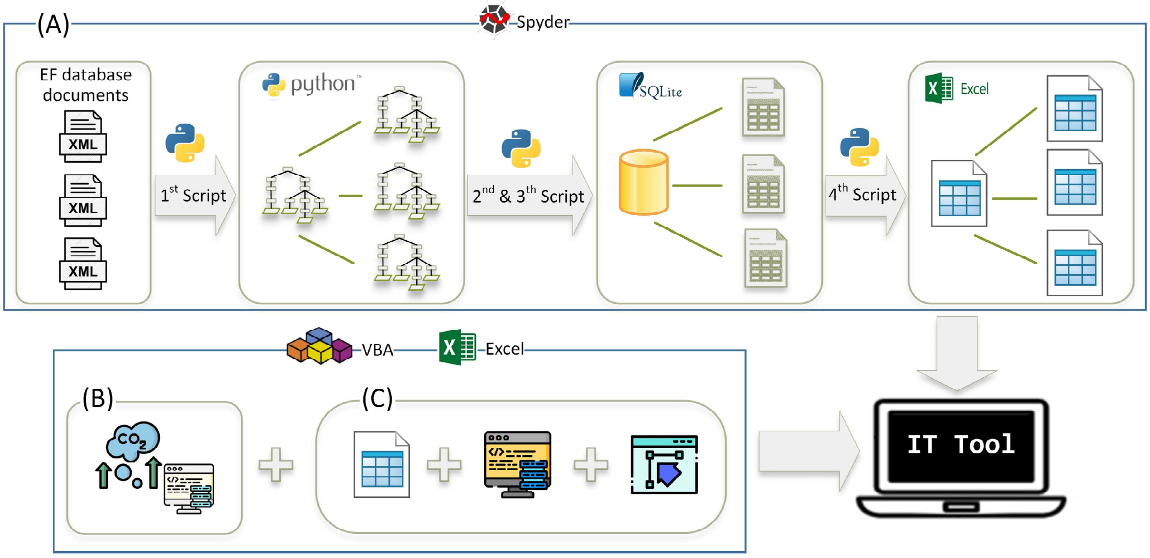


Figure 3.3: Schematic structure for the development of CalcPEF$_{\text{Dairy}}$ tool for dairy products. (A) transformation of the EF reference package, (B) modelling of on-farm emissions and (C) deployment of the tool.

The first task retrieves data from EF 2.0 reference package which is a collection of EF compliant data, mostly saved as Extensible Mark-up Language (XML) documents. The EF-database is part of this collection of XML document and its specific XML documents are known as datasets (EF-datasets$_{\text{XML}}$). Therefore, through four Python 3.6 scripts executed in the Spyder 3.3.1 platform, the EF-datasets$_{\text{XML}}$ data is retrieved, managed and saved in SQLite database to later be incorporated in the tool which uses as host Microsoft Excel.

The final two tasks are executed in Microsoft Excel and its Visual Basic for Applications (VBA) built-in platform. The first of these two tasks is the execution of the PEFCR-D compliant on-farm emission models so their results can be used for the development of the LCI. For the successful execution of these task, the required models were encoded in VBA language so the tool can use them when required.

Then, in the next task, CalcPEF$_{\text{Dairy}}$ is deployed through the generation of its three main components Microsoft Excel objects, VBA objects and VBA code scripts. These components are used as the tool's user interface objects to add and visualise data (Excel and VBA objects) and are in charge of managing the tool's data (VBA code scripts) to achieve the desired PEFCR-D compliant results. Further sections will present more details about the actions done in each of these two main development tasks.

3.2.1 Extraction of data and creation of databases

This task extracts data from the EF-datasets$_{\text{XML}}$ (XML documents) in the EF-database; a collection of data in the EF 2.0 reference. To successfully extract this information, the first step is to understand how the EF-datasets$_{\text{XML}}$ and its data are ordered in the EF-database. Therefore, the following paragraphs aim to provide a general understanding of their structure and highlight key elements that are needed for the data extraction.

The EF-database and the data in the EF-datasets$_{\text{XML}}$ follow the International Life Cycle Data System (ILCD) format. The ILCD format is a complex LCA data format developed by the EPLCA to facilitate the exchange of environmental information and create a common basis for consistent, robust and quality-assured life cycle data. Thus, the EF-datasets$_{\text{XML}}$, in the EF-database, are organized in seven different collections (Table 3.9).

Table 3.9: Environmental footprint database collections of datasets.

EF-database data collections	EF-datasets (XML documents) content details
Process	Each EF-dataset includes the LCI data flows (inputs and outputs) for a system or unit process. Documentation and, in some cases, impact assessment results are included for specific methods.
Flow	Each EF-dataset corresponds to an elementary flow substance, product or waste. The name of the flow, its CAS number, flow property, etc. are included among other information.
Flow property	Each EF-dataset includes information regarding the flow's physical quantity e.g. mass
Unit group	Each EF-dataset provides information regarding the flow property's units or dimension e.g. kilograms and its conversion factors.
LCIA methods	Each EF-dataset represents an LCIA method and contains the characterization factors for an specific environmental impact category. The document also contains documentation regarding the method.
Source	Each EF-dataset contains information regarding the documents used to develop the elements in the database e.g. diagrams, links to other documents, etc.
Contact	Each EF-dataset contains contact information of the institutions that participated developing the database

Each EF-dataset$_{\text{XML}}$ has a Unique Universal Identifier (UUID) which identifies itself and links it to other EF-datasets$_{\text{XML}}$. Moreover, the UUID and the ILCD format relates specific data in a EF-datasets$_{\text{XML}}$ to specific data in another EF-datasets$_{\text{XML}}$ and external documents. This link of the data among EF-datasets$_{\text{XML}}$, through the UUID, is fundamental to generate robust LCI and LCIA results in a PEF study since it generates a network of interconnected EF-datasets$_{\text{XML}}$ and data which is the foundation of the EF-database (Figure 3.4).

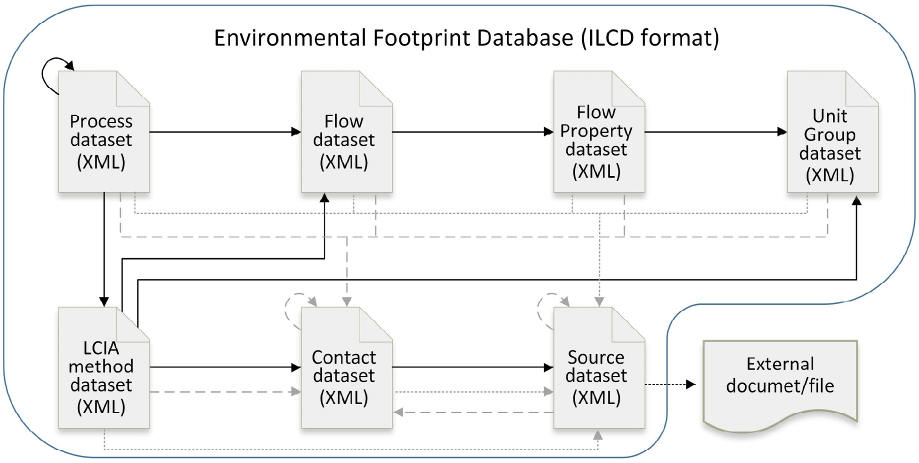


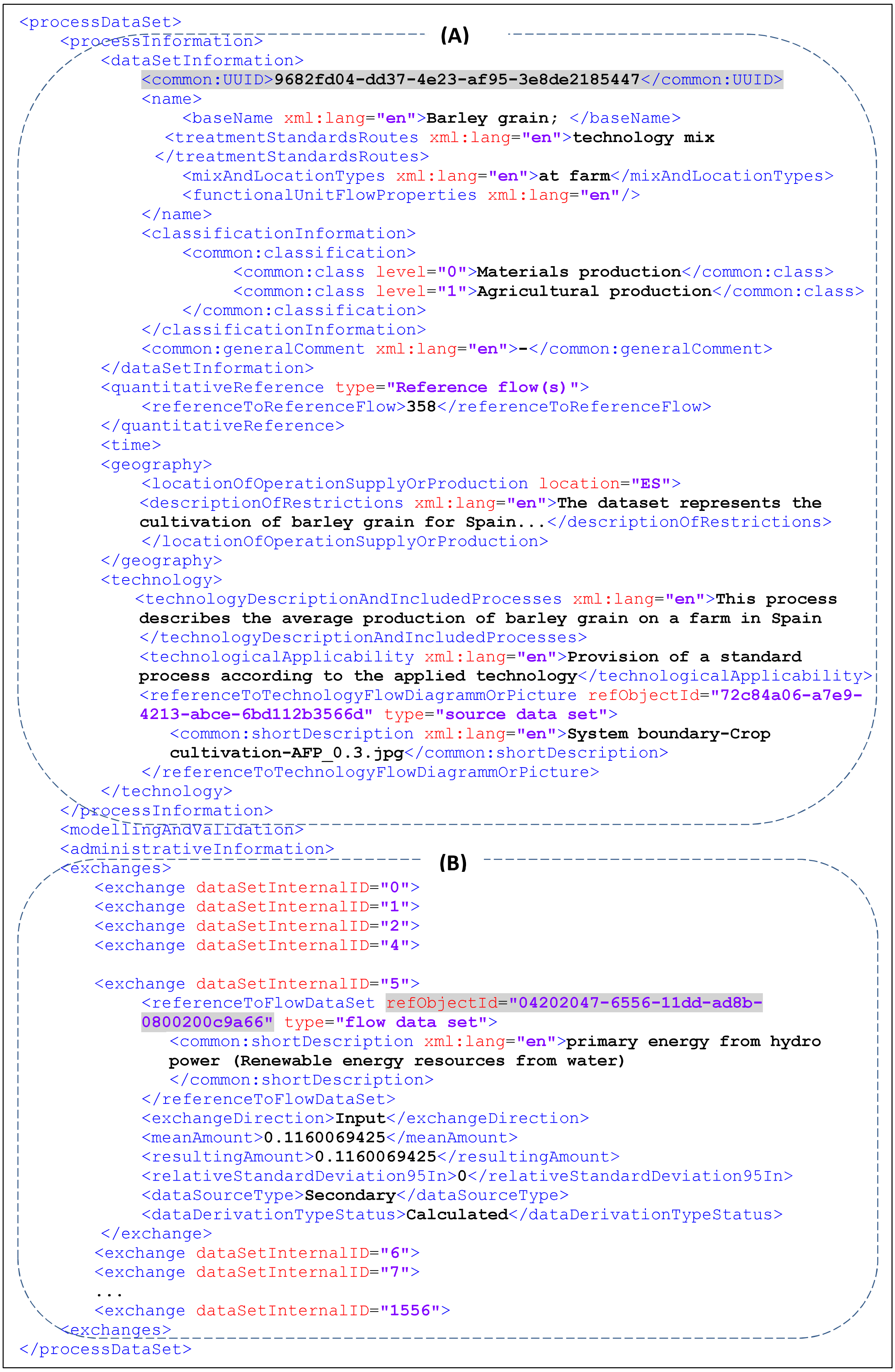
Figure 3.4:Schematic representation of the Environmental footprint database and its dataset collections

As any other XML document, the EF-datasets$_{XML}$ follow a hierarchy and its data is ordered in a labelled tree following the ILCD format requirements. Each node (joining point) of the tree is a *dataset element* and is written with an opening and closing *tag*. A dataset element can contain more elements or data (numerical or text values); and can also have one or more *dataset attributes* which can also contain data. Figure 3.5 is shown an example of an EF-dataset$_{XML}$ that belongs to the EF-database process collection which, among other data, has main information of the process and information about its elementary flows (inputs and outputs to nature).

As part of the process information, this EF-dataset$_{XML}$ (Figure 3.5-A) contains data regarding the process's name, classification, geography, technology and more. However, the most important data in this EF-dataset$_{XML}$ is its UUID (common:UUID=9682fd04-dd37-4e23-af95-3e8de2185447) since it is a key element to interconnect this EF-dataset$_{XML}$ data to other EF-datasets$_{XML}$ in different collections in the EF-database.

The information regarding the elementary flows of this process EF-dataset$_{XML}$(Figure 3.5-B) is mainly related to the flows' name, exchange directions which can be input or output, mean amount and the relative standard deviation of the mean amount. The most important data in the process's elementary flows information is the UUID of each flow (refObjectId=04202047-6556-11dd-ad8b-0800200c9a66). This since each elementary flow UUID will be used to retrieve data from the EF-datasets$_{XML}$ in the flows and LCIA methods collections of the EF-database, such as the flow units and its related characterization factors respectively.

Based on the ILCD structure of the EF-datasets$_{XML}$ and their UUIDs, four different code scripts were written to retrieve and implement the EF-database data in CalcPEF$_{Dairy}$. These code scripts are in the Python 3.6 language and executed in Spyder 3.3.1; a python platform for scientific programming,



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            process according to the applied technology</technologicalApplicability>
            <referenceToTechnologyFlowDiagrammOrPicture refObjectId="72c84a06-a7e9-
            4213-abce-6bd112b3566d" type="source data set">
               <common:shortDescription xml:lang="en">System boundary-Crop
               cultivation-AFP_0.3.jpg</common:shortDescription>
            </referenceToTechnologyFlowDiagrammOrPicture>
        </technology>
    </processInformation>
    <modellingAndValidation>
    <administrativeInformation>
    <exchanges>
       <exchange dataSetInternalID="0">
       <exchange dataSetInternalID="1">
       <exchange dataSetInternalID="2">
       <exchange dataSetInternalID="4">

       <exchange dataSetInternalID="5">
            <referenceToFlowDataSet refObjectId="04202047-6556-11dd-ad8b-
            0800200c9a66" type="flow data set">
               <common:shortDescription xml:lang="en">primary energy from hydro
               power (Renewable energy resources from water)
               </common:shortDescription>
            </referenceToFlowDataSet>
            <exchangeDirection>Input</exchangeDirection>
            <meanAmount>0.1160069425</meanAmount>
            <resultingAmount>0.1160069425</resultingAmount>
            <relativeStandardDeviation95In>0</relativeStandardDeviation95In>
            <dataSourceType>Secondary</dataSourceType>
            <dataDerivationTypeStatus>Calculated</dataDerivationTypeStatus>
        </exchange>
       <exchange dataSetInternalID="6">
       <exchange dataSetInternalID="7">
       ...
       <exchange dataSetInternalID="1556">
    <exchanges>
</processDataSet>
```

Figure 3.5:Estructure and representation of an XML document containing data of a process in the EF-database. (A) process information and (B) process elementary flows

3.2.1.1 XML documents to Python ordered dictionaries

This first script is in charge of launching a python-based XML parser. As shown in Figure 3.6, the parser takes as input is an EF-datasets$_{XLM}$. It reads one by one the EF-datasets$_{XLM}$ characters, processes the data and arranges it in an ordered dictionary structure (EF-datasets$_{oDict}$); which is the parser output.

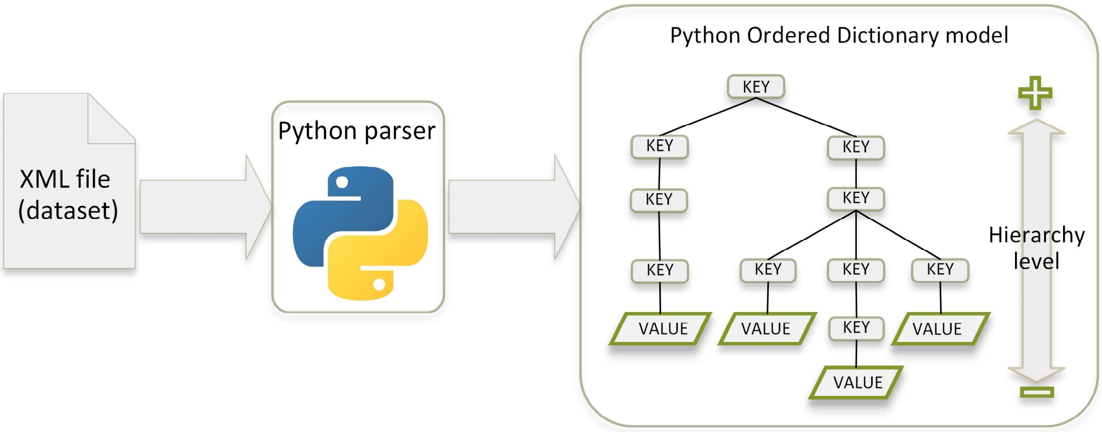


Figure 3.6: Transformation of the data in a XML document to a python Ordered Dictionary through the use of a python parser.

An ordered dictionary is a collection of python dictionaries which are elements that contain paired items keys and values (text or numerical). In an ordered dictionary a key could be related to either a value or to another key that leads to other dictionary. Consequently, the main outcome of this parsing process is to transform all the EF-datasets$_{XLM}$ in the EF-database into a pythonic structure of data (EF-datasets$_{oDict}$, Figure 3.7) from which its content can be visualised, retrieved and managed.

```
OrderedDict([('processDataSet',
    OrderedDict([('processInformation',
        OrderedDict([('dataSetInformation',
            OrderedDict([('common:UUID','9682fd04-dd37-4e23-af95-3e8de2185447'),
                         ('name',
                           OrderedDict([('baseName',
                                          OrderedDict([('#text','Barley grain;')])),
                                          ('treatmentStandardsRoutes',
                                          OrderedDict([('#text','technology mix')])),
                                          ('mixAndLocationTypes',
                                          OrderedDict([('#text','at farm')])),
                                          ('functionalUnitFlowProperties')])),
                                          ('classificationInformation',
                                          OrderedDict([('common:classification',
                                                        OrderedDict([('common:class',
                                                                       [OrderedDict([('@level','0'),
                                                                                   ('#text','Materials production')]),
                                                                       OrderedDict([('@level','1'),
                                                                                   ('#text','Agricultural production means')])])])]))])),
                         ('quantitativeReference',
                           OrderedDict([('@type','Reference flow(s)'),
                                        ('referenceToReferenceFlow','358')])),
                           ('time',OrderedDict(...)),
                           ('geography', OrderedDict([('locationOfOperationSupplyOrProduction',
                                           OrderedDict([('@location','ES'),
                                                         ('descriptionOfRestrictions',
                                                         OrderedDict([('#text','The dataset represents the cultivation of…..')]))])])),
                                         ('technology',OrderedDict(...)),
                  ('modellingAndValidation',OrderedDict(...)),('administrativeInformation',OrderedDict(...)),
                  ('exchanges',
                    OrderedDict([('exchange',
                        OrderedDict([('@dataSetInternalID','8'),
                                     ('referenceToFlowDataSet',
                        OrderedDict([('@refObjectId','04202047-6556-11dd-ad8b-0800200c9a66'),
                                     ('@type','flow data set'),
                                     ('common:shortDescription',
                        OrderedDict([('#text','primary energy from hydro power (Renewable energy resources from water)')]))])),
                        ('exchangeDirection','Input'),
                        ('meanAmount','0.1160069425'),
                        ('resultingAmount','0.1160069425'),
                        ('relativeStandardDeviation95In','0'),
                        ('dataSourceType','Secondary'),
                        ('dataDerivationTypeStatus','Calculated')]))]))]))])
```

Figure 3.7: Structure and representation of the XML document data in Figure 3.5 as a python ordered dictionary obtained after parsing. (A) process information and (B) process elementary flows

3.2.1.2 From Python ordered dictionaries to SQLite database

This second python script is responsible of identify, retrieve and rearrange the data from the new EF-datasets$_{\mathrm{oDict}}$ into a new format, so it can be exported to different tables in an SQLite database. This script takes as starting point the EF-datasets$_{\mathrm{oDict}}$ in the process collection; and for each EF-dataset$_{\mathrm{oDict}}$ in it, the script retrieves the input and output flows UUID and mean amount. When finishes the extraction, the script arranges the data following the SQLite data structure presented in Figure 3.8 and then exports it to an SQLite database. This data structure generates a table named *Process Exchanges* in the SQLite database (Figure 3.9) which is a consolidated table containing the elementary flows UUIDs and its related amounts for all the EF-datasets$_{\mathrm{oDict}}$ in the process' collection.

```
CREATE TABLE `1_Processes Exchanges` (
    `Flow_UUID` TEXT,
    `Process_name`   REAL);
```

Figure 3.8: Data structure exported from Python to create the Process Exchanges SQLite table.

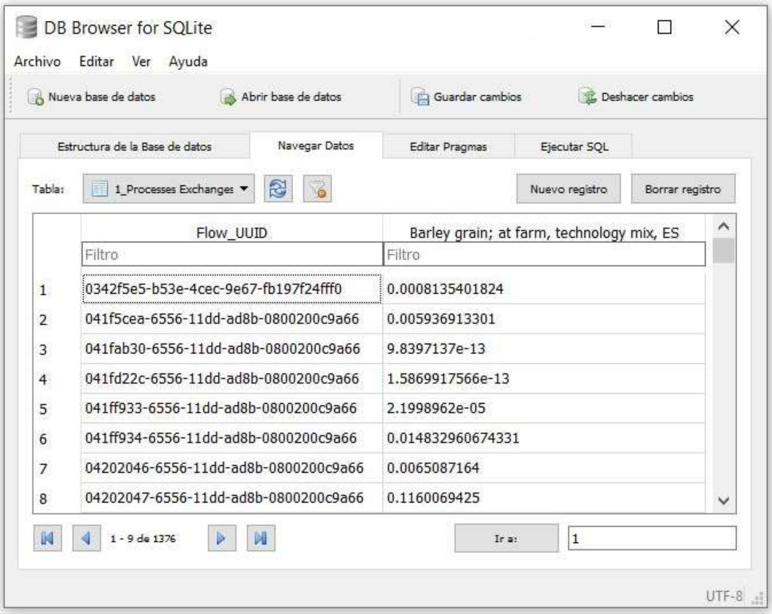


Tabla: 1_Processes Exchanges

	Flow_UUID	Barley grain; at farm, technology mix, ES
	Filtro	Filtro
1	0342f5e5-b53e-4cec-9e67-fb197f24fff0	0.0008135401824
2	041f5cea-6556-11dd-ad8b-0800200c9a66	0.005936913301
3	041fab30-6556-11dd-ad8b-0800200c9a66	9.8397137e-13
4	041fd22c-6556-11dd-ad8b-0800200c9a66	1.5869917566e-13
5	041ff933-6556-11dd-ad8b-0800200c9a66	2.1998962e-05
6	041ff934-6556-11dd-ad8b-0800200c9a66	0.014832960674331
7	04202046-6556-11dd-ad8b-0800200c9a66	0.0065087164
8	04202047-6556-11dd-ad8b-0800200c9a66	0.1160069425

1 - 9 de 1376

Ir a: 1

Figure 3.9: Capture of the Processes Exchange table and its content in the SQLite database

Then, for each of the retrieved elementary flow UUID, the script looks for a matching EF-datasets$_{\mathrm{oDict}}$ in the flows collection and when found retrieves the flows name and location. Simultaneously, the script looks for a matching flow UUID in the data of each LCIA method EF-datasets$_{\mathrm{oDict}}$. For this case, when there is a match, the script retrieves the LCIA method UUID, name and the matching flow characterization factor. Once all the data has been retrieved from these EF-datasets$_{\mathrm{oDict}}$ collections; the script organises the data by also following an SQLite structure (Figure 3.10) and , when finishes, exports this new data structure to the SQLite database.

In the database the exported data is visualized as a table named *EF methods*. This new consolidated table (Figure 3.11) contains, among other data, the EF compliant characterization factors for all the elementary flows used in the processes EF-datasets of the EF-database.

```
CREATE TABLE `2_EF methods` (
    `Method_UUID`   TEXT,
    `Method_name`   TEXT,
    `Imp Category`  TEXT,
    `Imp Indiactor` TEXT,
    `Flow_UUID` TEXT,
    `Flow_name` TEXT,
    `Flow_location` TEXT,
    `Characterization Factor`   REAL,);
```

Figure 3.10: Data structure exported from Python to create the EF methods SQLite table.

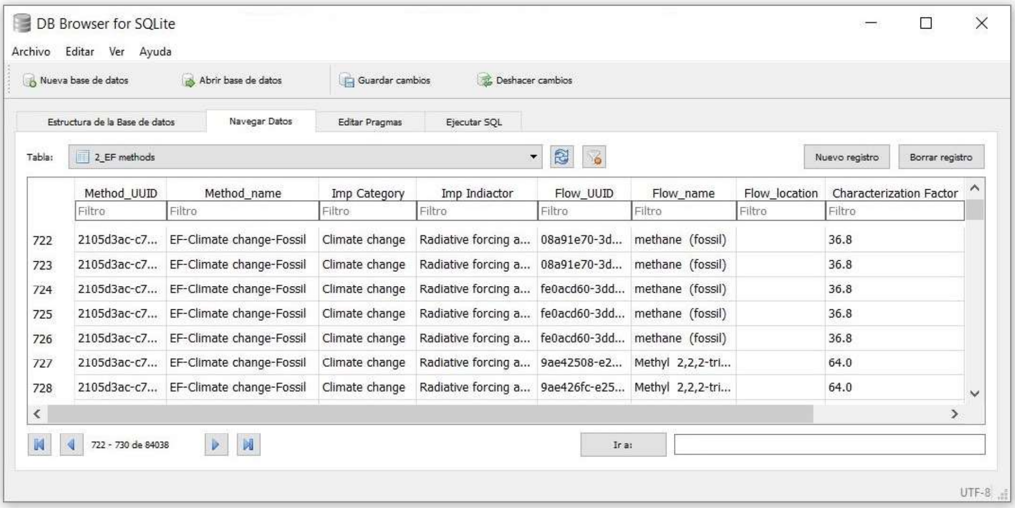


Tabla: 2_EF methods

	Method_UUID	Method_name	Imp Category	Imp Indiactor	Flow_UUID	Flow_name	Flow_location	Characterization Factor
	Filtro	Filtro	Filtro	Filtro	Filtro	Filtro	Filtro	Filtro
722	2105d3ac-c7...	EF-Climate change-Fossil	Climate change	Radiative forcing a...	08a91e70-3d...	methane (fossil)		36.8
723	2105d3ac-c7...	EF-Climate change-Fossil	Climate change	Radiative forcing a...	08a91e70-3d...	methane (fossil)		36.8
724	2105d3ac-c7...	EF-Climate change-Fossil	Climate change	Radiative forcing a...	fe0acd60-3dd...	methane (fossil)		36.8
725	2105d3ac-c7...	EF-Climate change-Fossil	Climate change	Radiative forcing a...	fe0acd60-3dd...	methane (fossil)		36.8
726	2105d3ac-c7...	EF-Climate change-Fossil	Climate change	Radiative forcing a...	fe0acd60-3dd...	methane (fossil)		36.8
727	2105d3ac-c7...	EF-Climate change-Fossil	Climate change	Radiative forcing a...	9ae42508-e2...	Methyl 2,2,2-tri...		64.0
728	2105d3ac-c7...	EF-Climate change-Fossil	Climate change	Radiative forcing a...	9ae426fc-e25...	Methyl 2,2,2-tri...		64.0

722 - 730 de 84038

Figure 3.11: Content of the EF methods table in the SQLite database

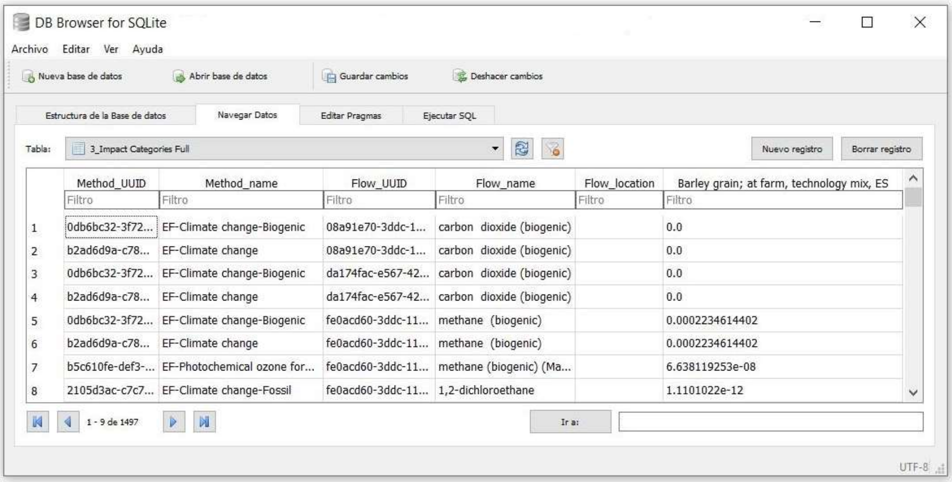
3.2.1.3 LCIA calculations and results to SQLite database

This third script uses the data on the previously created SQLite tables to execute the LCIA of all the processes in the EF-database. First this script matches the elementary flows UUIDs in the *Exchange process* SQLite table with the ones in the *EF methods* table. Once the UUIDs data is matched, it multiplies the amount values of the elementary flows with their respective characterization factor. Once again, these results are organized in an SQLite data structure (Figure 3.12) and exported to the database as a new SQLite table.

```
CREATE TABLE `3_Impact Categories Full` (
    `Method_UUID`   TEXT,
    `Method_name`   TEXT,
    `Flow_UUID` TEXT,
    `Flow_name` TEXT,
    `Flow_location` TEXT,
    `Process_name`  REAL);
```

Figure 3.12: Data structure exported from Python to create the Impact Categories Full SQLite table.

The name of this new added table is *Impact Categories Full* (Figure 3.13)and contains the characterized results for all the elementary flows that are part of the different processes; the table also has information regarding the characterization method UUID and name; the characterized elementary flow UUID and name. At this point the elementary flows of all the process in the EF-database have been characterized for the 16 environmental impact categories considered in the PEF methodology but, the results have not been grouped by environmental impact category.



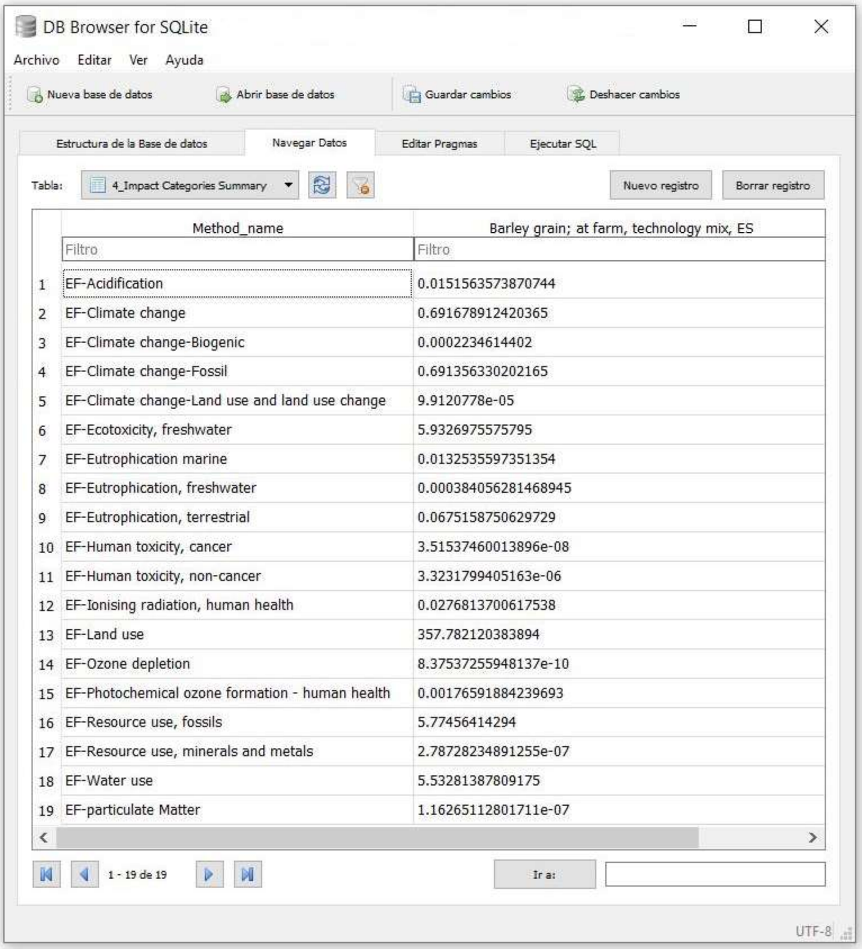
	Method_UUID	Method_name	Flow_UUID	Flow_name	Flow_location	Barley grain; at farm, technology mix, ES
	Filtro	Filtro	Filtro	Filtro	Filtro	Filtro
1	0db6bc32-3f72...	EF-Climate change-Biogenic	08a91e70-3ddc-1...	carbon dioxide (biogenic)		0.0
2	b2ad6d9a-c78...	EF-Climate change	08a91e70-3ddc-1...	carbon dioxide (biogenic)		0.0
3	0db6bc32-3f72...	EF-Climate change-Biogenic	da174fac-e567-42...	carbon dioxide (biogenic)		0.0
4	b2ad6d9a-c78...	EF-Climate change	da174fac-e567-42...	carbon dioxide (biogenic)		0.0
5	0db6bc32-3f72...	EF-Climate change-Biogenic	fe0acd60-3ddc-11...	methane (biogenic)		0.0002234614402
6	b2ad6d9a-c78...	EF-Climate change	fe0acd60-3ddc-11...	methane (biogenic)		0.0002234614402
7	b5c610fe-def3-...	EF-Photochemical ozone for...	fe0acd60-3ddc-11...	methane (biogenic) (Ma...		6.638119253e-08
8	2105d3ac-c7c7...	EF-Climate change-Fossil	fe0acd60-3ddc-11...	1,2-dichloroethane		1.1101022e-12

Figure 3.13: Content of the Impact Categories Full table in the SQLite database

In a second step and by taking as starting point the data in the *Impact Categories Full* SQLite table, this script groups the characterized flow results according to the method UUID. After grouping, the script organises the data in an SQLite structure (Figure 3.14) and exports it to the SQLite database as a new table named *Impact Categories Full*. As shown in Figure 3.15, this new table contains the PEF characterized profile for each of the processes in the EF-database; it presents the total characterized scores for 16 environmental impact categories and it also includes the three impact subcategories global warming for climate change.

```
CREATE TABLE `4_Impact Categories Summary` (
    `Method_name`    TEXT,
    `Process name`   REAL,);
```

Figure 3.14: Data structure exported from Python to create the Impact Categories Summary SQLite table.

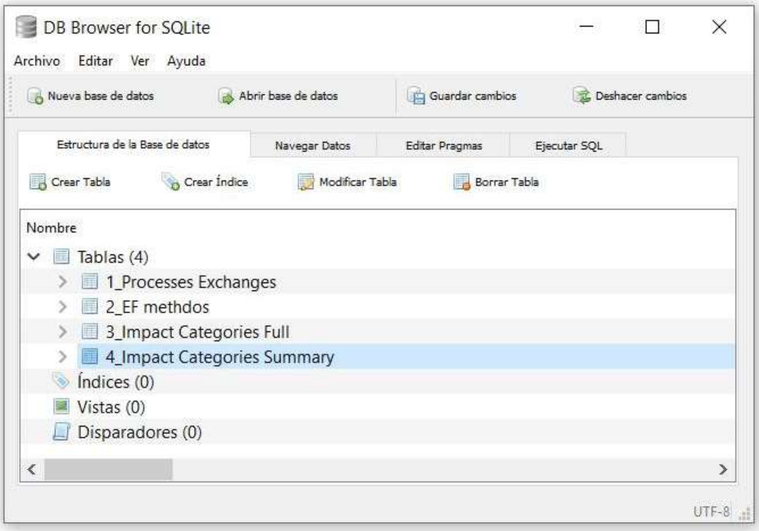


	Method_name	Barley grain; at farm, technology mix, ES
1	EF-Acidification	0.0151563573870744
2	EF-Climate change	0.691678912420365
3	EF-Climate change-Biogenic	0.0002234614402
4	EF-Climate change-Fossil	0.691356330202165
5	EF-Climate change-Land use and land use change	9.9120778e-05
6	EF-Ecotoxicity, freshwater	5.9326975575795
7	EF-Eutrophication marine	0.0132535597351354
8	EF-Eutrophication, freshwater	0.000384056281468945
9	EF-Eutrophication, terrestrial	0.0675158750629729
10	EF-Human toxicity, cancer	3.51537460013896e-08
11	EF-Human toxicity, non-cancer	3.3231799405163e-06
12	EF-Ionising radiation, human health	0.0276813700617538
13	EF-Land use	357.782120383894
14	EF-Ozone depletion	8.37537255948137e-10
15	EF-Photochemical ozone formation - human health	0.00176591884239693
16	EF-Resource use, fossils	5.77456414294
17	EF-Resource use, minerals and metals	2.78728234891255e-07
18	EF-Water use	5.53281387809175
19	EF-particulate Matter	1.16265112801711e-07

Figure 3.15: Content of the Impact Categories Summary table in the SQLite database

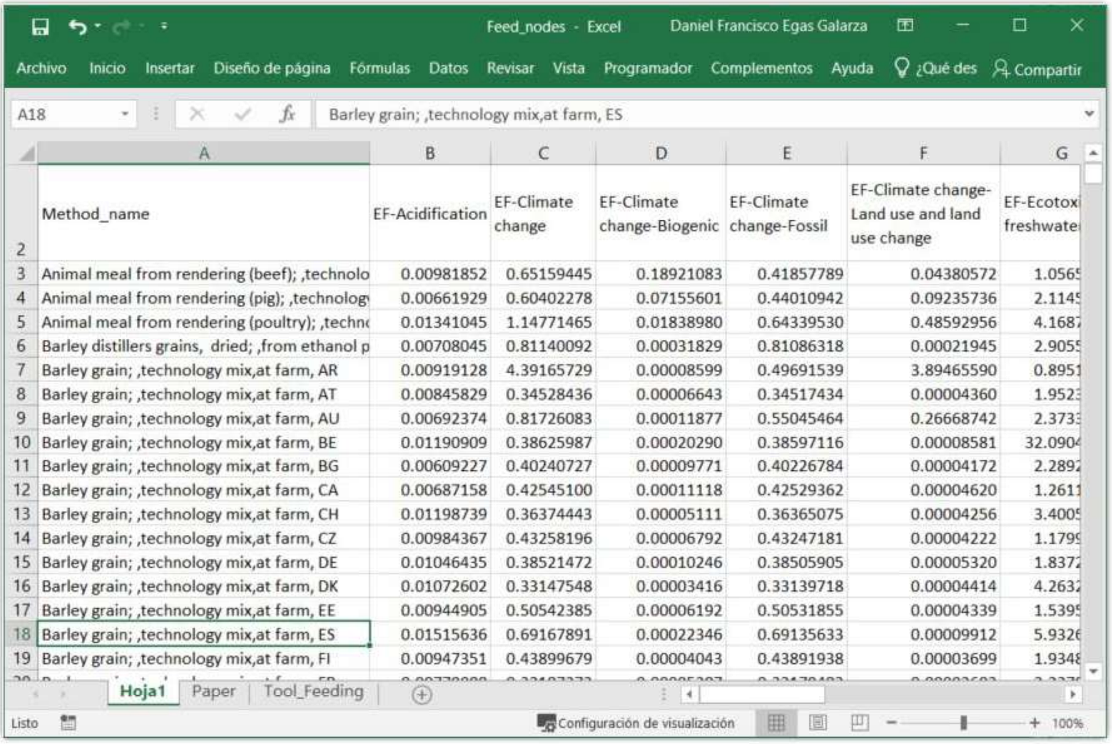
3.2.1.4 From SQLite dataset to Excel tables in the IT tool.

At the end of the previous script, an SQLite database with four different tables was created with the data retrieved from different EF-datasets in the EF-database as shown in Figure 3.16. However, since CalcPEF$_{\text{Dairy}}$ is developed in Microsoft Excel, the full data from the SQLite tables needs to be exported to Excel. To do so, the four and last script gives these SQLite tables an Excel format and saves them in an Excel document. Figure 3.17 is shown as an example of the final outcome of this script where the excel document contains the characterized profiles of many processes. Finally, after executing this fourth script the EF-database data can be used for the development of CalcPEF$_{\text{Dairy}}$.



- Tablas (4)
  - 1_Processes Exchanges
  - 2_EF methdos
  - 3_Impact Categories Full
  - 4_Impact Categories Summary
- Índices (0)
- Vistas (0)
- Disparadores (0)

Figure 3.16: Capture of the SQLite database with its four consolidated tables.



Barley grain; ,technology mix,at farm, ES

	A	B	C	D	E	F	G
2	Method_name	EF-Acidification	EF-Climate change	EF-Climate change-Biogenic	EF-Climate change-Fossil	EF-Climate change-Land use and land use change	EF-Ecotoxi freshwate
3	Animal meal from rendering (beef); ,technolo	0.00981852	0.65159445	0.18921083	0.41857789	0.04380572	1.056
4	Animal meal from rendering (pig); ,technolog	0.00661929	0.60402278	0.07155601	0.44010942	0.09235736	2.114
5	Animal meal from rendering (poultry); ,techn	0.01341045	1.14771465	0.01838980	0.64339530	0.48592956	4.168
6	Barley distillers grains, dried; ,from ethanol p	0.00708045	0.81140092	0.00031829	0.81086318	0.00021945	2.905
7	Barley grain; ,technology mix,at farm, AR	0.00919128	4.39165729	0.00008599	0.49691539	3.89465590	0.8951
8	Barley grain; ,technology mix,at farm, AT	0.00845829	0.34528436	0.00006643	0.34517434	0.00004360	1.952
9	Barley grain; ,technology mix,at farm, AU	0.00692374	0.81726083	0.00011877	0.55045464	0.26668742	2.373
10	Barley grain; ,technology mix,at farm, BE	0.01190909	0.38625987	0.00020290	0.38597116	0.00008581	32.090
11	Barley grain; ,technology mix,at farm, BG	0.00609227	0.40240727	0.00009771	0.40226784	0.00004172	2.289
12	Barley grain; ,technology mix,at farm, CA	0.00687158	0.42545100	0.00011118	0.42529362	0.00004620	1.261
13	Barley grain; ,technology mix,at farm, CH	0.01198739	0.36374443	0.00005111	0.36365075	0.00004256	3.400
14	Barley grain; ,technology mix,at farm, CZ	0.00984367	0.43258196	0.00006792	0.43247181	0.00004222	1.179
15	Barley grain; ,technology mix,at farm, DE	0.01046435	0.38521472	0.00010246	0.38505905	0.00005320	1.837
16	Barley grain; ,technology mix,at farm, DK	0.01072602	0.33147548	0.00003416	0.33139718	0.00004414	4.263
17	Barley grain; ,technology mix,at farm, EE	0.00944905	0.50542385	0.00006192	0.50531855	0.00004339	1.539
18	Barley grain; ,technology mix,at farm, ES	0.01515636	0.69167891	0.00022346	0.69135633	0.00009912	5.932
19	Barley grain; ,technology mix,at farm, FI	0.00947351	0.43899679	0.00004043	0.43891938	0.00003699	1.934

Figure 3.17:Capture of the Excel spreadsheet that contains the data imported from the Impact Categories Summary SQLite table

3.2.2 Product Environmental Footprint compliant emission models

Since most of the dairy products' environmental impacts are attributed to the emissions arising from the different dairy farm activities, CalcPEF$_{Dairy}$ calculates them according to the models stated in the PEFCR-D and presented in Table 3.10; a complete and detailed information regarding each of these emission models can be obtained from their respective sources. The requirements and calculation procedures of these emission models were encoded in the VBA language so the tool can execute when required as exemplified in Figure 3.18

Table 3.10:PEFCR-D included and excluded on-farm emissions with their respective source, calculation models and level of assessment.

Source	Emission	Calculation model
Included		
Enteric Fermentation Manure storage (and pre-treatment)	Methane (CH_4), emitted to air	IPCC [a] – 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 [a] – 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 [a] – 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 [b] – Tier 2
Manure excretion on the pasture Manure application Artificial fertilizer application	Phosphate (PO_4^-) emitted to ground and surface water	SALCA – Phosphorus [c]
Manure excretion on the pasture Manure application Artificial fertilizer application	Phosphorus (P) emitted to surface water	SALCA – Phosphorus [c]
Animal Housing	Particulate matter (PM2.5), emitted to air	EMEP/EEA [b] – Tier 2
Silage feeding Housing Grazing	Non-methane volatile solids (NMVOC), emitted to air	EMEP/EEA [b] – Tier 2
Manure excretion on the pasture Manure application Artificial fertilizer application Crop residues	Nitrate (NO_3), emitted to ground water	IPCC [a] – Tier 1
Application of lime Application of urea Peat drainage	Carbon dioxide (CO_2), emitted to air	IPCC [a] – Tier 1
Manure application	Heavy metals emitted to groundwater and soil	SALCA-Heavy metals [d]
Application of pesticides	Pesticides emitted to soil	PEFCR v6.3 [e]
Excluded		
Milk cooling	Refrigerants emitted to air	-
Carbon sequestration	Carbon dioxide (CO_2), emitted to air	-

[a] IPCC chapter 10 (2006a) and chapter 11(2006b), [b] EMEP/EEA section 3.B (2016a) and 3.D (2016b)
[c] SALCA – Phosphorus (Prasuhn, 2006), [d] SALCA-Heavy metals (Freiermuth, 2006)
[e] Active component applied 90% to agricultural soil, 9% to air and 1% to water (EC, 2018a)

```
Sub N2O_Indirect_E_Msoils()
Call IPCC_Calcs.Volat_N2O_Msoils
Call IPCC_Calcs.Leach_N2O_Msoils

    'FROM ATMOSPHERIC DEPOSITION OF N VOLATILISED FROM MANAGED SOILS (TIER 1)
    N2O_ATD__N = (((Fsn * Frac_GASF) + ((FON * Frac_GASM_MApp) + (Fprp *
    Frac_GASM_PRP))* EF4)) '(kg N2O-N/year)

    'FROM N LEACHING/RUNOFF FROM MANAGED SOILS IN REGIONS WHERE LEACHING/RUNOFF
    OCCURS (TIER 1)
    N2O_L__N = (Fsn + FON + Fprp + FCR + FSOM) * Frac_LEACH_H * EF5 '(kg N2O-N/year)
End Sub
```

Figure 3.18: VBA lines of code for the calculation of Indirect N2O emissions from managed soils due to volatilization and leaching/runoff as stated by the IPCC (2006b)

From a general perspective, the VBA code of CalcPEF$_{\text{Dairy}}$ determines CH_4 emissions through the application of the IPCC Tier 2 method, while the IPCC Tier 1 method is used to determine CO_2 emissions. While, the EMEP/EEA Tier 2 guidelines are employed to calculate the particular matter (PM) and non-methane volatile solids (NMVOC). For heavy metals (Cd, Cr, Cu, Hg, Ni, Pb and Zn), the Swiss Agricultural Life Cycle Assessment (SALCA) calculation model (Freiermuth, 2006) is used. For phosphorus (P and PO_4^-) emissions, the PEFCR-D does not explicitly state the model that should be applied; therefore, the tool implements the SALCA-phosphorus model (Prasuhn, 2006) since this calculation model is also used in for the development of other LCA databases such as Ecoinvent v3 (Wernet et al., 2016). Finally, for N emissions (N_2O, NH_3, NO_x and NO_3), the PEFCR-D states that the IPCC and the EMEP/EEA models should be simultaneously applied.

As previously discussed in the introduction of this work, the simultaneous use of the IPCC and EMEP-EEA models to calculated N emissions creates a mass balance conflict in the system. Hence, if the user desires it, CalcPEF$_{\text{Dairy}}$ can follow a N balanced approach that harmonizes the EMEP/EEA and IPCC results and vice versa. If not, the tool will follow an unbalanced approach where the EMEP/EEA and IPCC results are not harmonized.

The proposed N balanced approach is implemented by CalcPEF$_{\text{Dairy}}$ in four phases thought also VBA code. When the fourth phase is completed a common and balanced N flow is obtained; from which the on-farm N emissions are determined and reported according to the PEFCR-D requirements. Additionally, this approach includes extra N inputs and outputs that are not stated in the PEFCR-D but exist in a traditional dairy farm.

The approach proposes a sequential implementation of the equations and factors provided by the IPCC and EMEP-EEA, and it also manages the results to obtain a common harmonised and balanced N flow. The complete sequence of equations used to implement the proposed harmonisation approach are presented and discussed in detail in the Annex B. However, a general description of this proposed approach is presented in the paragraphs below and represented in Figure 3.19.

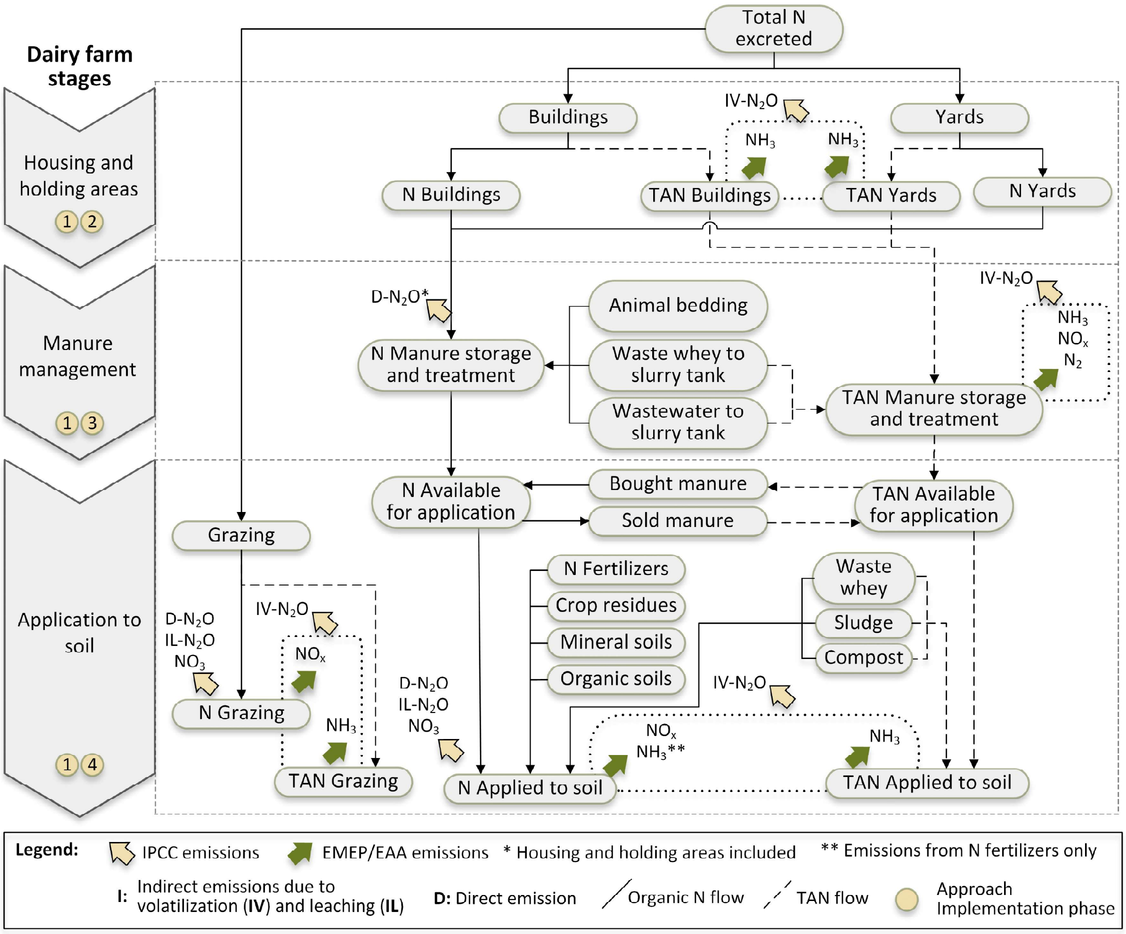


Figure 3.19: Schematic representation of the proposed harmonisation approach to implement the IPCC and EMEP/EEA N emission models.

The implementation of this approach starts with the calculation of the total excreted nitrogen (N_{ex}) that should be calculated according to the IPCC (2006a) Tier 2 guidelines since it the starting point of both IPCC and EMEP/EEA models. In addition to it, the EMEP/EEA requires the calculation of the excreted Total Ammoniacal Nitrogen (TAN) which is determined as a proportion (0.6) of N_{ex}. Both, the N_{ex} and its corresponding TAN fraction are calculated for each livestock subcategory present in the farm (e.g. high or low producing mature cows, non-productive cows or calves) and added together to obtain the total farm's TAN and N_{ex}. From these total values of Tan and N_{ex}, the approach will determine the total on-farm N emissions through its four calculation phases .

The *first phase* adds the extra N sources and independently applies the IPCC and the EMEP/EEA models through all the dairy farm stages. The IPCC Chapter 10 (2006a) and EMEP/EEA Section 3.B (2016a) calculate emissions during the livestock housing, holding areas and manure storage.

While the IPCC Chapter 11 (2006b) and EMEP/EEA Section 3.D (2016b) to quantify N emissions from the application of manure or fertilizers. This phase calculated emissions are the starting point for the following harmonization phases.

Since the emissions from one farm stage depend on the N flow that comes from the previous stage, the second, third and fourth implementation phases will focus on balancing the N flows from one specific farm stage at a time (housing and holding areas, manure management and application respectively). However, each implementation phase will still have an effect on the next stage of the farm until completing the fourth phase; reason why, balancing the system is an iterative process. At the end of the last phase the N flow in the complete dairy farm system has been balanced and therefore, PEFCR-D compliant emissions arising from it can be reported.

3.2.3 Deployment of the specialized IT tool

The main software used to develop and deploy CalcPEF$_{\text{Dairy}}$ is Microsoft Excel™; which acts as a host for the Visual Basic for Applications (VBA) platform. CalcPEF$_{\text{Dairy}}$ has three main components; two of which can be accessed by the user (Excel and VBA objects) to add, visualize and edit the data; while the third component (VBA code scripts) is not accessible and operates in the tool background. This third element is responsible of managing the data added to the tool in order to generate the desired results.

3.2.3.1 Excel and VBA objects

Spreadsheets, which are Excel objects, are used as data bases and to report the final results as graphs and tables. Whereas, the VBA objects (user forms, list boxes text boxes, buttons, etc) are used as user-interface objects for data input and management; and also used to trigger and execute the tasks defined in the VBA scripts. These spreadsheets and VBA objects can be accessed and used through the tool’s main menu (Figure 3.20).

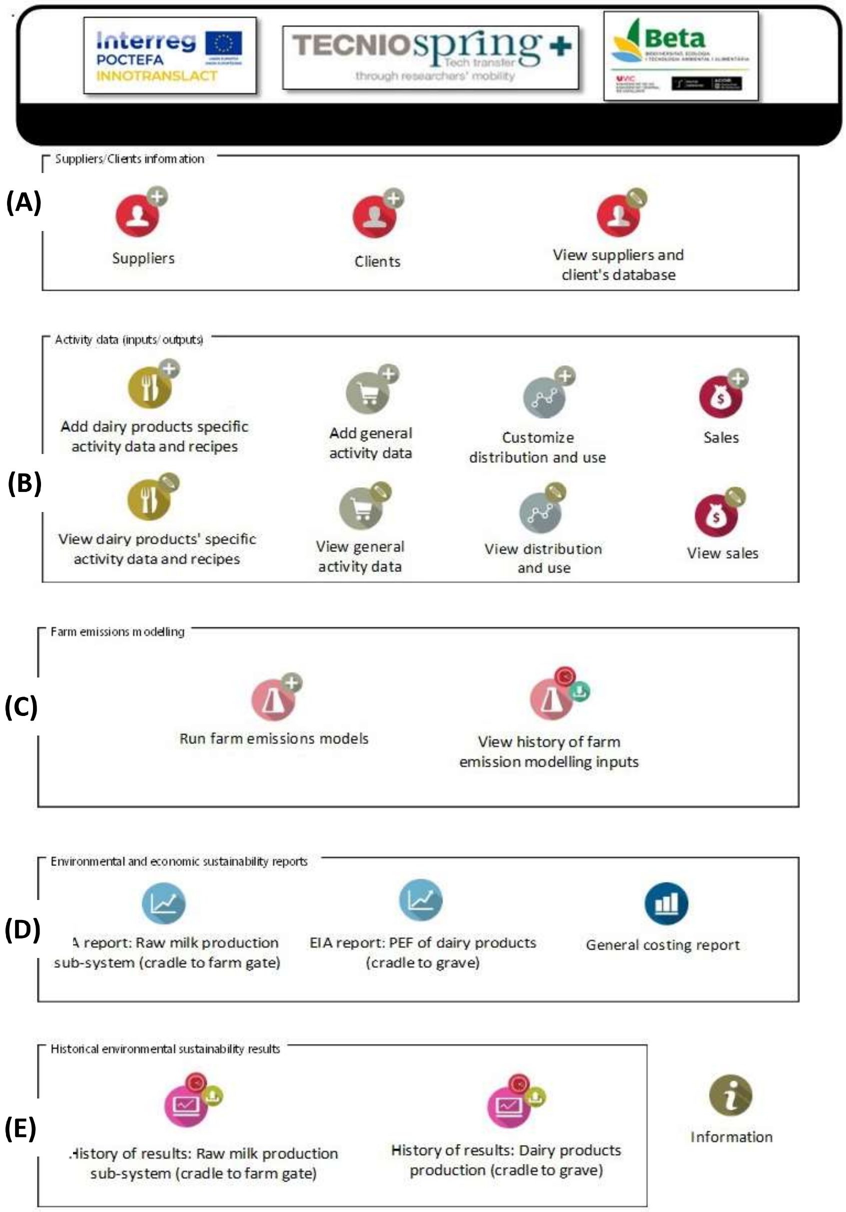
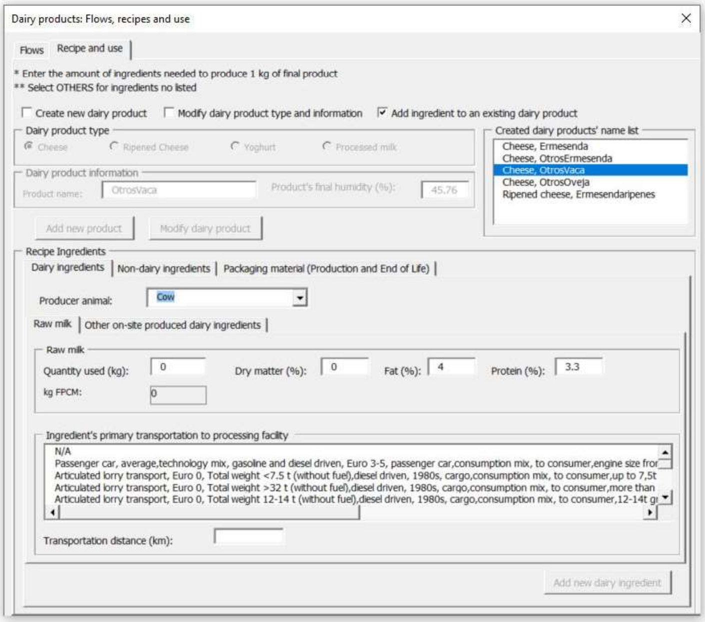


Figure 3.20:Main menu: buttons to access (A) Clients and suppliers' information, (B) Activity data: input and output flows, (C) Farm emission models (D) Environmental and cost reports and (E) historical environmental results.

The main menu buttons are sorted in five groups; the first of which is *Group A* (Figure 3.20-A). This button activates the S*uppliers and Client's information user forms* and also the open their respective database (DB); where the added data can be visualized and delete.

Buttons in *Group B* (Figure 3.20-B) activate the (i) products recipes, (ii) general activity data (iii) distribution and use, and (iv) the sales user forms; where information regarding these four sub-groups of activity data can be added to the tool. These added data can be later visualised in the DB of each activity data sub-group.

The *dairy products' properties and recipes user form* (Figure 3.21) collects data related to the dairy product's properties and its recipe to produce 1 kilogram of final dairy products. Here, the dairy product's type (cheese, ripened cheese, yoghurt or processed milk), name and humidity shall be defined to later add the amount and type of ingredients (dairy, non-dairy and packing materials) needed for its production.


Dairy products: Flows, recipes and use

* Enter the amount of ingredients needed to produce 1 kg of final product
** Select OTHERS for ingredients no listed

☐ Create new dairy product ☐ Modify dairy product type and information ☑ Add ingredient to an existing dairy product

Dairy product type: ● Cheese ○ Ripened Cheese ○ Yoghurt ○ Processed milk

Product name: OtrosVaca
Product's final humidity (%): 45.76

Created dairy products' name list:
Cheese, Ermesenda
Cheese, OtrosErmesenda
Cheese, OtrosVaca
Cheese, OtrosOveja
Ripened cheese, Ermesendaripenes

Producer animal: Cow

Quantity used (kg): 0
Dry matter (%): 0
Fat (%): 4
Protein (%): 3.3
kg FPCM: 0

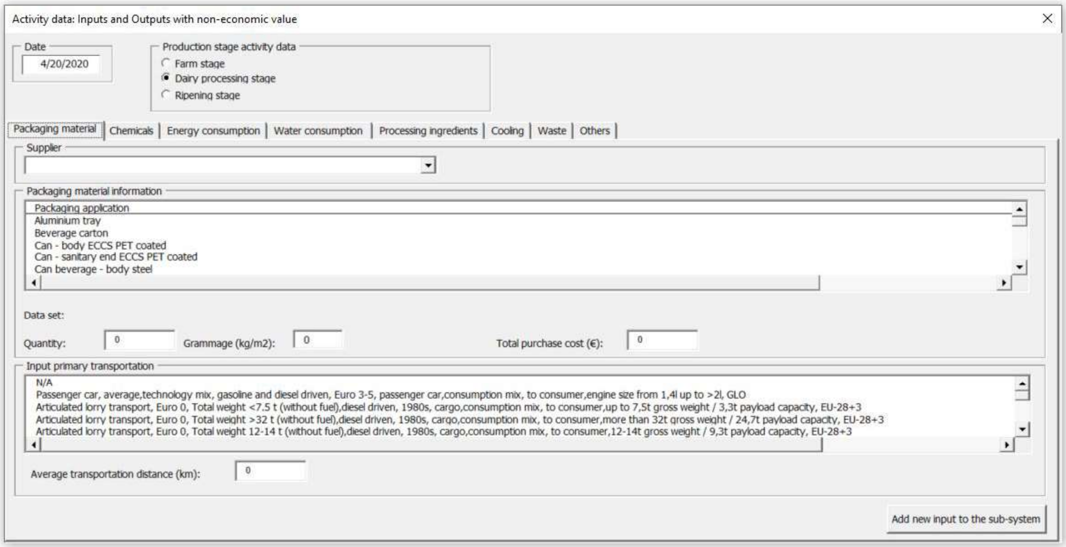
Ingredient's primary transportation to processing facility:
N/A
Passenger car, average,technology mix, gasoline and diesel driven, Euro 3-5, passenger car,consumption mix, to consumer,engine size fro
Articulated lorry transport, Euro 0, Total weight <7.5 t (without fuel),diesel driven, 1980s, cargo,consumption mix, to consumer,up to 7,5t
Articulated lorry transport, Euro 0, Total weight >32 t (without fuel),diesel driven, 1980s, cargo,consumption mix, to consumer,more than
Articulated lorry transport, Euro 0, Total weight 12-14 t (without fuel),diesel driven, 1980s, cargo,consumption mix, to consumer,12-14t g

Transportation distance (km):

*Figure 3.21: D*airy products' properties and recipes user form

The *general activity data user form* (Figure 3.22) collects data regarding the dairy farm and processing facility total Inputs (consumed supplies) and Outputs (generated wastes). Depending on the assessed system (raw milk production or dairy processing) and its foreground stages (farming, processing or cheese ripening). The cheese ripening stage is part of the dairy processing life-cycle stage but it can be done outside of the assessed systems boundaries or also it can be the only process in the system since some dairy producers buy fresh cheese to be ripened. Because of these reasons, the ripening stage data is collected separately by this user form.

Depending on the case, this user form can collect total activity data flows related to the animal feed, fertilizers, phytosanitary compounds, animal bedding materials, chemicals, energy, water, packaging materials, processing ingredients, cooling agents, wastes and others.



Date: 4/20/2020

Production stage activity data
○ Farm stage
● Dairy processing stage
○ Ripening stage

Packaging application
Aluminium tray
Beverage carton
Can - body ECCS PET coated
Can - sanitary end ECCS PET coated
Can beverage - body steel

Data set:

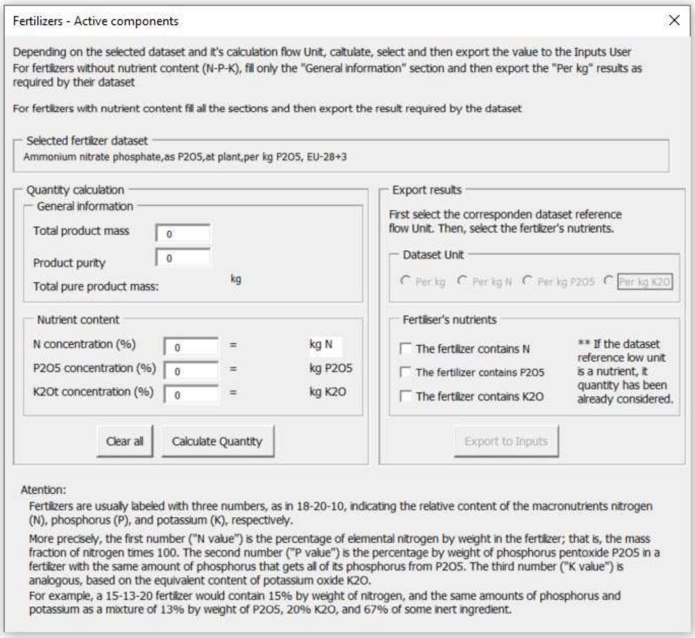
Quantity: 0
Grammage (kg/m2): 0
Total purchase cost (€): 0

N/A
Passenger car, average,technology mix, gasoline and diesel driven, Euro 3-5, passenger car,consumption mix, to consumer,engine size from 1,4l up to >2l, GLO
Articulated lorry transport, Euro 0, Total weight <7.5 t (without fuel),diesel driven, 1980s, cargo,consumption mix, to consumer,up to 7,5t gross weight / 3,3t payload capacity, EU-28+3
Articulated lorry transport, Euro 0, Total weight >32 t (without fuel),diesel driven, 1980s, cargo,consumption mix, to consumer,more than 32t gross weight / 24,7t payload capacity, EU-28+3
Articulated lorry transport, Euro 0, Total weight 12-14 t (without fuel),diesel driven, 1980s, cargo,consumption mix, to consumer,12-14t gross weight / 9,3t payload capacity, EU-28+3

Average transportation distance (km): 0

Figure 3.22: General activity data user form

In addition to the General activity data user form (Figure 3.22), extra user forms are activated and used to collect further data regarding fertilizers, water consumption and wastewater treatment activity data flows. This complementary data is needed by the VBA code scripts to generate the desired PEFCR-D compliant results. For instance, when adding data regarding mineral fertilizers, it is required to define the exact amount and type of nutrients content in the *Fertilizers-Active components user from* presented in Figure 3.23; this since several emissions will arise from its application at the farm stage.



Depending on the selected dataset and it's calculation flow Unit, caltulate, select and then export the value to the Inputs User
For fertilizers without nutrient content (N-P-K), fill only the "General information" section and then export the "Per kg" results as required by their dataset

For fertilizers with nutrient content fill all the sections and then export the result required by the dataset

Selected fertilizer dataset: Ammonium nitrate phosphate,as P2O5,at plant,per kg P2O5, EU-28+3

Total product mass: 0
Product purity: 0
Total pure product mass: kg

N concentration (%) 0 = kg N
P2O5 concentration (%) 0 = kg P2O5
K2Ot concentration (%) 0 = kg K2O

First select the corresponden dataset reference flow Unit. Then, select the fertilizer's nutrients.

○ Per kg ○ Per kg N ○ Per kg P2O5 ○ Per kg K2O

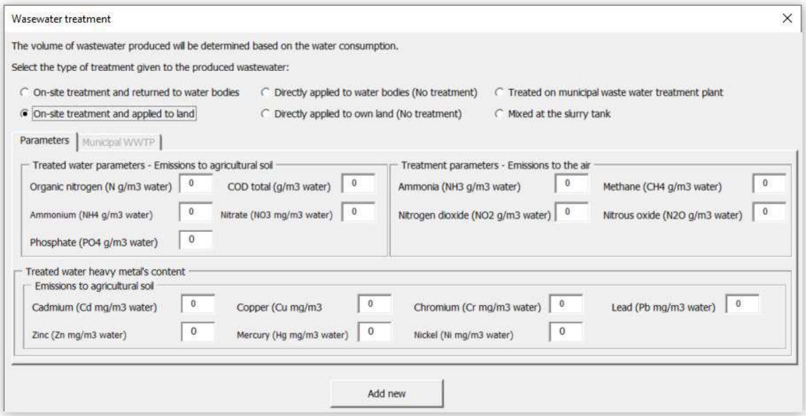
☐ The fertilizer contains N
☐ The fertilizer contains P2O5
☐ The fertilizer contains K2O

** If the dataset reference low unit is a nutrient, it quantity has been already considered.

Atention:
Fertilizers are usualy labeled with three numbers, as in 18-20-10, indicating the relative content of the macronutrients nitrogen (N), phosphorus (P), and potassium (K), respectively.
More precisely, the first number ("N value") is the percentage of elemental nitrogen by weight in the fertilizer; that is, the mass fraction of nitrogen times 100. The second number ("P value") is the percentage by weight of phosphorus pentoxide P2O5 in a fertilizer with the same amount of phosphorus that gets all of its phosphorus from P2O5. The third number ("K value") is analogous, based on the equivalent content of potassium oxide K2O.
For example, a 15-13-20 fertilizer would contain 15% by weight of nitrogen, and the same amounts of phosphorus and potassium as a mixture of 13% by weight of P2O5, 20% K2O, and 67% of some inert ingredient.

Figure 3.23: Fertilizers-Active components user form

A similar situation occurs when adding the water consumption and water treatment activity data to CalcPEF$_{\text{Dairy}}$ since additional information is needed to determine the Water Scarcity impacts related to the production system. For the consumed water, complementary data related to its final use in the system (cleaning, irrigation or animal drinking) and its evaporation rate is needed. While, depending on the selected wastewater treatment option (on-site treatment, mixed with slurry tank, municipal treatment, no treatment) different treatment parameters (emissions to air, water, etc) must be complete in the *Wastewater treatment user form* presented in Figure 3.24



The volume of wastewater produced will be determined based on the water consumption.

Select the type of treatment given to the produced wastewater:

○ On-site treatment and returned to water bodies
● On-site treatment and applied to land
○ Directly applied to water bodies (No treatment)
○ Directly applied to own land (No treatment)
○ Treated on municipal waste water treatment plant
○ Mixed at the slurry tank

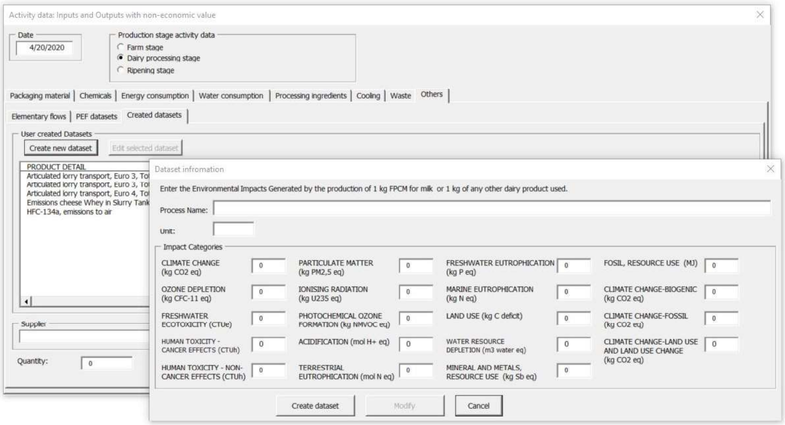
Treated water parameters - Emissions to agricultural soil
Organic nitrogen (N g/m3 water): 0
COD total (g/m3 water): 0
Ammonium (NH4 g/m3 water): 0
Nitrate (NO3 mg/m3 water): 0
Phosphate (PO4 g/m3 water): 0

Treatment parameters - Emissions to the air
Ammonia (NH3 g/m3 water): 0
Methane (CH4 g/m3 water): 0
Nitrogen dioxide (NO2 g/m3 water): 0
Nitrous oxide (N2O g/m3 water): 0

Treated water heavy metal's content
Emissions to agricultural soil
Cadmium (Cd mg/m3 water): 0
Copper (Cu mg/m3: 0
Chromium (Cr mg/m3 water): 0
Lead (Pb mg/m3 water): 0
Zinc (Zn mg/m3 water): 0
Mercury (Hg mg/m3 water): 0
Nickel (Ni mg/m3 water): 0

Figure 3.24: Wastewater treatment user form.

Finally, in the General activity data user form, it is possible to also add Other activity data flows to the system. These flows can be in the form of elementary flows or as the output of a unit process created by the user. For the first case, the elementary flow entering or exiting the system shall be defined; while for the second case the environmental impact of a modelled unit process must be added into CalcPEF$_{\text{Dairy}}$ (Figure 3.25)



Date: 4/20/2020

Production stage activity data
○ Farm stage
● Dairy processing stage
○ Ripening stage

PRODUCT DETAIL
Articulated lorry transport, Euro 3, To
Articulated lorry transport, Euro 3, To
Articulated lorry transport, Euro 4, To
Emissions cheese Whey in Slurry Tank
HFC-134a, emissions to air

Supplier:
Quantity: 0

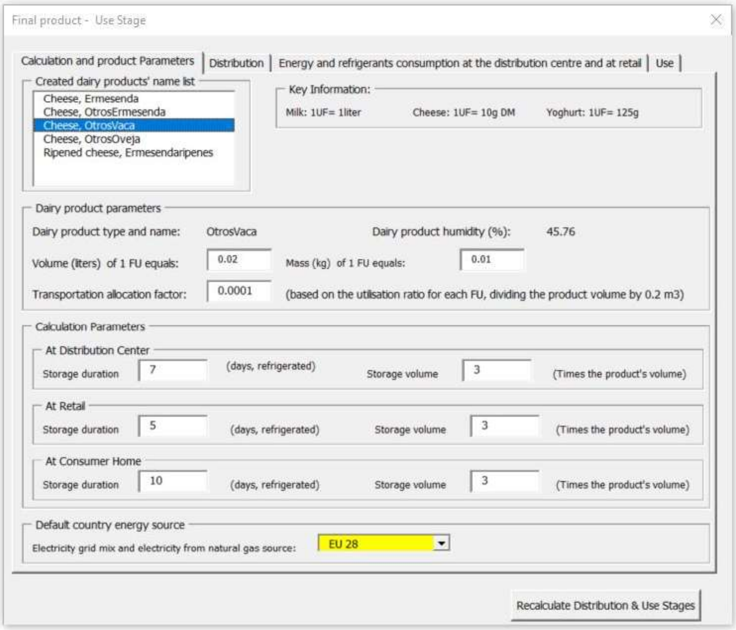
Enter the Environmental Impacts Generated by the production of 1 kg FPCM for milk or 1 kg of any other dairy product used.

Process Name:
Unit:

Impact Categories
CLIMATE CHANGE (kg CO2 eq): 0
PARTICULATE MATTER (kg PM2,5 eq): 0
FRESHWATER EUTROPHICATION (kg P eq): 0
FOSIL, RESOURCE USE (MJ): 0
OZONE DEPLETION (kg CFC-11 eq): 0
IONISING RADIATION (kg U235 eq): 0
MARINE EUTROPHICATION (kg N eq): 0
CLIMATE CHANGE-BIOGENIC (kg CO2 eq): 0
FRESHWATER ECOTOXICITY (CTUe): 0
PHOTOCHEMICAL OZONE FORMATION (kg NMVOC eq): 0
LAND USE (kg C deficit): 0
CLIMATE CHANGE-FOSSIL (kg CO2 eq): 0
HUMAN TOXICITY - CANCER EFFECTS (CTUh): 0
ACIDIFICATION (mol H+ eq): 0
WATER RESOURCE DEPLETION (m3 water eq): 0
CLIMATE CHANGE-LAND USE AND LAND USE CHANGE (kg CO2 eq): 0
HUMAN TOXICITY - NON-CANCER EFFECTS (CTUh): 0
TERRESTRIAL EUTROPHICATION (mol N eq): 0
MINERAL AND METALS, RESOURCE USE (kg Sb eq): 0

Figure 3.25: User form to add environmental impacts arising from a modelled unit process

Moving forward, the (i) *Distribution and use user form* and the (ii) *Sales user form* are the two last user forms activated by the buttons in *Group B*. The first one (Figure 3.26) collects data regarding the processes involved in the distribution and use life cycle stages; while the second one collects data regarding the outputs with economic value that leave the dairy farm (raw milk, animals and manure) or the dairy processing facility (final dairy products).



Created dairy products' name list
Cheese, Ermesenda
Cheese, OtrosErmesenda
Cheese, OtrosVaca
Cheese, OtrosOveja
Ripened cheese, Ermesendaripenes

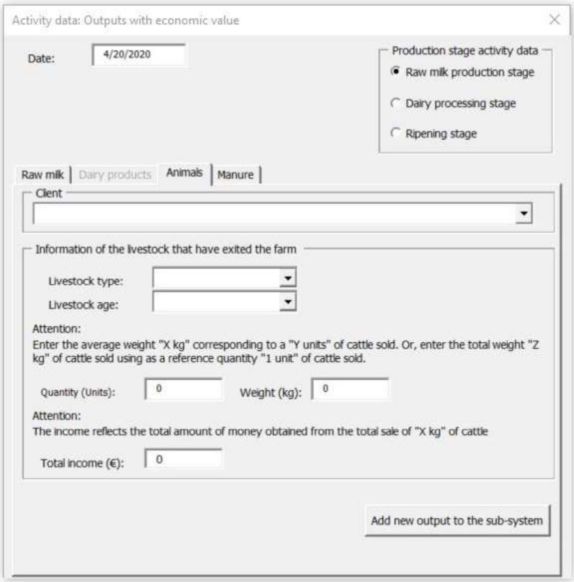
Key Information:
Milk: 1UF= 1liter Cheese: 1UF= 10g DM Yoghurt: 1UF= 125g

Dairy product parameters
Dairy product type and name: OtrosVaca
Dairy product humidity (%): 45.76
Volume (liters) of 1 FU equals: 0.02
Mass (kg) of 1 FU equals: 0.01
Transportation allocation factor: 0.0001 (based on the utilisation ratio for each FU, dividing the product volume by 0.2 m3)

Calculation Parameters
At Distribution Center
Storage duration 7 (days, refrigerated) Storage volume 3 (Times the product's volume)
At Retail
Storage duration 5 (days, refrigerated) Storage volume 3 (Times the product's volume)
At Consumer Home
Storage duration 10 (days, refrigerated) Storage volume 3 (Times the product's volume)

Default country energy source
Electricity grid mix and electricity from natural gas source: EU 28

Figure 3.26: Distribution and use user form



Date: 4/20/2020

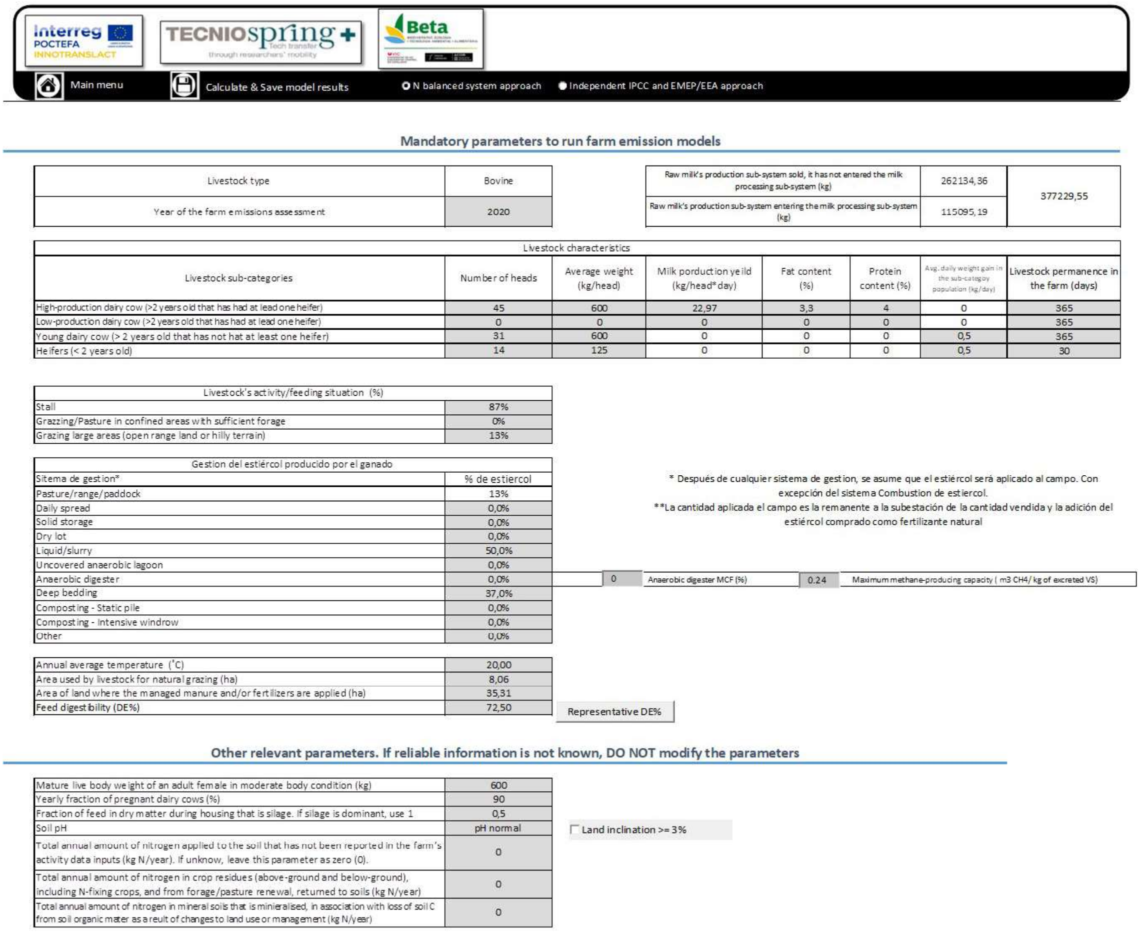
Production stage activity data
● Raw milk production stage
○ Dairy processing stage
○ Ripening stage

Client

Information of the livestock that have exited the farm
Livestock type:
Livestock age:
Attention:
Enter the average weight "X kg" corresponding to a "Y units" of cattle sold. Or, enter the total weight "Z kg" of cattle sold using as a reference quantity "1 unit" of cattle sold.
Quantity (Units): 0
Weight (kg): 0
Attention:
The income reflects the total amount of money obtained from the total sale of "X kg" of cattle
Total income (€): 0

Figure 3.27: Sales user form

The next group of buttons in the tool's main menu is the *Group C* (Figure 3.20-C). This group's buttons allow the input of specific farm and livestock data and parameters thought an excel spreadsheet (Figure 3.28). This information is needed to run the emission models coded in VBA.



Mandatory parameters to run farm emission models

Livestock type	Bovine
Year of the farm emissions assessment	2020

Raw milk's production sub-system sold, it has not entered the milk processing sub-system (kg)	262134,36	377229,55
Raw milk's production sub-system entering the milk processing sub-system (kg)	115095,19	

Livestock characteristics							
Livestock sub-categories	Number of heads	Average weight (kg/head)	Milk porduction yeild (kg/head* day)	Fat content (%)	Protein content (%)	Avg. daily weight gain in the sub-categoy population (kg/day)	Livestock permanence in the farm (days)
High-production dairy cow (>2 years old that has had at lead one heifer)	45	600	22,97	3,3	4	0	365
Low-production dairy cow (>2 years old that has had at lead one heifer)	0	0	0	0	0	0	365
Young dairy cow (> 2 years old that has not hat at least one heifer)	31	600	0	0	0	0,5	365
Heifers (< 2 years old)	14	125	0	0	0	0,5	30

Livestock's activity/feeding situation (%)	
Stall	87%
Grazzing/Pasture in confined areas with sufficient forage	0%
Grazing large areas (open range land or hilly terrain)	13%

Gestion del estiércol producido por el ganado	
Sitema de gestion*	% de estiercol
Pasture/range/paddock	13%
Daily spread	0,0%
Solid storage	0,0%
Dry lot	0,0%
Liquid/slurry	50,0%
Uncovered anaerobic lagoon	0,0%
Anaerobic digester	0,0%
Deep bedding	37,0%
Composting - Static pile	0,0%
Composting - Intensive windrow	0,0%
Other	0,0%

* Después de cualquier sistema de gestion, se asume que el estiércol será aplicado al campo. Con excepción del sistema Combustion de estiercol.
**La cantidad aplicada el campo es la remanente a la subestación de la cantidad vendida y la adición del estiércol comprado como fertilizante natural

0	Anaerobic digester MCF (%)	0.24	Maximum methane-producing capacity (m3 CH4/ kg of excreted VS)

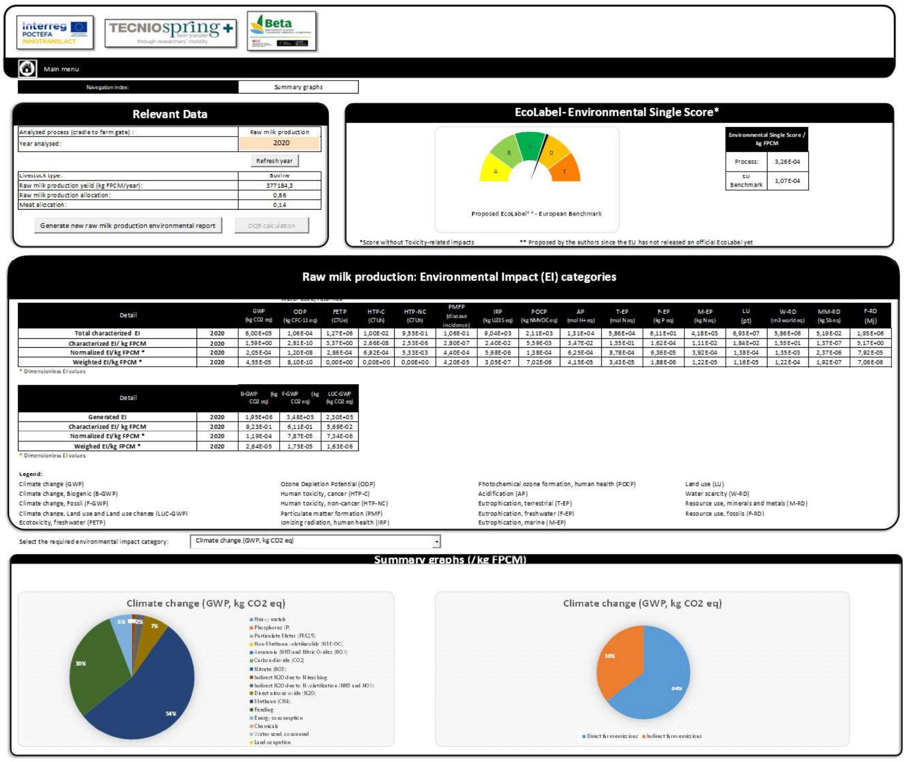
Annual average temperature (˚C)	20,00
Area used by livestock for natural grazing (ha)	8,06
Area of land where the managed manure and/or fertilizers are applied (ha)	35,31
Feed digestibility (DE%)	72,50

Other relevant parameters. If reliable information is not known, DO NOT modify the parameters

Mature live body weight of an adult female in moderate body condition (kg)	600
Yearly fraction of pregnant dairy cows (%)	90
Fraction of feed in dry matter during housing that is silage. If silage is dominant, use 1	0,5
Soil pH	pH normal
Total annual amount of nitrogen applied to the soil that has not been reported in the farm's activity data inputs (kg N/year). If unknow, leave this parameter as zero (0).	0
Total annual amount of nitrogen in crop residues (above-ground and below-ground), including N-fixing crops, and from forage/pasture renewal, returned to soils (kg N/year)	0
Total annual amount of nitrogen in mineral soils that is minieralised, in association with loss of soil C from soil organic mater as a reult of changes to land use or management (kg N/year)	0

Figure 3.28: Capture of the CalcPEF$_{Dairy}$ tool Excel spread sheet to input data to model direct on-farm emissions.

The buttons in *Group D* (Figure 3.20-D) generate the environmental impact assessment results (Figure 3.29) in separated reports depending on the assessed systems (raw milk production and dairy processing) and also the visualization of the system's general costing report (Figure 3.30). Finally, the buttons in Group E (Figure 3.20-E) opens the DB containing the yearly history of the reported environmental impact results.



Main menu

Navigation index: Summary graphs

Relevant Data

Analysed process (cradle to farm gate) :	Raw milk production
Year analysed:	2020

Refresh year

Livestock type:	Bovine
Raw milk production yeild (kg FPCM/year):	377184,3
Raw milk production allocation:	0,86
Meat allocation:	0,14

Generate new raw milk production environmental report

DQR calculation

EcoLabel- Environmental Single Score*

Environmental Single Score / kg FPCM	
Process:	3,26E-04
EU Benchmark	1,07E-04

Proposed EcoLabel** - European Benchmark

*Score without Toxicity-related impacts

** Proposed by the authors since the EU has not released an official EcoLabel yet

Raw milk production: Environmental Impact (EI) categories

Detail		GWP (kg CO2 eq)	ODP (kg CFC-11 eq)	FETP (CTUe)	HTP-C (CTUh)	HTP-NC (CTUh)	PMFP (disease incidence)	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)	LU (pt)	W-RD (m3 world eq)	MM-RD (kg Sb eq)	F-RD (Mj)
Total characterized EI	2020	6,00E+05	1,06E-04	1,27E+06	1,00E-02	9,55E-01	1,06E-01	9,04E+03	2,11E+03	1,31E+04	5,86E+04	6,11E+01	4,18E+03	6,93E+07	5,86E+06	5,19E-02	1,95E+06
Characterized EI/ kg FPCM	2020	1,59E+00	2,81E-10	3,37E+00	2,66E-08	2,53E-06	2,80E-07	2,40E-02	5,59E-03	3,47E-02	1,55E-01	1,62E-04	1,11E-02	1,84E+02	1,55E+01	1,37E-07	5,17E+00
Normalized EI/kg FPCM *	2020	2,05E-04	1,20E-08	2,86E-04	6,92E-04	5,33E-03	4,40E-04	5,68E-06	1,38E-04	6,25E-04	8,78E-04	6,36E-05	3,92E-04	1,38E-04	1,35E-03	2,37E-06	7,92E-05
Weighted EI/kg FPCM *	2020	4,55E-05	8,10E-10	0,00E+00	0,00E+00	0,00E+00	4,20E-05	3,05E-07	7,02E-06	4,15E-05	3,43E-05	1,88E-06	1,22E-05	1,16E-05	1,22E-04	1,92E-07	7,06E-06

* Dimensionless EI values

Detail		B-GWP (kg CO2 eq)	F-GWP (kg CO2 eq)	LUC-GWP (kg CO2 eq)
Generated EI	2020	1,95E+06	3,48E+05	2,30E+05
Characterized EI/ kg FPCM	2020	9,23E-01	6,11E-01	5,69E-02
Normalized EI/kg FPCM *	2020	1,19E-04	7,87E-05	7,34E-06
Weighed EI/kg FPCM *	2020	2,64E-05	1,75E-05	1,63E-06

* Dimensionless EI values

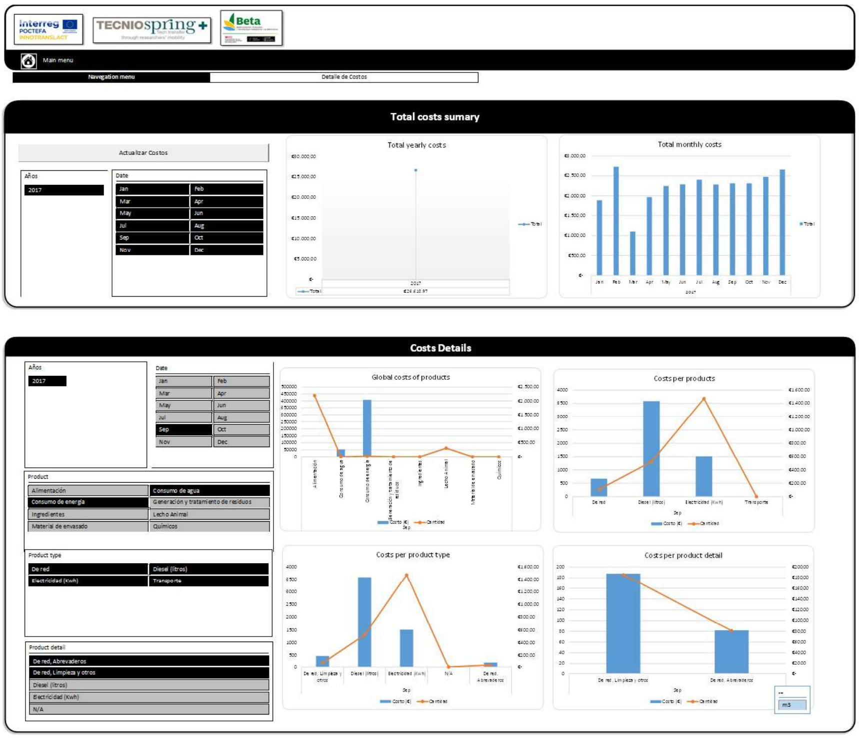
Legend:

Climate change (GWP)
Climate change, Biogenic (B-GWP)
Climate change, Fossil (F-GWP)
Climate change, Land use and Land use change (LUC-GWP)
Ecotoxicity, freshwater (FETP)
Ozone Depletion Potential (ODP)
Human toxicity, cancer (HTP-C)
Human toxicity, non-cancer (HTP-NC)
Particulate matter formation (PMF)
Ionizing radiation, human health (IRP)
Photochemical ozone formation, human health (POCP)
Acidification (AP)
Eutrophication, terrestrial (T-EP)
Eutrophication, freshwater (F-EP)
Eutrophication, marine (M-EP)
Land use (LU)
Water scarcity (W-RD)
Resource use, minerals and metals (M-RD)
Resource use, fossils (F-RD)

Select the required environmental impact category: Climate change (GWP, kg CO2 eq)

Summary graphs (/kg FPCM)

Figure 3.29: Capture of the CalcPEF$_{Dairy}$ tool Excel spreadsheet that reports the environmental impact results of the assessed system: raw milk production system (cradle-to-farm gate) or dairy system (cradle-to-grave).



Main menu

Navegation menu: Detalle de Costos

Total costs sumary

Actualizar Costos

Años: 2017

Date: Jan, Feb, Mar, Apr, May, Jun, Jul, Aug, Sep, Oct, Nov, Dec

Costs Details

Años: 2017

Date: Jan, Feb, Mar, Apr, May, Jun, Jul, Aug, Sep, Oct, Nov, Dec

Product: Alimentación, Consumo de agua, Consumo de energia, Generación y tratamiento de residuos, Ingredientes, Lecho Animal, Material de envasado, Químicos

Product type: De red, Diesel (litros), Electricidad (Kwh), Transporte

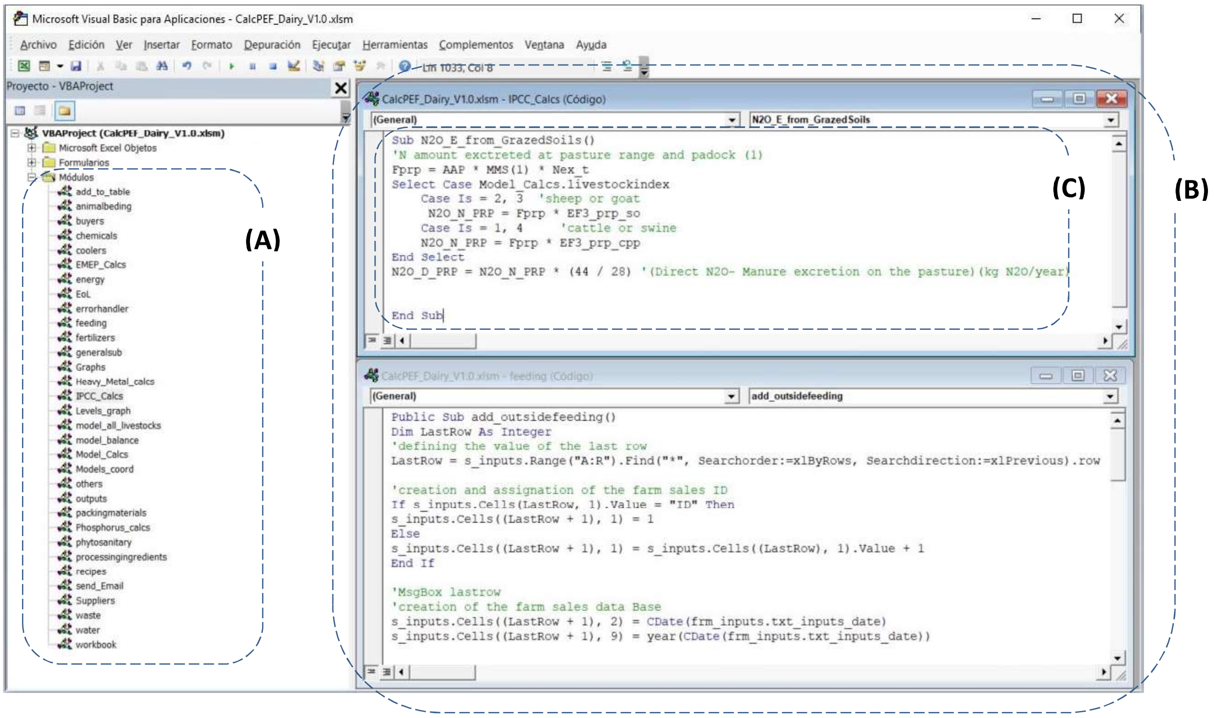
Product detail: De red, Abrevaderos; De red, Limpieza y otros; Diesel (litros); Electricidad (Kwh); N/A

Figure 3.30:Capture of the CalcPEF$_{Dairy}$ tool Excel spreadsheet that reports the costs of the assessed system: raw milk production system (cradle-to-farm gate) or dairy system (cradle-to-grave).

3.2.3.2 VBA code scripts

As previously presented the buttons in the tool’s main menu activate VBA objects to add activity data (input/output flows) regarding the assessed system and, if it’s the case, also activate a spreadsheet to add specific data to determine the on-farm emissions. All these added data is managed and processed in the tool’s background by VBA scripts in order to (i) generate the different DBs (Excel Spread sheets), (ii) run the VBA code containing the on-farm emission models and (iii) generate reports with PEFCR-D compliant results.

The VBA platform of Microsoft excel is used to generate and manage the VBA scripts and also the VBA objects used for the development of CalcPEF$_{\text{Dairy}}$. This platform is also used as complier so the computer can read and execute the lines of code in the VBA scripts. Figure 3.31 shows a capture of the Excel’s VBA platform used for the development of the tool where the VBA modules, scripts and lines of code can be visualized. A VBA module is a collection of VBA scripts where the scripts are organized according to their general tasks. CalcPEF$_{\text{Dairy}}$ has a total of 32 VBA modules with over 200 different scripts and more than 200.000 lines of code to execute different subroutines for specific defined tasks.



```
Sub N2O_E_from_GrazedSoils()
'N amount exctreted at pasture range and padock (1)
Fprp = AAP * MMS(1) * Nex_t
Select Case Model_Calcs.livestockindex
    Case Is = 2, 3  'sheep or goat
     N2O_N_PRP = Fprp * EF3_prp_so
    Case Is = 1, 4      'cattle or swine
    N2O_N_PRP = Fprp * EF3_prp_cpp
End Select
N2O_D_PRP = N2O_N_PRP * (44 / 28) '(Direct N2O- Manure excretion on the pasture)(kg N2O/year)


End Sub
```

```
Public Sub add_outsidefeeding()
Dim LastRow As Integer
'defining the value of the last row
LastRow = s_inputs.Range("A:R").Find("*", Searchorder:=xlByRows, Searchdirection:=xlPrevious).row

'creation and assignation of the farm sales ID
If s_inputs.Cells(LastRow, 1).Value = "ID" Then
s_inputs.Cells((LastRow + 1), 1) = 1
Else
s_inputs.Cells((LastRow + 1), 1) = s_inputs.Cells((LastRow), 1).Value + 1
End If

'MsgBox lastrow
'creation of the farm sales data Base
s_inputs.Cells((LastRow + 1), 2) = CDate(frm_inputs.txt_inputs_date)
s_inputs.Cells((LastRow + 1), 9) = year(CDate(frm_inputs.txt_inputs_date))
```

Figure 3.31:Capture of the Visual Basic for Applications platform of Microsoft excel. (A) VBA modules, (B) VBA scripts and (C) VBA lines of code

Workflow path followed by the VBA scripts

Due to the overwhelming amount of scripts and code needed to run CalcPEF$_{\text{Dairy}}$, Figure 3.32 presents a general perspective of the workflow path followed by the tool to manage the data and obtain PEFCR-D compliant results. First, through different User Forms, the VBA scripts collects the activity data. Then, specific VBA code differentiates, selects and retrieves specific data from the existing Activity Data DB, depending on the assessed system (raw milk production or dairy processing).

To calculate assess the raw milk production system (cradle-to-farm gate), CalcPEF$_{\text{Dairy}}$ identifies the dairy farm and its activities as foreground process. Thus, the on-farm emission models are executed by retrieving activity data related to the farm activities and livestock characteristics. The emissions from the system's background processes are obtained by using data from the General DB and the EF-datasets incorporated in CalcPEF$_{\text{Dairy}}$.

Then, the foreground and background processes emissions are characterized and allocated to the farms raw milk thought the biophysical allocation criterion. Finally, the outcomes are reported as characterized, normalized, and weighted environmental impact profiles per kilogram of FPCM.

To assess the dairy system (cradle-to-grave), the tool identifies the dairy processing facility and its activities as foreground process. The emissions attributed to the foreground and background process are obtained by retrieving data from the General DB and their respective EF-datasets incorporated in CalcPEF$_{\text{Dairy}}$. These emissions are characterized and allocated according to a Dry Matter allocation criterion since these emissions are related to supplies that are not physically present in the final dairy product.

While specific data regarding the dairy products is retrieved from the ingredients DB. If the dairy producer has its own dairy farm, CalcPEF$_{\text{Dairy}}$ is capable to link the raw milk production system environmental results as a raw milk input; if not, the dairy producer can use any raw milk production EF-dataset to retrieve the farm emissions. the ingredient emissions are also characterised and allocated but, since these emissions are related to supplies that are physically present in the final dairy product, they are allocated as function of the final product functional unit.

Once the allocation is done, the characterised scores are organized according to their life cycle stages and its total is finally reported as characterized, normalized, and weighted environmental impact profiles per FU of dairy product.

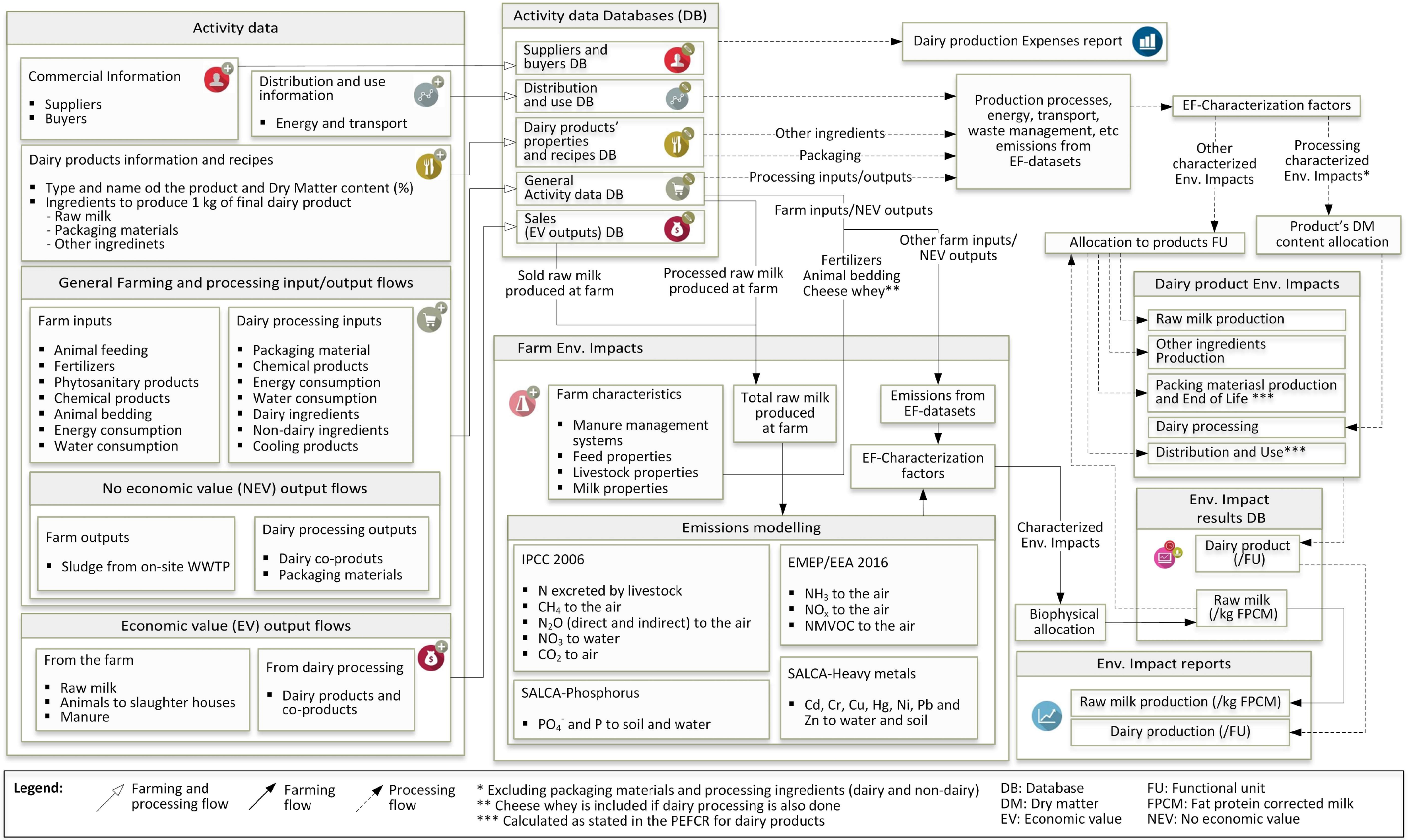


Figure 3.32: Tool scheme: Farming and processing data flow to perform an environmental and economic assessment of the dairy products.

3.3 Energy Audits

As discussed earlier, LCA is an efficient tool to identify environmental hot-spots however, in-depth studies shall be carried out to suggest specific measures to reduce the emissions related to the hot-spots. For the case of the identified energy consumption hot-spot, energy audits are valid tools to execute this detailed and deeper assessment.

Based on the results of the energy audit, the decision-maker can make an informed decision regarding the measures that could be implemented to improve the energy consumption of the system; and thus, achieve its optimal environmental performance.

On an international level the requirements for executing energy audits are standardized by the ISO 50001 (2018) and the ISO 50002 (2014); the first of which stets general requirements while the other provides further guidance when performing audits in the context on an energy management system. this last one. On a European level, the methodology to carry out energy audits is clearly defined in the EN 16247 (2012) normative; therefore, this thesis follows the methodology stated in it.

In summary this European normative is divided in five parts where is stated the needed requirements to carry out an energy audit; as well as the auditing methodology and the expected audit deliverables. The first part sets this normative general framework while the second, third and fourth part provide complementary guidelines to perform energy audits to buildings, processes and transports respectively. The last part of this normative sets the quality requirements for the energetic auditors. Figure 3.33 illustrates the EN 16247 normative methodology to carried out energy audits.

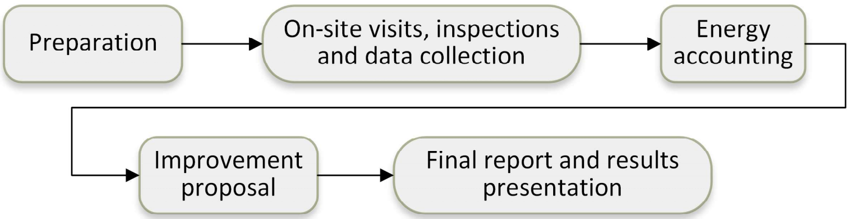


Figure 3.33: Steps for executing an energy audit. Adapted from EN 16247 (2012)

Preparation

In this thesis nine small dairy facilities were evaluated to present general and particular guidelines about the most efficient improvement measures in terms of their costs and environmental performance. Hence, the identification and selection of these facilities was done as part of the preparation stage.

Onsite-visits, inspections and data collection

Two on-site visits and inspections to the dairy facilities were done with the aim of understand the production system and collect energy data. The on-site data collection included the quantification of the facility's yearly energy consumption and the identification of the consumed energy type (electric or thermal), source (electricity, diesel, butane, propane or biomass) and final use (agricultural or processing machinery, boilers, etc). All the data was obtained from the available energy bills, interviews to the staff and by carrying out a thermographic study of boilers and hot-water pipes using a Testo 880-3 Thermal Camera as shown in .

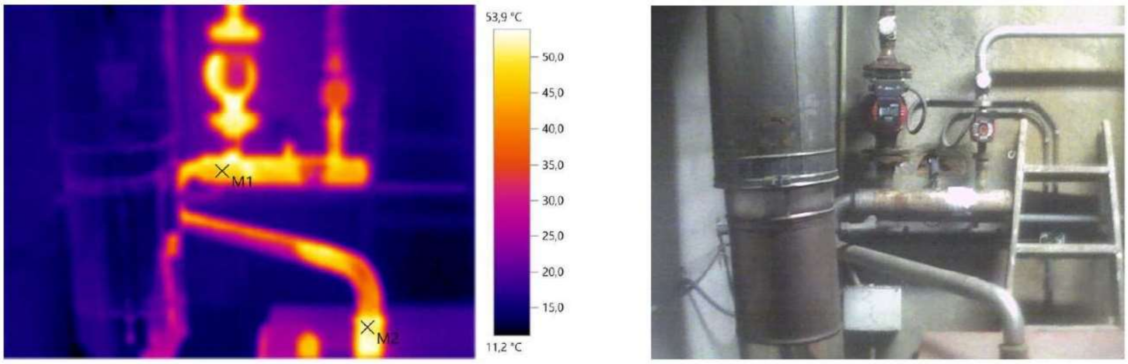


Figure 3.34: Example of the thermographic study of the boiler pipes of a dairy facility.

Energy accounting

Then, the collected data was used to execute an energy accounting assessment of the facilities by differentiating the type and source of the consumed energy. The kWh unit was used to homogenise the collected energy data for the assessment; because since the energy bills report the consumed energy in different units depending on the energy source such as litres for diesel, kg for liquid petroleum gas (LPG) and kWh for thermal and electric energy

The energy accounting assessment identifies the facilities' high energy consumption points "hot-spots" which are often related to high emissions and costs. Taking as starting point these hot-spots possible improvements to reduce the facilities' energy consumption, GHG emissions and costs are identified. This assessment also defines the facilities' yearly energy consumption, GHG emissions and costs; where each of these last ones is a baseline for each respectively. Baseline results for each of the facilities are obtained.

Additionally, the base line results together with other yearly parameters of the dairy facilities (operational hours, kg of final dairy products and kg of processed milk) can be used to obtain some facilities' key performance indicators (KPIs) regarding energy consumption, GHG emissions and costs.

Improvement proposal

After the energy accounting assessment and based on the identified possible improvements, final improvements can be proposed. This is done by determining the implementation feasibility for each of the possible improvements in addition to account their possible reductions regarding energy consumption, GHG emissions and costs.

On one hand, for a specific facility, the potential reductions attributed to each possible improvement are obtained as a direct comparation between the facility's baseline performance and its potential performance after implementing the possible improvement. This comparation is done with all the possible improvements and with the three defined baselines (consumption, GHG emissions and costs) per assessed dairy facility.

For the case of the GHG emissions, its reduction is reported as a reduction on the Global Warming Potential environmental impact. For which, PEF compliant energy production processes and characterization factors were used. Moreover, the Catalan GHG emissions guideline was used to calculate some combustion GHG emissions and to obtain the Low-Heating Values for the different energy sources when applicable (Oficina Catalana del Canvi Climàtic, 2019).

The reductions show the strengths and weakness of each potential improvement per assessed dairy facility. However, that information is not enough to finally propose an improvement for a facility. The aforementioned because it is considered that any type of consumption, emission or cost reduction obtained as consequence of any possible improvement is beneficial and equally important for the facility. Therefore, the implementation feasibility of a possible improvement is determined through its profitability. For this finality, the Net Present Value (NPV) economic indicator is used to determine the improvement profitability (NPV>0).

Later, if the improvement is profitable, it is finally proposed and its Internal Rate of Return (IRR) indicator outcome is used to rank the priority (medium or high) of its implementation in the dairy facility. The implementation of a proposed improvement is defined as high priority if its IRR is greater or equal to 10%; while, it is defined as medium priority if its IRR is lower than 10%.

The NPV and IRR formulas are presented by Equation 3.6 and Equation 3.7 respectively; where *i* is the discount rate, and *t* is the cash flow period. The, NPV is calculated with a discount rate of 6% for each of their respective cash flows periods. These economic indicators are calculated by assuming a same lifetime for the suggested improvements

$$NPV = \sum_{t=1}^{T} \frac{Cash\ Flow_t}{(1+i)^t} - Initial\ Cash\ Investment$$ *(Equation 3.6)*

$$0 = \sum_{t=1}^{T} \frac{Cash\ Flow_t}{(1+IRR)^t} - Initial\ Cash\ Investment$$ *(Equation 3.7)*

Chapter 4: Results

4.1 Implementation of the Product Environmental Footprint Category Rules for dairy products: An approach to assess nitrogen emissions in a mass balanced dairy farm system.

Egas, D., Vasilaki, V., Katsou, E., Stanchev, P., Ponsá, S., & Colon, J. (2019).

Journal of Cleaner Production . https://doi.org/10.1016/j.jclepro.2019.01.110

4.2 CalcPEF$_{\text{Dairy}}$: A Product Environmental Footprint compliant tool for a tailored assessment of raw milk and dairy products

Egas D, Ponsá S, Colon J (2020)

Journal of Environmental Management 260:110049. https://doi.org/10.1016/j.jenvman.2019.110049

4.3 Multilevel environmental assessment of the anaerobic treatment of dairy processing effluents in the context of circular economy

Stanchev, P., Vasilaki, V., Egas, D., Colon, J., Ponsá, S., & Katsou, E. (2020)

Journal of Cleaner Production, 261, 121139. https://doi.org/10.1016/j.jclepro.2020.121139

4.4 Direct energy consumption of small dairy production chains: A consumption, environmental and economic assessment

Egas D, Ponsá S, Colon J. (2021)

Manuscript under review at the Journal of Sustainable Production and Consumption

Chapter 5: Discussion

5.1 The artisan dairy sector

Artisan dairy products are a reachable source of dietary nutrients and a source of income for rural households. European artisan dairy products are well known to be high-quality since they are produced through traditional (no industrialised) farming and processing activities; this has made them highly demanded within rural communities and nearby cities. However, and despite such successful potential, the European artisan dairy production system is often inefficient and has been facing threats and challenges to reach new markets and a more sustainable production.

In 2015, the EC removed the European dairy quotas to develop a more competitive and market-oriented dairy industry in light of the increasing world food demand of dairy products and to benefit from it. However, the quota's removal threats the artisan dairy sector since it is likely to encourage the concentration of the production systems in most favourable areas to reduce logistic costs, enlarge dairy farms (industrialized farming) and increase raw milk yields. Moreover, it encourages the dairy industry to reach more efficient production systems by reducing its economic costs and environmental impacts. Thus, the European artisan dairy sector is obliged to compete in this liberated dairy market and consolidate its presence in it.

More competitive artisan dairy products are obtained by reducing their production costs and by continuously optimizing their production system; which means reducing the consumption of resources, decreasing the generation of wastes, revalorization of coproducts, etc. Furthermore, since artisan dairy products are considered as premium products, its environmental performance is a relevant parameter for the consumer when making the decision of purchasing them or not. Thus, the correct communication of the products' environmental performance, through Eco-labels or any other green credential, enhances its competitivity and consolidate them in the market.

In this context, the EU Product Environmental Footprint (PEF) methodology has a key role since it aims to produce clear, comparable and reliable information regarding the environmental performance of dairy products; and its assessment outcomes can be used to obtain environmental declarations and eco-labels. Thus, the use of the PEF to environmentally assess artisan dairy products would not only allow them to be more competitive in the liberalised dairy market but also would allow them to be compliant with the regulations of the promoted EU market for green products and compete in it.

In this thesis, the CalcPEF$_{\text{Dairy}}$ tool was developed to environmentally assess dairy production systems and identify their impacts drivers (hot-spots). While, energy audits and circularity indicators were showed to be valid tools to identify and assess in deep possible improvements for the systems. Bespoke improvements that would not only enhance the dairy systems' environmental performance, but would also lead them towards an energy efficient and circular economy model. The results of this thesis are used and discussed in this chapter when evaluating Spanish artisan dairy systems as a first step towards reaching an environmentally sustainable dairy industry.

In a first part, CalcPEF$_{\text{Dairy}}$ is used to environmentally assess artisan dairy systems. The outcomes are presented and discussed together with possible improvements; so, assessed artisan dairy systems can achieve greater environmentally sustainable status. While, in a second part, the experience of passing a verification process carried out by an external audit team is presented. The auditors verified the CalcPEF$_{\text{Dairy}}$ tool compliance with the PEFCR-D; and later verify its results to obtain an environmental declaration and eco-label for a product that is available in the market.

5.2 Environmental optimization of artisan dairy systems

This thesis was carried out in the framework of the INNOTRANSLACT project; for which the environmental performance of nine Spanish traditional dairy systems was determined with the CalcPEF$_{\text{Dairy}}$ tool. The assessed systems obtain raw milk from sheep (4 systems), goats (2 systems) and cows (3 systems) to produce cheese and yogurts. Therefore, the artisan systems involve the farming and dairy processing life-cycle stages. Due to a confidentiality agreement, only average data is shared in this section. The average data and its results are presented and discusses according to the systems' raw milk type.

5.2.1 Assessed artisan systems description

The following paragraphs together with Table 5.1 summarise main characteristics of the three artisan dairy systems. Nonetheless, the complete average life cycle inventories are presented in Annex C.

Table 5.1: Average main characteristics of the assessed artisan dairy systems.

Parameter	**Unit**	**Amount per average artisan dairy system**		
		Cow milk	**Sheep milk**	**Goat milk**
Productive livestock	heads	45	211	57
Milk production yield	kg/head*day	22.9	0.6	0.7
Dry matter (DM) content	%	12.3	12.3	12.3
Fat content	%	3.3	8.31	4.1
Protein content	%	4.0	5.77	3.6
Livestock for natural grazing area	ha	8.06	7.20	1.5
Managed manure and/or fertilizers are application area	ha	35.3	22.60	54.73
Total managed manure (at farm)	tonnes	1,122.3	880.9	172.2
Total raw milk produced (at farm)	tonnes	377.2	44.4	14.7
Total raw milk for processing (at dairy facility)	tonnes	115.1	42.6	14.7
Total cheese produced	tonnes (%DM)	14.3 (70%)	6.0 (75%)	1.6 (65%)
Total yoghurt produced	tonnes (%DM)	30.4 (12%)	2.6 (5%)	-
Total cheese whey produced (6.8%DM, 1.039kg/l)	m^3	55.4	34.0	8.3

Cow milk artisan dairy system

The system is composed by a total of 90 livestock heads from which 45 are high-production dairy cows, 31 is young cattle (> 2 years old that has not had at least one heifer) and 14 are heifers. The productive cows have a milk production yield of 22.96 kg/day·head with a 4% fat content and a 3.3% protein content. The total cattle spend most of its time in the stall (87% of the year) and is mainly fed with forage and grains produced in the farm. However, other feeding supplements such as soy bean powder, maize grains and animal meals are also used and purchased. It is estimated that this combination of feeding provides the cattle a feed digestibility energy ratio (DE) of 72.5%.

The remining time of the year (13%) the cattle is pasturing in an area of 35.31 ha; land that is also used to produce the animal feed. Therefore, the excreted manure is applied to it after being managed in liquid (50%), deep bedding (37%) systems. The excreted manure during pasturing (13%) is not collected for management; it is directly applied to the land.

In total, the dairy farm produces 377.22 tonnes of raw milk per year from which a 69% is directly sold as raw milk and the remaining shares (24% and 7%) is used to produce 88.92 tons of cheese (70%dry matter) and 26.17 tonnes of yogurt (12.2% dry matter) respectively. To produce cheese and yogurt additional ingredients such as dairy ferments, rennet and salt are used; and packing materials such as paper and plastic bags are used. In addition to the raw milk and the dairy products other outputs with economic value is the cattle sent to slaughter or sold. A total of 7.2 tons of mature cattle and 1.5 tonnes of young cattle exit the system per year.

On the other hand, the produced wastewater and the cheese whey are wastes from the system. It is considered that from the total consumed water (4,227.2 m^3) a 45% will turn to wastewater since it has been used at the dairy facility for cleaning. The remain water is consumed in the farm for animal drinking and irrigation purposes. The generated wastewater is managed in the slurry tank thus, it will be later applied to the land. The generated cheese whey is also a waste from the processing facility but it is used as animal feeding for livestock outside the assessed dairy farm hence, it exits the system and it is considered as a system's output which economic value is zero.

Sheep milk artisan dairy system

This artisan dairy system has a total of 559 sheep from which 211 are mature dairy ewes and the remining are young no productive ewes and lambs. The ewes milk production yield is 0.6 kg/day·head with an 8.31% fat content and a 5.77% protein content. The total of sheep spends half of the year in housing and the other half grazing in hilly and flat pastures, hence their diet is composed by pasture and forage produced in the farm; additionally, a fraction of the produced cheese whey (12.64 m^3) is fed to the sheep as dietary supplement. This feeding characteristic give the sheep an estimated 60% DE.

The system has an agricultural area of 22.6 ha which is used to produce the forages and grazing. To this agricultural land, the excreted manure is applied directly when the sheep are pasturing (50%) and after being managed in liquid and deep bedding systems (43% and 7% of the excreted manure respectively). In addition to the excreted manure, phosphate fertilizer (241.3 kg) and a fraction of the produced cheese whey (6.83 m^3) are also applied to land as mineral and organic fertilizers.

The farm produces a total of 44.41 tonnes of sheep raw milk per year from which a 91% is used to produce 6.02 tonnes of cheese (75%DM) and a 5% to produce 2.22 tonnes of yoghurt (5%DM); the remaining raw milk share is sold. The system uses dairy ferments, rennet and salt as other ingredients for the products; and also uses corrugated carton, paper bags and plastic bags and film as packaging materials. Other system's outputs with economic value are 3.13 tonnes of sheep sold or sent to slaughter houses, 68.4 tonnes of managed manure sold as organic fertilizer and 14.56 m^3 of cheese whey sent out of the system as dietary supplement.

The produced wastewater and the cheese whey are wastes from the system which follow different management. A 59% of the total consumed water (916.4 m^3) will turn into wastewater as consequence of cleaning da dairy processing facilities and it will be managed in the slurry tank; while the remaining consumed water will be used in farming activities. As previously mentioned, different shares of the total produced cheese whey have been used either in the farm as fertilizers or dietary supplements; considered as a system's output which economic value is zero.

Goat milk artisan dairy system

A total of 117 goats conform this artisan system, where 57 are mature dairy goats and the remaining are no productive goats (36 heads) and immature goats (24 heads). These dairy goats produce 0.71 kg milk/day·head which contains 4.1% fat and a 3.6% protein. The total of livestock spends 77% of the year in housing conditions and the remaining 23% grazing in hilly and flat pastures, hence their diet is composed mainly forage produced in the farm; additionally, a fraction of the produced cheese whey (6.64 m^3) together with purchased salt and maize is fed to the livestock as dietary complements. This feeding characteristic give the goats an estimated 60%DE.

This system has 54.73 ha of total agricultural land for animal feeding production and grazing. The excreted goats' manure is directly applied to this land during grazing (23%), while the remaining excreted manure is applied to it after being collected from the housing facilities and managed in deep bedding (68%) and composting (9%) systems.

The system produces 14.7 tonnes of raw milk which is completely used to produce cheese (65%DM). The system also uses salt, rennet and dairy ferments as no dairy ingredients and paper and plastic bags as packaging materials. In addition to this product other systems outputs with economic value are the animals (556 kg of mature goats and 281 kg of young goats) that are either sold or sent to slaughter houses and the 4.71 tonnes of managed manure that is also sold as natural fertilizer. The cheese whey that exists the system (1.62m^3) is to feed other system's livestock.

As wastes the systems generates 87.97 m^3 of waste water due to the processing facility activities (44% of the total consumed water) which is managed by the municipal wastewater facility. Other produced waste is the cheese whey (8.26 m^3) which, as previously indicated, is used in an 80% as dietary complement for the system's livestock; while the 20% left is sent out of the system with an economic value of zero.

5.2.2 Environmental assessment results and discussion.

The PEF baseline results for the artisan dairy systems are presented below. In a first part, the general baseline results for the artisan dairy products (cheese and yogurt) are presented and discussed; which were obtained by following a cradle-to-grave assessment approach and have the dairy processing facility as core. Then, the dairy farm (cradle-to-farm gate approach) baseline results are presented followed by the processing facility (gate-to-gate approach) baseline results.

The following sections will compare the artisan cow milk products with the EU benchmark due to its availability and validation in the current PEFCR-D. However, it is still not possible to state if the environmental performance of the artisan cow milk products and the cow raw milk production are better or worse than their respective EU benchmarks environmental performance since the EC has not released a guideline for a standardized interpretation of the ESS. Due to the lack of this guideline, an environmental performance statement will be a speculation and it will not be done in this work. To our knowledge, this guide should be expected to be available any time now during the current PEF transition phase and it would allow to rank the products in different levels depending on its ESS.

Currently, there are no EU benchmarks for dairy products containing sheep and goat raw milk since there are neither EU benchmark results for the production of these raw milk types. Therefore, the next sections will present the artisan sheep and goat dairy products and raw milk production outcomes of this study but, they will not be directly compared against the EU benchmarks since a direct comparation to the benchmark is not fully coherent and representative and could miss lead the obtained conclusions. Also, the any of the processing facilities' outcomes will not be contrasted with the EU benchmark since there no available benchmarks for dairy processing facilities.

Furthermore, despite belonging to the same dairy product subcategory, a cautious comparation of all the produced raw milks' results is done due to the influence that the FU (kg of Fat Protein Corrected Milk) on the raw milk characterized impact results. To more total raw milk production; and to more fat or protein content than 4% and 3.3% respectively, the total kg of FPCM increases. Thus, less characterized impacts are assigned and later reported per kg of FPCM. These FU characteristics are relevant and are taken into count when discussing the raw milk production results since they variate among assessed raw milk producing livestock.

Along the presentation and discussion of these baseline results, the environmental hot-spots are highlighted to finally propose improvements to the artisanal dairy systems; with the aim of enhancing their products environmental performance.

5.2.2.1 Baseline general results for the artisan dairy products (cradle-to-grave)

The baseline general results of the artisan cheeses and yoghurts are presented in Table 5.2 together with the cheese and yoghurt EU benchmark scores. The PEF Environmental Single Scores (ESS) represent the products' total impact to the environment thus, Table 5.3 reveals which of the assessed impact categories (excluding toxicity related impact categories) affect the most to the products' ESS.

As shown Table 5.2 and Table 5.3, the characterized impact results and the ESS of the artisan cow milk cheeses and yoghurts are above their respective EU benchmark. Among the assessed artisan chesses, the one produced with goat milk cheese reports the highest category impact and ESS results. While, for artisan yoghurts, the produced with cow milk has the highest impacts and ESS.

Regardless the raw milk type used to produce the assessed artisan cheeses and yoghurts, the raw milk production or farming life-cycle stage affects the most to the products' environmental performance since this stage contribution to the different products' ESS is between 83% and 98%.

Table 5.2: Baseline general scores of the environmental impact categories for the assessed artisan dairy products; and their respective variation (Δ%) with the EU benchmark scores.

Impact category	**Unit**	**Cheese (FU= 10gDM)**				**Yoghurt (FU= 125g)**		
		EU Benchmark*	**Cow milk**	**Sheep milk**	**Goat milk**	**EU Benchmark***	**Cow milk**	**Sheep milk**
GWP	kg $CO_{2\,eq}$	1.22E-01	1.47E-01	1.45E-01	3.52E-01	1.94E-01	2.66E-01	2.30E-01
	Δ%	-	20.8	-	-	-	37.1	-
ODP	kg $CFC\text{-}11_{eq}$	2.39E-09	3.51E-11	1.86E-11	1.00E-10	1.27E-09	0.0	0.0
	Δ%	-	-98.5	-	-	-	-95.2	-
FETP	CTUe	5.97E-01	2.03E-01	5.74E-01	1.20E+00	1.99E+00	3.45E-01	8.51E-01
	Δ%	-	-66.0	-	-	-	-82.6	-
HTP-C	CTUh	1.70E-09	1.42E-09	4.54E-09	7.66E-09	2.42E-09	2.56E-09	6.89E-09
	Δ%	-	-16.3	-	-	-	6.0	-
HTP-NC	CTUh	1.25E-07	1.68E-07	9.10E-07	1.62E-06	1.86E-07	2.85E-07	1.35E-06
	Δ%	-	34.5	-	-	-	53.0	-
PMFP	DI **	8.05E-09	1.93E-08	6.81E-09	1.10E-07	1.10E-08	3.27E-08	1.01E-08
	Δ%	-	139.2	-	-	-	197.2	-
IRP	kg $U235_{eq}$	3.29E-03	1.00E-02	2.15E-03	2.66E-03	1.49E-02	1.62E-02	2.40E-03
	Δ%	-	204.7	-	-	-	9.0	-
POCP	kg $NMVOC_{eq}$	2.61E-04	4.55E-04	5.90E-04	1.49E-03	4.11E-04	8.24E-04	9.18E-04
	Δ%	-	74.1	-	-	-	100.5	-
AP	mol $H+_{eq}$	1.06E-03	2.36E-03	8.99E-04	1.37E-02	1.38E-03	4.04E-03	1.39E-03
	Δ%	-	122.6	-	-	-	192.7	-
T-EP	mol N_{eq}	4.55E-03	1.03E-02	4.18E-03	6.15E-02	5.70E-03	1.77E-02	6.46E-03
	Δ%	-	126.0	-	-	-	209.7	-
F-EP	kg P_{eq}	9.46E-06	1.00E-05	2.86E-06	1.14E-05	1.33E-05	1.77E-05	5.88E-06
	Δ%	-	6.0	-	-	-	33.2	-
M-EP	kg N_{eq}	3.21E-04	7.41E-04	1.20E-03	3.67E-03	4.79E-04	1.28E-03	1.80E-03
	Δ%	-	130.8	-	-	-	166.8	-
LU	pts	1.18E+01	6.96E+00	1.66E+01	2.53E+01	1.49E+01	1.17E+01	2.45E+01
	Δ%	-	-41.0	-	-	-	-21.3	-
W-RD	$m^3_{world\ eq}$	2.21E-02	1.07E+00	6.99E-02	1.07E+00	9.49E-02	1.79E+00	5.49E-02
	Δ%	-	4734.9	-	-	-	1784.6	-
MM-RD	kg Sb_{eq}	1.23E-07	2.69E-08	1.66E-08	3.39E-08	4.25E-07	4.33E-08	2.01E-08
	Δ%	-	-78.1	-	-	-	-89.8	-
F-RD	MJ	4.22E-01	1.09E+00	2.87E-01	3.64E-01	1.43E+00	2.07E+00	6.38E-01
	Δ%	-	159.0	-	-	-	44.9	-
B-GWP	kg $CO_{2\,eq}$	6.38E-02	5.90E-02	1.03E-01	2.10E-01	6.61E+02	1.00E-01	1.53E-01
	Δ%	-	-7.5	-	-	-	-100.0	-
F-GWP	kg $CO_{2\,eq}$	4.18E-02	8.47E-02	4.14E-02	1.41E-01	1.10E+01	1.60E-01	7.72E-02
	Δ%	-	102.7	-	-	-	-98.5	-
LUC-GWP	kg $CO_{2\,eq}$	1.66E-02	3.65E-03	3.24E-05	2.03E-04	1.73E+02	6.15E-03	5.19E-05
	Δ%	-	-78.0	-	-	-	-100.0	-

* Produced with EU-28+3 Cow milk
** DI= disease index

Table 5.3: Contribution of the impact categories to the Environmental Single Score (ESS) for the EU benchmarks and for the assessed artisan dairy products.

Impact category	Cheese				Yoghurt		
	EU benchmark*	**Cow milk**	**Sheep milk**	**Goat milk**	**EU benchmark***	**Cow milk**	**Sheep milk**
GWP	36.8%	17.4%	36.6%	13.8%	35.3%	18.0%	38.1%
ODP	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
PMFP	12.7%	11.9%	9.0%	22.6%	10.5%	11.6%	8.7%
IRP	0.4%	0.5%	0.2%	0.0%	1.2%	0.5%	0.2%
POCP	3.5%	2.4%	6.6%	2.6%	3.3%	2.4%	6.7%
AP	13.4%	11.7%	9.5%	22.4%	10.5%	11.4%	9.6%
T-EP	10.6%	9.4%	8.2%	18.6%	8.0%	9.2%	8.2%
F-EP	1.2%	0.5%	0.3%	0.2%	1.0%	0.5%	0.4%
M-EP	3.7%	3.4%	11.7%	5.5%	3.4%	3.3%	11.5%
LU	7.9%	1.8%	9.3%	2.2%	6.0%	3.0%	8.9%
W-RD	1.8%	34.7%	4.9%	11.5%	4.7%	33.2%	2.5%
MM-RD	1.8%	0.2%	0.2%	0.1%	3.8%	0.1%	0.2%
F-RD	6.1%	6.2%	3.5%	0.7%	12.4%	6.7%	5.0%
Total	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
ESS (pts)	9.48E-06	2.42E-05	1.13E-05	7.31E-05	1.57E-05	4.23E-05	1.73E-05

* Produced with EU-28+3 Cow milk

The farming stage is the main source of the emissions causing GWP, W-RD, AP, M-EP, T-EP, F-EP, LU and PMFP (Figure 5.1 and Figure 5.2). The total contribution of these impact categories to the ESS of the assessed artisan dairy products is above 88% (Table 5.3) thus, they are considered as the most relevant impact categories for the all the assessed artisan dairy produced with all raw milk types.

The processing stage has a maximum contribution of 13% to the ESS of the assessed artisan dairy products. However, an important amount of emissions triggering ODP, IRP and F-RD originate from it (Figure 5.1 and Figure 5.2). The total contribution of the ODP, IRP and F-RD category impacts to all the artisan dairy products' ESS is less than 10%.

The presented baseline outcomes are in accordance with the reviewed literature. The assessment outcomes evidence the clear the influence of the farming stage on almost all the assessed impact categories and thus, on the environmental performance of the assessed artisan dairy products. Consequently, a detailed discussion about the cause of the dairy farm emissions that lead to these environmental impacts is done in Section 5.2.2.2. While, the sources of the emissions triggering the environmental impacts attributed to the processing facility environmental impacts are presented and discussed in Section 5.2.2.3 .

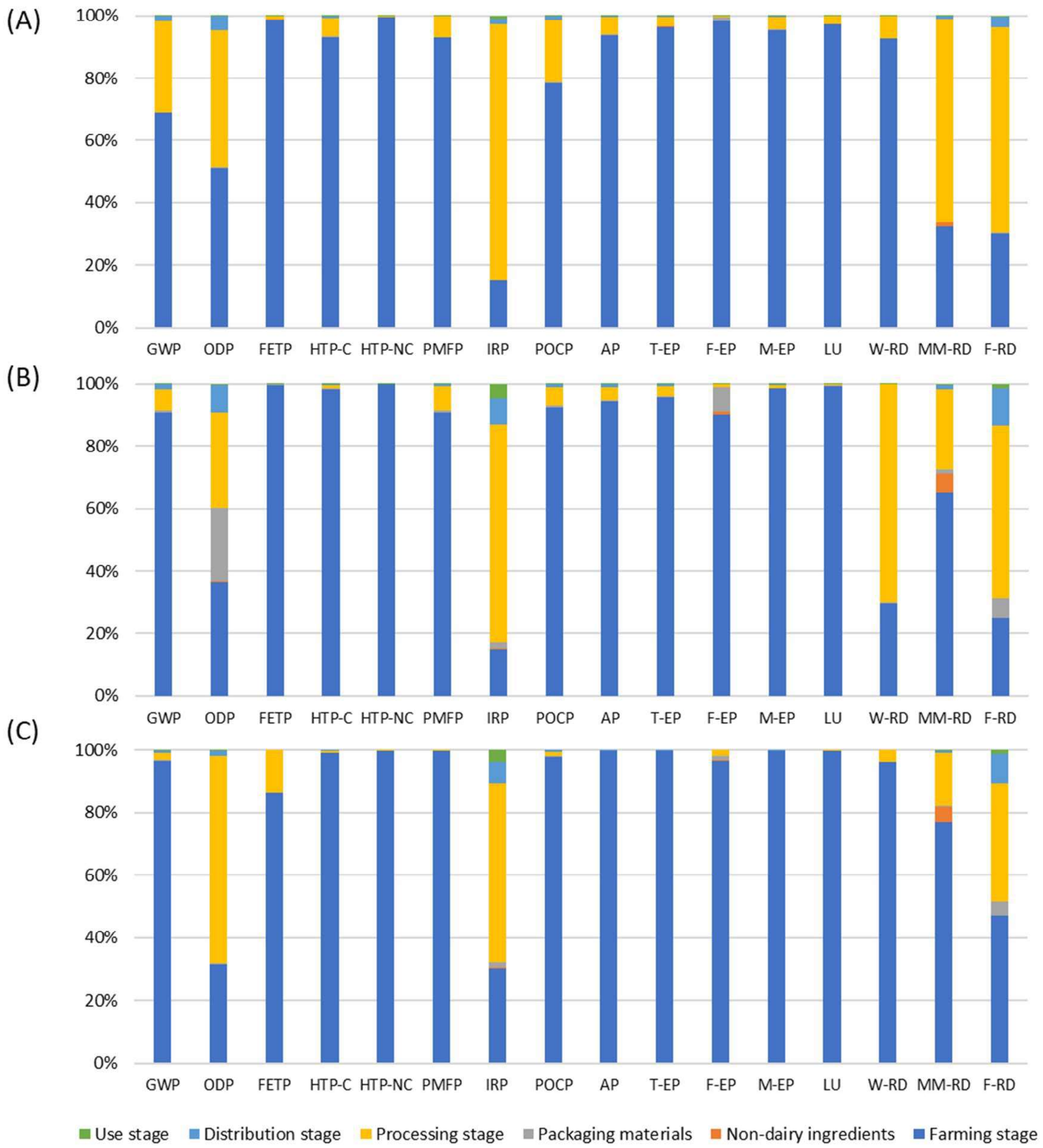


Figure 5.1: Contributions of the life-cycle stages to the baseline general impact category scores for the artisan cheeses produced with (A) cow, (B) sheep and (C) goat milk.

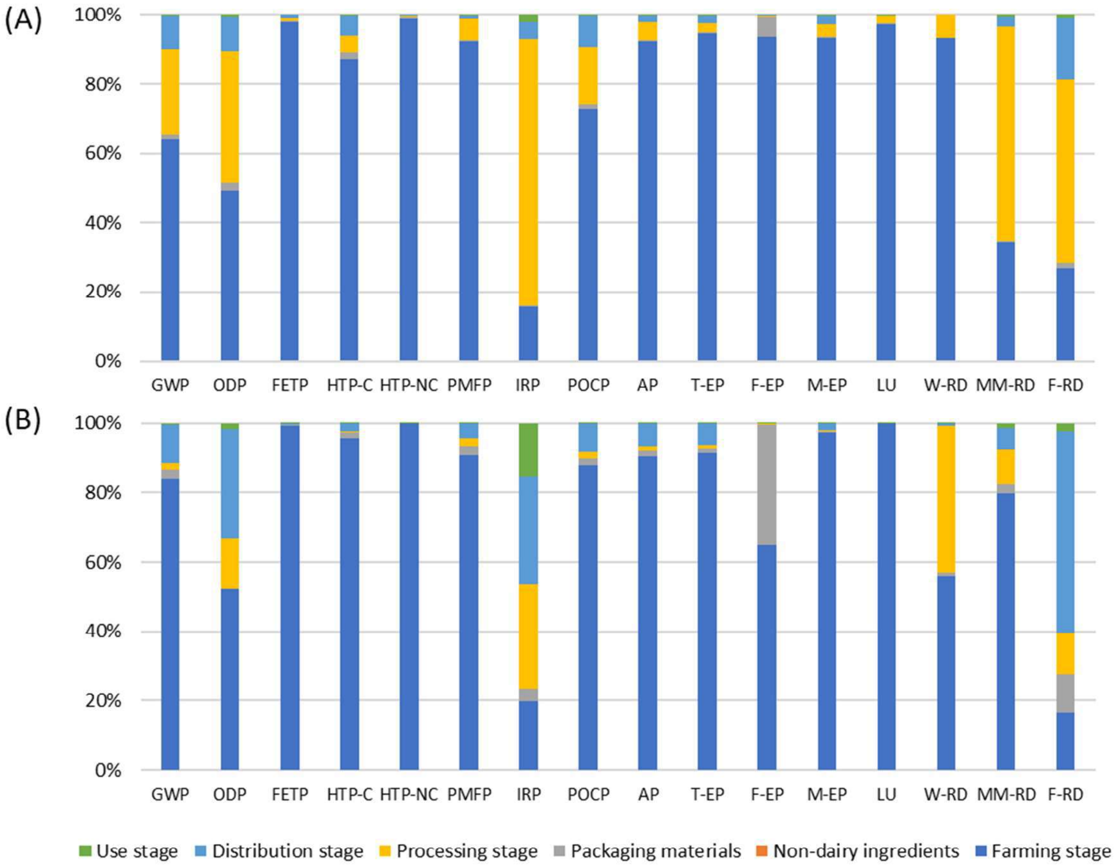


Figure 5.2: Contributions of the life-cycle stages to the general baseline impact category scores for the artisan yoghurts produced with (A) cow and (B) sheep milk.

5.2.2.2 Baseline dairy farm results (cradle-to-farm gate)

The raw milk production or farming life-cycle stage has a great influence the total environmental performance of the assessed artisan dairy products. Hence, this section gives a deeper look into the dairy farms through a more detailed discussion of the baseline results of the cow, sheep, and goat raw milk production stages.

The cow, sheep and goat dairy farms' baseline results per FU (1 kg FPCM) of raw milk are presented in Table 5.4; while the contributions of the impact categories (excluding toxicity related impact categories) to the ESS is presented in Table 5.5. As shown, the cow raw milk production characterized and ESS outcomes are above the EU benchmark; while among the three assessed raw milk production systems the production of goat raw milk reports the highest characterized and ESS.

As expected and in line with the dairy products' baseline general results, GWP, W-RD, AP, M-EP, T-EP, F-EP, LU and PMFP are the most relevant impact categories for the assessed dairy farms since their total contribution to the raw milks' ESS is above 92% (Table 5.5)

Table 5.4: Baseline dairy farm scores of the environmental impact categories for the assessed artisan dairy products; and their variation (Δ%) with the EU benchmark scores.

Impact category	**Unit**	**Raw milk at dairy farm (FU= 1 kg FPCM)**			
		EU Benchmark*	**Cow milk**	**Sheep milk**	**Goat milk**
GWP	kg $CO_{2\ eq}$	1.37E+00	1.59E+00	1.05E+00	2.54E+00
	Δ%	-	16.4	-	-
ODP	kg CFC-11$_{eq}$	2.88E-09	2.81E-10	5.41E-11	2.36E-10
	Δ%	-	-90.3	-	-
FETP	CTUe	2.36E+00	3.14E+00	4.57E+00	7.79E+00
	Δ%	-	32.9	-	-
HTP-C	CTUh	2.00E-08	2.08E-08	3.57E-08	5.68E-08
	Δ%	-	3.6	-	-
HTP-NC	CTUh	1.36E-06	2.62E-06	7.27E-06	1.21E-05
	Δ%	-	92.2	-	-
PMFP	DI **	9.55E-08	2.80E-07	4.94E-08	8.21E-07
	Δ%	-	193.8	-	-
IRP	kg U235 $_{eq}$	1.89E-02	2.40E-02	2.58E-03	5.97E-03
	Δ%	-	26.7	-	-
POCP	kg NMVOC $_{eq}$	2.98E-03	5.59E-03	4.35E-03	1.09E-02
	Δ%	-	87.6	-	-
AP	mol H+ $_{eq}$	1.27E-02	3.47E-02	6.78E-03	1.02E-01
	Δ%	-	174.2	-	-
T-EP	mol N $_{eq}$	5.48E-02	1.55E-01	3.20E-02	4.59E-01
	Δ%	-	183.5	-	-
F-EP	kg P $_{eq}$	1.06E-04	1.55E-04	2.06E-05	8.24E-05
	Δ%	-	45.4	-	-
M-EP	kg N $_{eq}$	3.77E-03	1.11E-02	9.49E-03	2.74E-02
	Δ%	-	193.7	-	-
LU	pts	1.43E+02	1.06E+02	1.32E+02	1.89E+02
	Δ%	-	-25.6	-	-
W-RD	m^3 $_{world\ eq}$	2.59E-01	1.55E+01	1.65E-01	7.70E+00
	Δ%	-	5888.3	-	-
MM-RD	kg Sb $_{eq}$	1.28E-06	1.37E-07	8.66E-08	1.96E-07
	Δ%	-	-89.2	-	-
F-RD	MJ	3.15E+00	5.17E+00	5.73E-01	1.28E+00
	Δ%	-	63.9	-	-
B-GWP	kg $CO_{2\ eq}$	7.85E-01	9.23E-01	8.24E-01	1.57E+00
	Δ%	-	17.5	-	-
F-GWP	kg $CO_{2\ eq}$	3.77E-01	6.11E-01	2.25E-01	9.71E-01
	Δ%	-	62.0	-	-
LUC-GWP	kg $CO_{2\ eq}$	2.05E-01	5.69E-02	1.56E-04	1.47E-03
	Δ%	-	-72.2	-	-

* PEF compliant EU-28+3 Cow milk production

** DI= disease index

Table 5.5: Contribution of the impact categories to the Environmental Single Score (ESS) for the EU raw milk benchmark and for the assessed raw milks.

Impact	**Raw milk**			
category	**EU benchmark***	**Cow milk**	**Sheep milk**	**Goat milk**
GWP	36.5%	14.2%	37.8%	13.5%
ODP	0.0%	0.0%	0.0%	0.0%
PMFP	13.3%	13.1%	9.3%	22.8%
IRP	0.2%	0.1%	0.0%	0.0%
POCP	3.5%	2.2%	6.9%	2.5%
AP	14.1%	12.9%	10.2%	22.7%
T-EP	11.3%	10.7%	8.9%	18.8%
F-EP	1.1%	0.6%	0.3%	0.2%
M-EP	3.9%	3.8%	13.2%	5.6%
LU	8.4%	2.1%	10.5%	2.2%
W-RD	1.9%	38.0%	1.6%	11.2%
MM-RD	1.7%	0.1%	0.2%	0.1%
F-RD	4.0%	2.2%	1.0%	0.3%
Total	100.0%	100.0%	100.0%	100.0%
ESS (pts)	1.07E-04	3.21E-04	7.93E-05	5.39E-04

*PEF compliant EU-28+3 Cow milk production

Global Warming Potential (GWP)

The cow raw milk production GWP outcome is ~16% above the EU benchmark. The GWP influence on the ESS results is lower for the assessed cow raw milk (~14%) than for the EU benchmark (~37%). In fact, all the impact categories report lower contributions to the cow raw milk ESS due to the particularly high contribution of the W-RD category; the cause of it will be further discussed in the following paragraphs.

Around 54% of the GWP reported by the assessed cow dairy farm is attributed to Methane (CH_4) emissions while, the EU benchmark attributes ~56% of the GWP score to CH_4 emissions. The raw milk EU benchmark data does not specify the origin of the CH_4 emissions so a deeper analysis and comparation between the outcomes is not possible. Nonetheless, the $\text{CalcPEF}_{\text{Dairy}}$ results show that ~55% of the CH_4 produced in the cow dairy farm is due to the cow's enteric fermentation digestive process.

Among the cow, sheep and goat dairy farms, the goat raw milk reports the highest GWP per FU; which is at least 1.5 times higher than the GWP score reported by the cow dairy farm. However, GWP has a more important influence on the sheep raw milk ESS (~38%) than on the ESS of the goat raw milk (~14%). As well as for the cow raw milk, CH_4 contributes the most to the sheep and goat milk GWP outcomes (Figure 5.3); and, to the sheep and goat enteric fermentation processes are attributed nearly 74% and 59% of the generated CH_4 emissions respectively.

The enteric fermentation CH_4 emissions depend on the animals' type of digestive tract, age, and weight, and on the quality and quantity of the feed consumed (IPCC, 2006a). There is no doubt regarding the important role of the dairy animals' biological characteristics on the enteric fermentation emissions but, certainly, the issue core is the type and quality of the animals' feed. Animal feed with a poor digestibility energy (DE) ratio lead to a higher gross energy (GE) demand by the animal therefore, it has to remain more time in the animal's digestive systems and more CH_4 emissions are generated.

The assessed cows' feed has a better DE ratio (72.5%) than the sheep and goats feed (60%) since they are fed with good pastures; good preserved forages and its diet is supplemented with grains such is maize. Therefore, the cow raw milk should report lower GWP per FU than sheep and goats however, it does not occur because cows are much heavier ruminants than sheep and goats; so, they demand much more GE and thus, produce more enteric fermentation CH_4 emissions. Additionally, the cow raw milk fat (3.3%) and protein (4%) content is lower than the sheep (8.3% fat and 5.8% protein) which increases the assignation of the GWP burdens per FU of cow's raw milk; regardless of being the raw milk type with the highest production.

Sheep and goats consume feed with similar DE ratio but do not report similar GWP nor CH_4 enteric fermentation emissions since the GE demands of the animals are different; for example, sheep require more GE since they produce wool while goat do not. However, the main difference on the sheep and goat GWP results could be caused by their raw milk production and raw milk nutritional parameters that influence the assignation of the environmental burdens per kg FPCM.

The sheep raw milk impact characterized outcomes are lower than the goat's raw milk outcomes because sheep farm produces 3 times more raw milk than the goat farm; and the sheep raw milk contains almost twice fat and protein than the goat raw milk (4.1% fat and 3.6%). Thus, these conditions would explain the higher sheep raw milk GWP results in comparation to the goat raw milk; and also, until some degree, their differences among the remaining impact categories.

Water Resource Depletion (W-RD)

The cow raw milk production W-RD outcomes is ~5888% above the EU benchmark reason why it is the impact category that contributes the most to the ESS result of the cow raw milk (~38%). Since the EU raw milk benchmark is a weighted average of different PEF compliant European raw milk production systems (grazing, non-grazing, organic, etc), it could be possible that the assessed cow dairy farm system belongs to the minority of the dairy systems that conform the EU benchmark. Thus, its characterized impact outcomes could highly differ against the benchmark.

The EU organic raw milk production system (UUID: b22c9e8f-9392-4369-b451-e1407365a550) is part of the PEF database and was used to determine the EU raw milk production benchmark; but, since the organic milk share in the EU market is minimum, its influence in the EU benchmark is also low. Therefore, when comparing the W-RD outcomes of the EU organic raw milk production system against the EU benchmark, the EU organic raw milk W-RD result is ~877% above the EU benchmark.

This evidences that high differences are possible among raw milk production systems even for the ones included in the PEF database; nonetheless these differences not invalidate the assessment results. Thus, some possible explanations for the differences between assessed cow raw milk and the EU benchmark W-RD results are explored.

A first possible explanation is the weak or no representation of artisan raw milk production systems in the current EU benchmark. Since these systems are poorly represented, their results are more likely to differ from the Benchmark's results for W-RD or for any other environmental impact category. Thus, for a more coherent and realistic comparation, an EU benchmark for artisan or no industrialized raw milk production could be developed and validated.

Another explanation could be the role of regionalized characterization factors that the AWARE model proposes to determine the W-RD impact; which varies depending of the location (country or region) from where the water is withdrawal. For example, the consumption of 1 m^3 of fresh water in a German dairy farm results on 1.36 $m^3_{world\ eq}/m^3$ while in a Spanish farm results on 77.7 $m^3_{world\ eq}/m^3$. The AWARE characterization factors do not only affect the W-RD results related to the farms' direct water consumption but, also affect the W-RD results related to the production of the farms' supplies such as animal feed. Therefore, they influence the W-RD of the complete raw milk supply chain.

Hence, due to the regionalized AWARE characterization factors, the W-RD EU benchmark is more representative for the EU countries with a bigger share of the EU raw milk market share (The Neverlands, Germany, the United Kingdom) than for the countries with smallest shares. Furthermore, since the raw milk produced in Spain is not included in the EU benchmark, the Spanish W-RD results for raw milk will probably differ when compared to the benchmark; regardless the type of the assessed raw milk production system.

For instance, the W-RD result of an Italian raw milk produced in a non-grazing system is ~50% higher than a German raw milk produced in a same system. Additionally, when comparing the non-grazing system W-RD results with the EU benchmark, the Italian raw milk reports a bigger difference (~72%) than the German cow raw milk (~19%).

The EU benchmark does not indicate the activities that withdraw the highest quantity of water however, for the assessed cow raw milk, the production of animal feed was identified as the activity that generates most of the reported W-RD (Figure 5.3). The production of the purchased maize to cover the cows' dietary needs is highly responsible of the cows' raw milk W-RD results in a ~98%.

Despite consuming 261.83m^3 less water, raw milk produced in the goat dairy farm reports higher W-RD than the raw milk produced in the sheep dairy farm; also due to the consumption of maize. The production of the maize consumed by goat represents ~97% of the goat milk W-RD.

Since the sheep do not consume maize to satisfy its dietary need, the W-RD outcome of the sheep raw milk is the lower than the cow and goat results. All the sheep feed is produced in the dairy farm reason why the water consumed in the farm for irrigation purposes and also for animal drinking accounts for ~81% of the sheep raw milk W-RD outcome.

Land Use (LU)

The LU score for the cow raw milk is lower than the score reported by the EU benchmark; its difference is ~26%. Due to this difference, the cow raw milk contribution to the ESS is also lower (~2%) than the LU contribution to the benchmark ESS (~8%). The LU score differences with the EU benchmark are due to two main aspects. The first one is that the inventory for cow raw milk production is only considering the two current farm's land uses: land for animal grazing purposes and land for agricultural use to produce animal feed or crops; to which ~52% and ~48% of the cow raw milk LU score are attributed respectively.

According to the information provided by the EU benchmark the land used for animal pastures represents ~ 50% of its LU score; while a ~ 31% of the reported benchmark LU is attributed to the use of the farms land for agricultural purposes. Nonetheless, the EU benchmark considers different land uses and also changes on its use. Therefore, it would be understandable for its LU score to be above the score for the assessed cow raw milk.

However, the differences are mainly triggered by the amount of land needed to produce cow raw milk. According to the EU benchmark a total of ~0.64 m^2·year of grassland and ~0.32 m^2·year of agricultural land are used to produce a FU of cow raw milk; whereas, the assessed cow raw milk requires ~0.21 m^2·year of grassland and ~0.19 m^2·year of agricultural land per produced FU. This lower demand of land of the assessed dairy farms would be affecting the cow raw milk LU outcomes. The land use differences could be coherent since this study's outcomes reflect the reality of an artisan dairy system while the benchmark probably represents the reality of more industrialized and extensive dairy systems.

Moreover, even if the amount of used land is similar between the assessed farm and the EU benchmark, the LU results would not be nearly close since the LANCA methodology (Bos et al., 2016) applied to determine LU also uses regionalized characterization factors. Thus, similarly to the W-RD benchmark, the LU the EU benchmark is more representative for the raw milk produced in the countries that have a bigger share of the raw milk EU market. For example, the use of 1 m^2·year of land for agricultural purposes in a German dairy farm results on 137.14 pts/ m^2·year while, in a Spanish farm results on 89.95 pts/ m^2·year.

Acidification Potential (AP) and Terrestrial Eutrophication Potential (T-EP)

The reviewed literature has shown that the AP and T-EP environmental impacts are both mainly triggered by Ammonia (NH_3) and nitric oxides (NO_x) emissions; meaning that, at the dairy farm, both environmental impact scores are obtained from the same kg of NH_3 and NO_x per FU; and what changes is the characterization factor. For instance, the EU benchmark reports a total of 8.25 g NH_3 per FU and uses a factor of 3.02 mol/kg to determine AP and 13.47/mol/kg to determine T-EP. A similar situation is observed in the CalcPEFDairy results thus, the AP and T-EP impact results for the assessed raw milks will be discussed together in the next paragraphs since the origin of their triggering compounds in the dairy farms is common.

The cow raw milk production AP and T-EP results are both almost 2 times above the EU benchmark however, the influence of the AP and T-EP categories on the ESS results is nearly the same between both the assessed cow raw milk (~13% and ~11% respectively) and the EU benchmark (~14% and ~11% respectively).

A ~76% of the reported cows raw milk AP and T-EP is attributed to ammonia (NH_3) and nitric oxides (NO_x) emissions arising from different manure related farm activities; from which a ~95% is attributed to NH_3 arising from the storage and application of the cow managed manure to the soil. AP and T-EP are also affected by the production of the purchased cows feed (~22%); a ~60% which is related to the production of maize.

Since cows excrete more manure than sheep and goat, it would be expected for the cow raw milk to report the highest AP and T-EP scores. However, it was not the case since the goats' raw milk reports almost 3 times more AP and T-EP than the cows' raw milk. This could be due to the influence of the reporting FU which, as previously mentioned, affects the assignation of AP and T-EP burdens per FU (kg of FPCM). In fact, AP and T-EP are the impact categories that affect the most (~23% and ~19%) to the goat raw milk ESS. For both, the cow and sheep raw milk, the AP contribution to their ESS is less than 13% while the T-EP contribution is less than 11%.

Similarly, to the cow raw milk, NH_3 and NO_x emissions contribute the most to the sheep and goat raw milk AP and T-EP outcomes (Figure 5.3). A ~90% of the goat raw milk AP and T-EP scores are specifically attributed to NH3 emissions released during the storage and application of the goat's manure to soil. While, for the sheep raw milk, a ~70% of the AP and T-EP impact scores are attributed to NH_3 emissions arising from the manure excreted in the pastures represent and also, from the storage and later application of the managed manure.

The NO_2 emissions released from the application of manure has more impact on the sheep raw milk AP (~18%) and T-EP (~22%) scores than over the cow raw milk (~2% for AP and T-EP both) and goats (~3% AP and ~4% T-EP). A ~50% of the NO_2 emissions leading to sheep raw milk AP and T-EP scores are attributed to the manure excreted while the livestock is grazing and does not enters the storage stage. Since cows and goats do not spend that much time grazing as sheep, around 80% of its NO_2 are attributed to the application of the managed manure that did enter storage. The AP and T-EP hotspot is the application of manure (managed or no managed) and their differences and effect on the total AP and T-EP scores are attributed to the emissions trade between manure related activities; storage and application.

The managed or no managed manure application NO_2 emissions are determined from the manure's N content(EMEP/EEA, 2016b). Since the applied managed manure has enter storage, NO_2 and other N related losses are reported; which reduces its N content at application. Thus, when using the manure application NO_2 characterization factor (0.04 kg NO/kg N applied), the no managed manure reports more NO_2 emission than the one that has managed and entered storage.

The trade-off would suggest that the storage NO_2 emissions will gain relevance when for cows and goats since they spend less time in grazing and more excreted manure is stored. However, this is not the case due to the EMEP/EAA methodology used to estimate the NO_2 emissions. For instance, the storage stage affects in less than 1% to all the assessed livestock's AP and T-EP scores.

On contrary to the manure application emissions, the storage NO_2 emissions are determined as a fraction of the manure's Total Ammoniacal Nitrogen (0.01 kgNO/kg $TAN_{\text{solid manure}}$ and 0.0001 kgNO/kg $TAN_{\text{liquid manure}}$) which is a proportion of the manure's N content (0.6 for cows and 0.5 for sheep and goats) (EMEP/EEA, 2016a). Due to these methodological characteristics, the storage stage reports less NO_2 emissions than the application stage and thus, leads to less AP and T-EP impacts. In fact, with exception of the manure application NO_2 emissions, the EMEP/EAA methodology determines all the other manure related N emissions by taking as basis the manure's TAN content.

Another methodological gap that affects the results is that the EMEP/EAA only considers two manure management system types (solid and liquid) and does not provides solid and liquid manure characterisation actors for some livestock types. For instance, there are no specific NH_3 and NO_x characterization factors for composting as manure management system and neither factors for sheep and goat liquid manure. These methodological gaps affect the sheep and goat raw milk results since 43% of the sheep excreted manure is managed as liquid manure; and 9% of the goats' manure is managed in a composting system. Therefore, the sheep and goat results would be failing to adequately represent the related manure farm activities.

The representation lack of more specialized manure related activities in the current methodology would be responsible, until some degree, of the AP and T-EP results among the assessed raw milks; and also affect other N emissions related impact categories.

Marine Eutrophication Potential (M-EP)

The cow raw milk production M-EP outcome is ~194% above the EU benchmark but, its contribution to the cow raw milk ESS result is in less than 4% similarly to the EU benchmark the M-EP contribution. M-EP is mainly caused by NH_3 and nitrates (NO_3^-) released by direct manure deposition and the application of manged manure and fertilizers that reach coastal areas through water streams or erosion; the EU benchmark does not indicate the origin of this compounds but, confirms the relevance of NH_3 and NO_3^- on the M-EP impact result.

For the assessed cow raw milk, the NO_3^- emission released during the application of the managed manure to the farms soil account for ~31% of the reported M-EP; while the NO_3^- released by the excretion of manure while the animal is grazing accounts by ~6% of the M-EP. The NH_3 emissions generated from the manure storage and the application of managed and no manged manure account for a total of ~7% of the reported M-EP.

The production of the maize purchased to feed the cows contributes ~40% to M-EP. The Maize production dataset does not indicate the origin of the NO_3^- leading to M-EP but also it is highly possible that they are related to the application of natural or mineral fertilizers to soil.

The sheep raw milk reports a lower M-EP since it does not consume maize and also because it also favoured by the FU characteristics when allocating the environmental burdens; the goat raw milk reports the highest M-EP score. Moreover, since sheep spend 50% of its time under grazing conditions, the application of managed and no managed manure to soil influences in a same amount to the M-EP (~43%). These similarities are attributed to the, the IPCC methodology used to determine the leached NO_3^- due to application of manure. The methodology provides a unique NO_3^- emission factor; reason why there is no NO_3^- emission differences among the application of liquid or solid managed or no managed manure (IPCC, 2006b). For the case of the goat raw milk, since goats spends less time in grazing conditions the most amount of leached NO_3^- are attributed to the application of managed manure (~51%).

Fresh Water Eutrophication Potential (F-EP)

The F-EP outcome for the cow raw milk has a ~45% difference in comparation to the EU benchmark, but its contribution to the ESS is almost half of the contribution of this impact to the EU benchmark ESS (~1.1%). F-EP is exclusively attributed to the P that reaches freshwater bodies through leaching, run-off or erosion. The production of the cow's feed for ~96% of the F-EP for the produced raw milk; ~86% of which is specifically attributed to the production of the maize purchased to feed the animals. The maize production dataset does not specify the origin of the P that ends up reaching the fresh waterbodies but it is highly possible that its origin is the application of fertilizers to land.

The maize production for animal feed is also the main source of P that affects the goats raw milk F-EP (~75.99%); the goat raw milk has the second higher F-EP score among the assessed raw milks below the cow raw milk and above the sheep raw milk. However, the goat milk F-EP has a lower contribution to the ESS (~0.2%) than the cow (~0.6%) and the sheep raw milks (~0.3%).

Since the sheep farm produces all the animal feed, its leached P emissions from the application of the manure to soil account for ~62% of the sheep raw milk F-EP; followed by the production of the purchased animal bedding (~36%). It is not possible to define the origin of the P emissions related to the production of the animal bedding since the used datasets do not provide this information however, the emissions are likely to be related to the application of fertilizers to the soil.

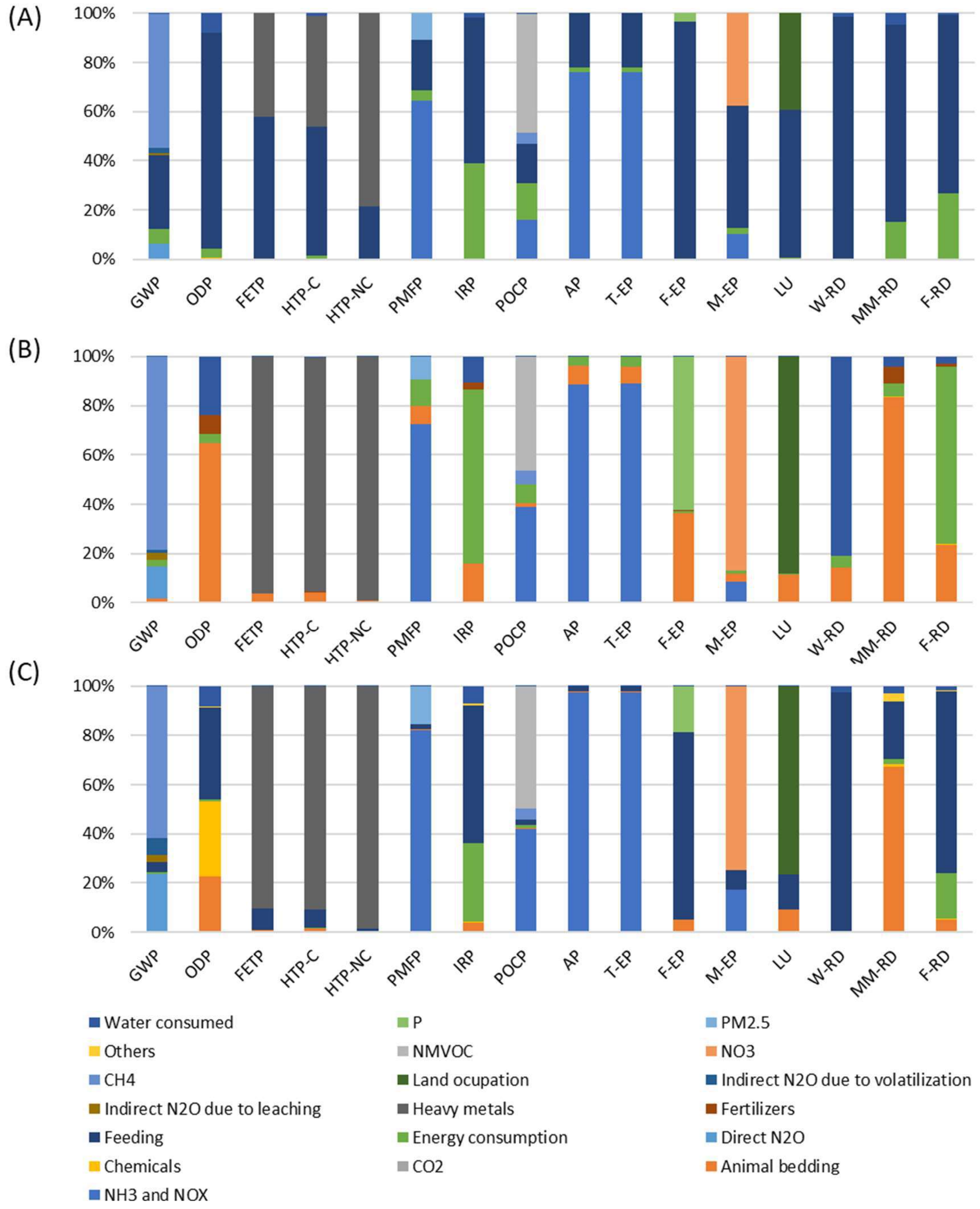


Figure 5.3: Contributions of the dairy farm emissions and supplies to the baseline impact category scores of the produced (A) cow,(B) sheep and (B) goat raw milk.

5.2.2.3 Baseline dairy processing facility results (gate-to-gate)

As show in the baseline general results the processing life-cycle stage has a minimum influence on most of the assessed environmental impacts but, also a relevant one in others. Table 5.6 presents the processing facilities' baseline characterized results for all impact categories per FU of cheese (10g DM) and yoghurt (125 g). The ESS of the assessed processing facilities and the contribution of the different impact categories to them are not presented nor contrasted with an EU benchmark since, currently, there are neither characterised nor ESS EU benchmark gate-to-gate results for this life cycle-stage.

Since all the assessed artisan dairy systems are multiproduct systems, they share the processing facility to produce cheeses and yoghurts and the total impact burdens are assigned to the products by the DM allocation criterion. Thus, similar processing facility hot-spots are obtained for the assessed cheeses and yoghurts. In fact, Figure 5.4. and Figure 5.5 reveal the great relevance of energy (electricity, heat and diesel) supplies over all the impact categories of the assessed dairy facilities regardless the type of raw milk used to produce the cheeses or yoghurts.

Since the baseline general results showed that the processing life-cycle stage has an important influence on the IRP, ODP and F-RD impact categories, the production of energy (electricity, diesel and thermal) and its consumption at the artisan dairy farms it's a relevant environmental hot-spots for the total environmental performance of the assessed artisan cheeses and yoghurts.

For instance, the dairy facilities' results show that above 90% of the IRP scores of the assessed cow, sheep and goat milk cheeses are attributed to the consumption of electricity from the Spanish network. The consumption of electricity also affects above 90% to the F-RD scores of the cow and goat milk cheeses while for the sheep milk cheeses its influence over F-RD is just above 75%. The consumption of electricity and tap water are the main responsible of the ODP scores for the cow and sheep cheeses while the consumption of chemicals (~93%) is the most relevant supply affecting the goat milk cheese ODP.

Due to the artisan systems multiproduct functionality and the DM allocation criterion, the hotspots triggering the IRP, F-RD and ODP outcomes of the assessed artisan cow and sheep milk yoghurts are the same as the cheeses produced with cow and sheep raw milk.

The differences among the assessed cheeses and yoghurts are mainly attributed to the quantity of the electricity, taped water and chemicals consumed by the assessed artisan cow, sheep and goat raw milk processing facilities.

For instance, the cow milk processing facility consumes nearly 19 and 91 times more kWh of electricity ;and nearly 3.5 and 21 times more m^3 of tap water than the sheep and goat milk processing facilities respectively. While, regarding chemicals, the goat milk processing facility consumes around 2 times more kg than both the cow and sheep milk processing facilities.

Despite these important differences regarding the total electricity, tap water and chemicals consumption, the IRP, F-RD and ODP differences per FU of cow milk cheese and yoghurt are not as high as expected; due to the role of the facilities' total production of cheese and yogurts and the DM allocation criterion used to assign the environmental burthens to the facilities' multiproduct.

For example, the differences of the IRP score for the cow milk cheese among the sheep and goat milk cheeses should be much higher than ~82% and ~81% respectively. However, since the cow milk processing facility production of cheeses DM is greater than the production of the sheep and goat milk processing facilities DM, less environmental burdens are assigned per FU of produced cow milk cheese. This reduces the assignation of environmental burdens per FU of produced cow milk cheese and evidences the relevance of the DM allocation criteria of the environmental burdens at the processing facility.

Table 5.6: Baseline dairy facility scores of the environmental impact categories for the assessed artisan dairy products.

Impact category	**Cheese (FU= 10gDM)**			**Yoghurt (FU= 125g)**	
	Cow milk	**Sheep milk**	**Goat milk**	**Cow milk**	**Sheep milk**
GWP (kg $CO_{2\ eq}$)	4.30E-02	9.75E-03	8.54E-03	6.55E-02	4.67E-03
ODP (kg CFC-11$_{eq}$)	1.53E-11	5.74E-12	6.67E-11	2.34E-11	2.75E-12
FETP (CTUe)	2.20E-03	9.48E-04	1.62E-01	3.35E-03	4.54E-04
HTP-C (CTUh)	7.98E-11	5.07E-11	4.36E-11	1.22E-10	2.43E-11
HTP-NC (CTUh)	8.48E-10	3.60E-10	5.67E-09	1.29E-09	1.72E-10
PMFP (DI *)	1.30E-09	5.27E-10	3.28E-10	1.99E-09	2.52E-10
IRP (kg U235 $_{eq}$)	8.21E-03	1.50E-03	1.53E-03	1.25E-02	7.18E-04
POCP (kg NMVOC $_{eq}$)	9.00E-05	3.48E-05	2.21E-05	1.37E-04	1.66E-05
AP (mol H+ $_{eq}$)	1.36E-04	3.78E-05	3.03E-05	2.08E-04	1.81E-05
T-EP (mol N $_{eq}$)	3.27E-04	1.29E-04	8.42E-05	4.98E-04	6.16E-05
F-EP (kg P $_{eq}$)	5.06E-08	2.74E-08	2.13E-07	7.72E-08	1.31E-08
M-EP (kg N $_{eq}$)	3.03E-05	1.17E-05	7.62E-06	4.62E-05	5.62E-06
LU (pts)	1.81E-01	4.48E-02	3.20E-02	2.76E-01	2.14E-02
W-RD (m^3 $_{world\ eq}$)	7.79E-02	4.89E-02	3.95E-02	1.19E-01	2.34E-02
MM-RD (kg Sb $_{eq}$)	1.75E-08	4.33E-09	5.79E-09	2.67E-08	2.07E-09
F-RD (MJ)	7.21E-01	1.59E-01	1.37E-01	1.10E+00	7.60E-02
B-GWP (kg $CO_{2\ eq}$)	3.81E-05	9.43E-06	4.70E-05	5.81E-05	4.52E-06
F-GWP (kg $CO_{2\ eq}$)	4.29E-02	9.73E-03	8.49E-03	6.55E-02	4.66E-03
LUC-GWP (kg $CO_{2\ eq}$)	1.46E-05	1.03E-05	4.95E-06	2.23E-05	4.95E-06

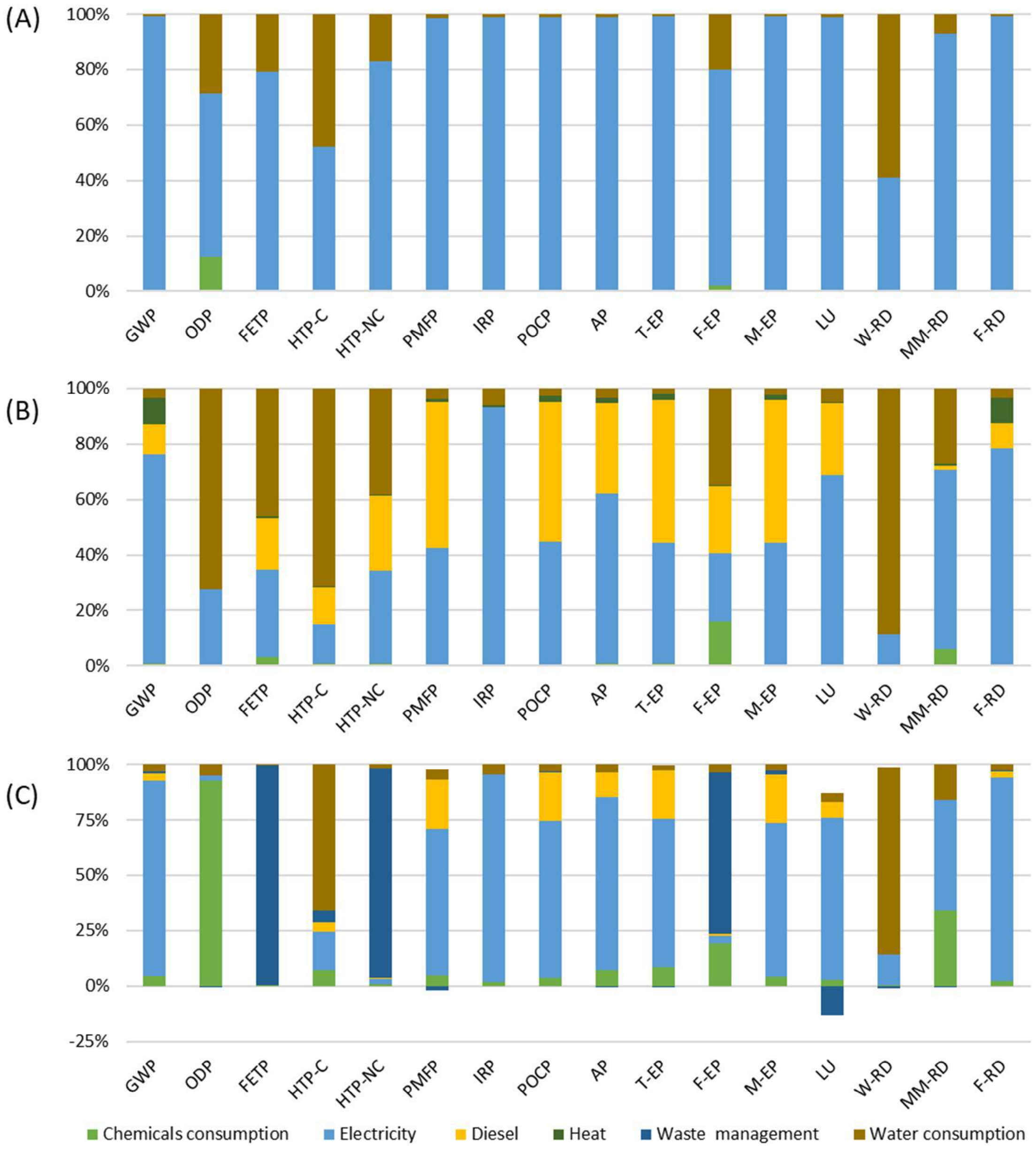


Figure 5.4:Contributions of the processing supplies to the processing facility baseline impact category scores for the artisan cheeses produced with (A) cow, (B) sheep and (C) goat milk.

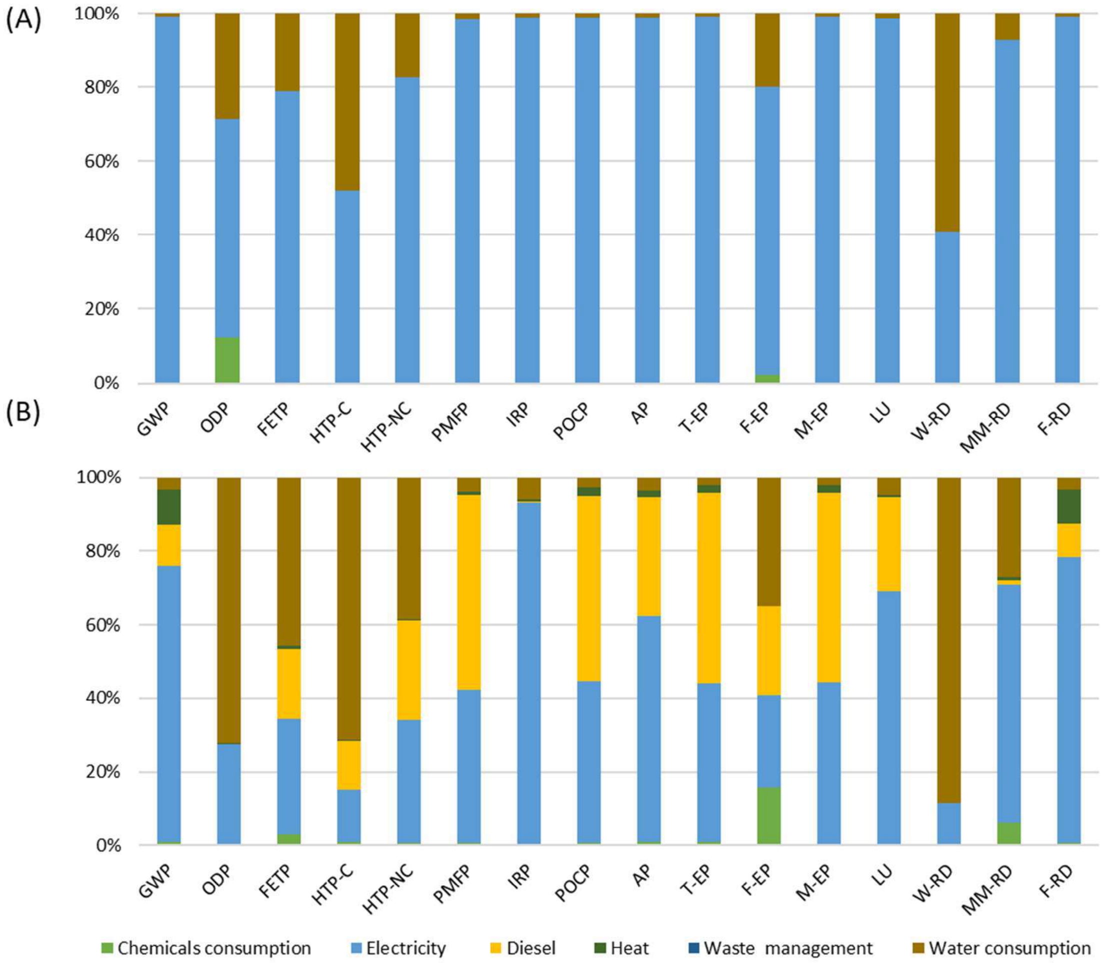


Figure 5.5: Contributions of the processing supplies to the processing facility baseline impact category scores of the artisan yoghurts produced with (A) cow and (B) sheep milk

5.2.3 Improvements for traditional dairy systems

The previous sections evidenced farming stage as the main contributor of the impact categories that threat the environmental performance of the artisanal cheeses and yoghurts produced with cow, sheep and goat milk. While the processing stage directly contributes to fewer but still important impact categories. Thus, this section discusses possible improvements to reduce emissions, limit the consumption of supplies and decrease the amount of generated wastes. So, the artisanal dairy systems can enhance their products' environmental performance through achieving a more environmentally sustainable status.

5.2.3.1 Dairy farm improvements

The manure related activities were found as relevant environmental hot-spots in the farming stage of the analysed artisanal dairy systems. Thus, possible alternatives to mitigate farm emissions due to manure management and manure application are further explored. Nonetheless, since the manure emissions are closely dependant to the animals' diet, the importance of improving the cows, sheep and goats' diet is also discussed. And finally, some actions to mitigate the environmental burdens of consuming maize as animal feed are further discussed due to its relevant influence on the cow and goat artisan systems.

Change of manure management systems

The baseline manure management conditions of the assessed artisan dairy systems (Table 5.7) shown that most of the total excreted manure collected in the barns, stables or any other animal housing facility is managed through deep bedding and liquid manure management systems (Table 5.8); prior its application to soil or before its revalorisation as organic fertilizer to be used in other agricultural production system.

Table 5.7: Shares of manure excreted during housing managed in different manure management systems types per manure livestock type.

Manure management system	Cow		Sheep		Goat	
	Baseline	Improvement	Baseline	Improvement	Baseline	Improvement
Deep bedding	37.0%	-	7.0%	-	68.0%	-
Liquid/slurry	50.0%	-	43.0%	-	-	-
Intensive windrow composting	-	52.0%	-	30.1%	9.0%	77.0%
Liquid/slurry + solid/liquid separation	-	35.0%	-	19.9%	-	-
No managed manure	13.0%	13.0%	50.0%	50.0%	23.0%	23.0%

Since the baseline results showed that the manure management activity in the farm is responsible of an important amount of emissions affecting the environmental performance of the assessed artisan dairy products, the option implementing an intensive windrow composting system and also, the improvement of the liquid/slurry manure management system with the installation of a solid/liquid manure separator are explored (Table 5.8).

Table 5.8: Definitions of the manure management systems that are currently used in the assessed dairy farms and that are proposed as improvements.

Manure management system	**Definition**
Deep bedding or bedded pack	System where the manure accumulates, animal bedding is constantly added to absorb moisture over a production cycle for as long as 6 to 12 months
Liquid/slurry	System where manure is stored as excreted or with some minimal addition of water in either tanks or ponds outside the animal housing. Manure is stored usually for periods of less than one year.
Intensive windrow composting	System where compost is produced in windrows. The compost is turned for mixing and aeration at least once per day.
Liquid/slurry + solid/liquid separation	A liquid/slurry manure management system with a solid/liquid separator system. The solid/liquid separation is a processing technology that partially separated the solids from the liquid manure using gravity or mechanical systems (e.g. pressure or centrifugation)

On one hand, compost would be produced through the aerobic degradation of organic matter mediated by microbes and it could be used to manage wastes and recycle nutrients into the soil (USCC, 2008). The main benefit of producing compost is methane generation avoidance.

Nonetheless, a good composting practice, such as the proposed intensive windrow composting, would provide an adequate aeration and moisture to the produced compost which would balance the compost's Carbon: Nitrogen ratio; and thus, the production of GHG from the composting process should be minimum. Due to these benefits, intensive row composting should positively affect the environmental performance of producing raw milk and artisanal dairy products (Brown et al., 2008).

On the other hand, the installation of a pressure solid/liquid manure separator, as an improvement of the current liquid/slurry manure management system, allows the farms to reduce their amount of time and energy consumed for handling and transport the manure. The separator would also add value to the manure stream, increase flexibility in the management of the manure's nutrients and mitigate environmental impacts related to the storage and land application of the manure.

For all assessed artisan dairy farms, the manure that was previously managed in a deep bedding system will be now managed in an intensive windrow composting system. While, it is considered that the installed pressure solid/liquid manure separator has a 30/70 working ratio. Therefore, after separation, the liquid manure's solid phase (30%) will be added to the windrow composting system; while, the remaining liquid phase (70%) will be keep managed as liquid/slurry manure (Table 5.7). The obtained results are presented in Table 5.9.

Table 5.9: General baseline variations of the characterized impact scores and the Environmental Single Score (ESS) results of the produced cheeses and yogurts with different types of milk when implementing an intensive windrow composting system and a solid/liquid separator in the liquid /slurry management system.

Impact category	**Baseline variations**				
	Cheese			**Yoghurt**	
	Cow milk	**Sheep milk**	**Goat milk**	**Cow milk**	**Sheep milk**
GWP	5.89%	11.27%	80.82%	5.50%	10.45%
ODP	0.00%	-23.60%	-7.12%	0.00%	-33.84%
FETP	-1.89%	-3.79%	-0.65%	-1.88%	-3.78%
HTP-C	0.00%	-3.95%	-1.82%	0.00%	-3.85%
HTP-NC	-3.32%	-1.01%	-0.37%	-3.30%	-1.01%
PMFP	-3.85%	48.21%	-8.31%	-3.82%	48.13%
IRP	0.00%	-2.36%	-1.19%	0.00%	-3.13%
POCP	-2.81%	-4.77%	-7.18%	-2.61%	-4.53%
AP	-4.59%	52.02%	-9.81%	-4.52%	49.81%
T-EP	-4.73%	49.69%	-9.79%	-4.65%	47.51%
F-EP	-0.10%	-33.00%	-5.00%	-0.10%	-23.74%
M-EP	-3.82%	-8.87%	-8.39%	-3.73%	-8.74%
LU	0.00%	-11.48%	-9.39%	0.00%	-11.52%
W-RD	0.00%	-4.25%	-0.01%	0.00%	-8.00%
MM-RD	0.00%	-54.28%	-51.89%	0.00%	-66.50%
F-RD	0.00%	-5.90%	-2.47%	0.00%	-3.93%
ESS	-0.61%	14.44%	4.32%	-0.59%	13.93%

Despite the implementation of these advanced manure management systems, the environmental performance of the assessed dairy products did not improve as expected due to the increase of the artisan products GWP scores. N_2O has the highest GWP characterization factor among the GHG (298 kg CO_{2eq}/kg N_2O); and its release during manure management increased since the IPCC N_2O emission factor for windrow composting is 10 times higher than the factor for deep bedding (IPCC, 2006a). Thus, despite reducing CH_4 emissions, the windrow composting system affected the GWP scores of the artisan dairy products.

The implementation of the solid/liquid separator has reduced amount of manure managed as liquid and increased the amount of manure handled as solid (compost). Which should lead to a reduction of NH_3 and NO_3 emissions; and thus, a reduction on the AP, T-EP and M-EP impacts. However, due to the lack of NH_3 emission factors for liquid sheep and goat manure on the EMEP/EAA (2016a) guideline, the expected outcomes cannot be obtained.

In fact, since the amount of sheep manure handled as solid (compost) has increased and thus, has NH_3 emission factors, the AP and T-EP results of the sheep milk dairy products have increased. Since any fraction of the goats' manure is handled as liquid, the lack of liquid manure NH_3 emission factors do not affect the sheep milk artisan dairy products' results; reductions below 10% on the AP and T-EP scores can be observed.

Since there are NH_3 emission factors for liquid and solid cow manure, the effect of the manure separator and the reduction of the manure managed as liquid can be seen in the AP and T-EP scores; which decreased in no more than 5%.

The IPCC guideline is used to determine NO_3 emissions however, this guideline only provides NO_3 emissions factor for manure application. Thus, the observed reductions on the M-EP outcomes for all the assessed dairy products are due to the higher N losses at the manure management stage which reduces the N content of the manure on the applications stage. This behaviour is possible to observe due to the implementation of the N mass balanced approach, proposed in this thesis, to determine N emissions in the dairy farm by following the IPCC and EMEP/EEA guidelines.

Optimal manure application and revalorization

The application of the managed manure on the farms' soil is another important GHG emission hot-spot than affects the environmental performance of the assessed artisan dairy products. Thus, to mitigate its related environmental burdens, an optimum recirculation and application and of the managed manure nutrients on the farm must be achieved. However, this is limited by the EU Nitrates directive (EC, 1991).

Taking as a basis the application emissions estimated with the IPCC and EMEP/EEA guidelines, the baseline conditions of the assessed dairy farms show that all the farms already exceed the 170 kg N/ha EU directive limit for N application (Table 5.10). Thus, to avoid managed manure application emissions, farmers could optimize the amount of managed manure that is revalorized as organic fertilizer to be used in other agricultural systems; and also, implement of up to date manure application techniques to mitigate the generated emissions.

Table 5.10: Estimated quantities of produced and exported managed manure per livestock type in a year

Dairy farm	Total N available for application (kg)	Area for application (ha)	N application (kg N/ha)		Revalorized managed manure share (%)	
			Baseline	Optimum	Baseline	Optimum
Cow	5200.6	7.25	716.8	170.0	0.0	76.0
Sheep	1313.9	4.58	186.6	170.0	35.0	41.0
Goat	1140.4	1.39	794.5	170.0	3.0	79.0

For all the assessed dairy, the optimum recirculation, application and revalorization of the managed manure has improved the environmental performance of the artisan dairy products (Table 5.11). The differences among common dairy products are due to the economic allocation criterion used to assign environmental burdens to the farms' coproducts with economic value (raw milk, animals and manure); and also because of the differences between the farms' baselines and optimum manure revalorized shares.

Table 5.11: General baseline variations of the characterized impact scores and the Environmental Single Score (ESS) results of the produced cheeses and yogurts with different types of milk if the managed manure application and revalorization is optimum.

Impact category	**Baseline variations**				
	Cheese			**Yoghurt**	
	Cow milk	**Sheep milk**	**Goat milk**	**Cow milk**	**Sheep milk**
GWP	-5.12%	-2.27%	-59.72%	-4.79%	-2.11%
ODP	-3.80%	-0.91%	-19.41%	-3.67%	-1.31%
FETP	-7.35%	-2.50%	-53.46%	-7.28%	-2.49%
HTP-C	-6.93%	-2.46%	-61.27%	-6.48%	-2.40%
HTP-NC	-7.40%	-2.51%	-61.61%	-7.37%	-2.50%
PMFP	-6.92%	-2.28%	-61.61%	-6.87%	-2.28%
IRP	-1.14%	-0.38%	-18.55%	-1.18%	-0.50%
POCP	-5.84%	-2.32%	-60.53%	-5.43%	-2.20%
AP	-6.98%	-2.37%	-61.64%	-6.87%	-2.27%
T-EP	-7.18%	-2.40%	-61.70%	-7.05%	-2.30%
F-EP	-7.32%	-2.26%	-59.76%	-6.98%	-1.63%
M-EP	-7.10%	-2.47%	-61.64%	-6.94%	-2.44%
LU	-7.24%	-2.49%	-61.73%	-7.24%	-2.50%
W-RD	-6.90%	-0.74%	-59.52%	-6.95%	-1.40%
MM-RD	-2.43%	-1.63%	-47.69%	-2.54%	-2.00%
F-RD	-2.25%	-0.63%	-29.02%	-2.00%	-0.42%
ESS	-6.29%	-2.20%	-60.86%	-6.14%	-2.13%

The allocation criterion assigns environmental impacts to the cows, sheep and goat revalorized manure by using its relative economic value (0.03€/kg) in comparation to the raw milk (0.96€/kg) and the animals (2-3 €/kg) at the farm gate; and depends on the livestock raw milk production yield and live weight.

For instance, the high influence of the cows' milk production yield (23kg/head·day) and their live weight (332kg/head) over the economic allocation criterion explains why the revalorization of cow manure does not have the expected impact on the environmental performance of the artisan cow milk dairy products. Regardless of being one of the farms that increased the most the production of revalorized manure,

In comparison to cows, sheep and goats produce less raw milk (0.6 and 0.71 kg/head·day respectively), weight less (119 and 35 kg/head respectively) and also produce less manure than cows; reason why the economic allocation criteria has a different effect on the sheep and goat revalorized manure at the farm gate. Nonetheless, the important impact of the manure revalorization over the environmental performance of the goat milk cheese is mainly attributed to its relevant manure revalorization share from 3% to 79%. Whereas for the case of the sheep milk dairy products, the effect of reaching the optimum manure revalorization is less since this farm's baseline revalorized manure was very near to its optimum.

Despite the existence of different managed manure application methods such as broadcast spreading, band spreading or soil injection, it is not possible to account the emissions arising from them with the current methodologies. Therefore, determine the impact of using different application techniques on the environmental performance of the assessed artisan dairy products was not possible. Moreover, the current methodologies do not consider soil properties or climate conditions; which are known as relevant parameters that affect the manure application emissions. Due to these lacks on the methodologies, it was not possible to assess nor suggest better manure application practices in the dairy

Diet quality improvement

The livestock diet quality is defined, among other parameters, by the feed digestibility energy ratio (DE) which defines the portion of the feed's gross energy that is digested and is not excreted by the livestock. Thus, a livestock diet with a high DE implies that the livestock will mostly digest the ingested feed, up-take most of the nutrients and it will excrete less manure with a better-quality; while a low DE would have the opposite effect.

Currently the assessed artisan dairy systems report DE ratios of 72.5% for cows and 60% for sheep and goats since they are fed with good pastures, good preserved forages and grain supplemented diets. However, under these feeding conditions the cows, sheep and goats could reach DE ratios up to 75% depending on the diet combinations; and up to 85% if their diet is fully switch to a grain and concentrated based diet (IPCC, 2006a).

To explore the benefits of higher DE ratios on the environmental performance of the assessed artisan dairy products, a DE ratio of 75% has been assumed for all the livestock types since this is the IPCC maximum DE value for the type of diet that the animals have in the assessed systems. The outcomes of improving the feed DE ratio over the assessed artisan dairy products are presented in Table 5.12.

Table 5.12: General baseline variations of the characterized impact scores and the Environmental Single Score (ESS) results of the produced cheeses and yogurts with different types of milk when the feed DE ratio increases to 75% for all the livestock typed.

Impact category	**Baseline variations**				
	Cheese			**Yoghurt**	
	Cow milk	**Sheep milk**	**Goat milk**	**Cow milk**	**Sheep milk**
GWP	-2.9%	-24.5%	-20.8%	-2.7%	-22.7%
ODP	0.0%	0.0%	0.0%	0.0%	0.0%
FETP	-1.3%	-6.0%	-2.9%	-1.3%	-6.0%
HTP-C	-1.0%	-3.7%	-1.8%	-0.9%	-3.7%
HTP-NC	-3.0%	-8.0%	-7.0%	-3.0%	-8.0%
PMFP	0.0%	0.0%	0.0%	0.0%	0.0%
IRP	0.0%	0.0%	0.0%	0.0%	0.0%
POCP	-2.0%	-24.2%	-26.6%	-1.8%	-23.0%
AP	0.0%	0.0%	0.0%	0.0%	0.0%
T-EP	0.0%	0.0%	0.0%	0.0%	0.0%
F-EP	0.0%	0.0%	0.0%	0.0%	0.0%
M-EP	0.0%	0.0%	0.0%	0.0%	0.0%
LU	0.0%	0.0%	0.0%	0.0%	0.0%
W-RD	0.0%	0.0%	0.0%	0.0%	0.0%
MM-RD	0.0%	0.0%	0.0%	0.0%	0.0%
F-RD	0.0%	0.0%	0.0%	0.0%	0.0%
ESS	-0.6%	-9.2%	-2.7%	-0.5%	-9.0%

DE is a key parameter input in the used emission models to determine the livestock enteric fermentation CH_4 emissions (IPCC, 2006a) and manure related CH_4, NMVOC and heavy metals emissions during its management and application (EMEP/EEA, 2016a; Freiermuth, 2006; IPCC, 2006a). Therefore, the 2.5% DE improvement for cows and 15% for sheep and goats avoided the release of CH_4, NMVOC and heavy metals related emissions and reduced the outcomes of their related impact categories (GWP, FETP, HTP-C, HTP-NC and POCP).

Since the GWP outcome has more relevance on the sheep milk dairy products environmental performance than for the goat milk products, the sheep products' environmental performance improved more than the goat milk products. For instance, despite presenting similar GWP reductions, the cheese milk environmental performance improved more than the environmental performance of the goat milk cheese. The environmental performance of the cow milk dairy products improved the least since the DE quality ratio enhancement does not influences its most relevant impact category (W-RD).

In reality, the feeding DE ratio also influences the livestock excreted Nitrogen (N_{ex}) from which the IPCC determines the manure related N emissions. Therefore, the N related impact categories should also improve when enhancing the DE ratio of the animals feed. However, since the use of the IPCC Tier 1 approach to calculate N_{ex} is not mandatory by the PEFCR-D, the DE influence over the N_{ex} and the N emissions cannot be accounted despite its existence. Future versions of the PEFCR-D should strongly suggest the use of the Tier 2 approach to calculate N_{ex} since the optimisation of the DE ratio would lead to specially avoid N_2O emissions which have the highest GWP characterisation factor among GHG.

Due to the relevance of the GWP impact on the environmental performance of dairy products, the use of the IPCC N_{ex} Tier 2 approach is likely to have more impact towards improving it. Moreover, it would lead to a better representation of the feeding related improvements in the dairy farm and could encourage the PEFCR-D application among dairy producers.

Change on the maize supplier for animal feeding

Overall baseline results showed that W-RD contributes the most to the environmental performance of raw cow's milk, and thus to cow dairy products. At a dairy farm level W-RD mainly attributed to the high consumption of Spanish maize for animal feeding purposes. A ~ 98% of the cow milk W-RD impact score is attributed to this feed. Thus, a more competitive W-RD performance for the production of maize should be achieved through the identification of a more W-RD efficient supplier if possible.

As previously discussed, the WR-D impact scores depend on the regionalized AWARE characterization factors which varies depending of the location (country or region) from where the water is withdrawal. However, since these country-scale factors group and represent many different water basins within a country, they have high uncertainty. For this reason, subnational AWARE factors are available for cases where the practitioner has access to more detailed spatial information for the country, such as the state, province, or department from which the water is drawn (Boulay and Lenoir, 2019).

To model the environmental impact of the Spanish maize production, a PEF compliant dataset was used (UUID: 3adaeb2b-3605-4e19-a873-7062e4d8e2e8) which is a weighted average of the environmental burdens generated attributed to the production of maize in all the Spanish regions through different methods (irrigated or dry). The dataset only uses the country-scale Spanish AWARE factor (77.7 $m^3_{world\ eq}/m^3$) to determine the W-RD impact of the consumed Spanish water which contributes ~99.6% the datasets W-RD score . The following paragraphs will explore the effect of purchasing maize from specific Spanish states on the W-RD score, so artisan farms can identify maize suppliers in the Spanish states with the most efficient W-RD scores to improve their artisan dairy products environmental performance.

According to the Spanish Ministry of Agriculture, Fisheries and Food (MAPA, 2019a) around 93% of the total Spanish maize is produced in irrigated conditions thus, the dataset's Spanish water consumed to produce maize is more representative for this maize production conditions; and therefore, the datasets amount of Spanish water consumed (0.407 m^3/kg maize) will not be change for this analysis.

As shown in Table 5.13, the Castilla y Leon, Extremadura and Castilla y la Mancha Spanish states account for around 47% of the total Spanish maize production and provide a more competitive W-RD scores than the Spanish dataset per kg of maize produced due to their low subnational AWARE factors.

Table 5.13: Water Resource Depletion (W-RD) outcome per kg of produced maize for different Spanish states and its variation in comparation to the PEF Spanish maize production dataset

Spanish State Name	**Maize production share[a] (%)**	**AWARE factor[b] ($m^3_{\text{world eq}}/m^3$)**	**W-RD**	
			($m^3_{\text{world eq}}$)	**(Δ%)***
Andalucía	4.5	93.55	38.13	20.40
Aragón	25.0	88.98	36.27	14.52
Castilla y la mancha	5.5	63.93	26.06	-17.72
Castilla y león	28.3	67.69	27.59	-12.88
Cataluña	11.4	80.86	32.96	4.07
Extremadura	13.6	48.37	19.72	-37.75
La rioja	0.1	88.93	36.25	14.45
Navarra	4.1	-	-	-
País Vasco	0.1	70.05	28.55	-9.85
Others	7.5	-	-	-

[a] (MAPA, 2019b)

[b] Boulay and Lenoir, 2019

*variation in comparation to the Spanish maize production dataset W-RD score (31.67 $m^3_{\text{world eq}}$)

Thus, the assessed artisan dairy systems should identify maize producers from Castilla y Leon, Extremadura and Castilla y la Mancha; and buy the required maize from them. This specific purchase would improve the W-RD scores and the environmental performance of their artisan dairy products as presented in Table 5.14.

Table 5.14: General baseline variations of the Water Resource Depletion (W-RD) scores and the Environmental Single Score (ESS) results of the produced cheeses and yogurts with different types of milk if the maize is produced in different Spanish states.

Spanish state	**Impact category / Environmental single score**	**Baseline variations**		
		Cheese		**Yoghurt**
		Cow milk	**Goat milk**	**Cow milk**
Castilla y la mancha	W-RD	-16.3%	-16.8%	-27.5%
	ESS	-5.7%	-1.9%	-9.5%
Castilla y león	W-RD	-11.9%	-12.3%	-20.1%
	ESS	-4.1%	-1.4%	-7.0%
Extremadura	W-RD	-34.5%	-61.5%	-58.1%
	ESS	-12.0%	67.9%	-20.2%

However, when taking the decision of chaining maize suppliers, the impact of transporting the maize to the dairy farm shall be considered since it could significantly increase the GWP results of the dairy products and thus, affect the environmental performance of the dairy products due to its high weighting factor (22.19%). A sensitivity analysis of the maize transport on the dairy products environmental performance should be done.

Moreover, for the dairy farms that are located next to the Spanish borders, it could be possible to acquired maize produced in France or Portugal instead of purchasing from Castilla y Leon, Extremadura or Castilla y la Mancha. Which would affect all the assessed environmental impacts, including W-RD, and; therefore, generate a greater impact on the environmental performance for their products. For instance, if the dairy systems would be located in the Spanish state of País Vasco, major improves to their dairy products environmental performance would be obtained (Table 5.15) since French maize could be purchased not so far from the border.

The results presented in Table 5.15 were modelled using the PEF compliant dataset for French maize production (UUID: 934f83a1-94dc-47a4-b5f6-da934dc2ef4e).

Table 5.15: General baseline variations of the characterized impact scores and the Environmental Single Score (ESS) results of the produced cheeses and yogurts with different types of milk if the artisan dairy systems would be located in the País Vasco Spanish state and the maize purchased in France.

Impact category	Baseline scenarios		
	Cheese		Yoghurt
	Cow milk	Goat milk	Cow milk
GWP	1.9%	0.8%	1.8%
ODP	-4.3%	-1.6%	-4.2%
FETP	144.4%	12.3%	143.1%
HTP-C	12.7%	0.6%	12.0%
HTP-NC	4.8%	0.5%	4.8%
PMFP	1.5%	0.3%	1.5%
IRP	4.8%	18.7%	5.0%
POCP	3.8%	1.2%	3.5%
AP	1.2%	0.2%	1.1%
T-EP	0.9%	0.2%	0.9%
F-EP	-38.4%	-8.5%	-36.7%
M-EP	-5.8%	-1.2%	-5.7%
LU	13.3%	0.4%	13.3%
W-RD	-77.9%	-80.2%	-78.4%
MM-RD	2.2%	1.8%	2.3%
F-RD	3.1%	9.7%	2.8%
ESS	-25.6%	-6.7%	-25.0%

5.2.3.2 Dairy processing facility improvements

At the dairy processing facility, the decision-maker has control over two clear areas of improvements: the facilities' energy consumption and the facilities' waste generation.

Energy improvements

Currently the assessed artisanal dairy systems main energy sources are electricity obtained from the mixed national network and diesel. Electricity is consumed in the processing facility to power processing equipment and to control the temperature in the cooling and storage areas; whereas diesel is consumed to heat-up the curding baths for cheese production and to power other combustion machinery.

As discussed, the consumption of electricity at the processing facility has a key role in the GWP, ODP, IRP MM-RD, F-RD and ODP impact categories. Thus, the decision-maker could mitigate these impacts by switching the source of the consumed energy. To explore this option, it is considered a change in the electricity supplier: from the mixed national network to a national 100% Hydro powered electricity supplier.

Since the assessed dairy systems have only one electricity source, the switch would not only reduce the energy related impacts in the processing facility but also benefit the energy related impacts at the farming stage. Therefore, the switch is an integral improvement for the systems and a straight forward environmental optimisation opportunity that would enhance the environmental performance of the produced artisan dairy products with all three types of raw milk.

As presented in Table 5.16 the use of 100% Hydro powered electricity reduces the characterized sores of almost all the assessed impact categories. As expected, the greatest reductions are for the ODP, IRP and F-RD impact categories while, due to the specific characteristic of this electricity production system the W-RD increased.

Table 5.16: General baseline variations of the characterized impact scores and the Environmental Single Score (ESS) of the artisan cheeses and yoghurts if 100% Hydro powered electricity is used.

Impact category	**Baseline variations**				
	Cheese			**Yoghurt**	
	Cow milk	**Sheep milk**	**Goat milk**	**Cow milk**	**Sheep milk**
GWP	-30.44%	-5.77%	-2.46%	-25.90%	-2.23%
ODP	-27.59%	-9.68%	-1.86%	-24.31%	-5.79%
FETP	-0.91%	-0.13%	-0.03%	-0.82%	-0.09%
HTP-C	-3.09%	-0.39%	-0.11%	-2.63%	-0.28%
HTP-NC	-0.44%	-0.01%	-0.01%	-0.40%	0.00%
PMFP	-7.09%	-3.73%	-0.24%	-6.41%	-1.55%
IRP	-86.78%	-75.23%	-63.20%	-82.26%	-41.53%
POCP	-20.92%	-3.00%	-1.23%	-17.72%	-1.19%
AP	-6.10%	-2.98%	-0.20%	-5.47%	-1.19%
T-EP	-3.36%	-1.54%	-0.11%	-3.01%	-0.61%
F-EP	-0.42%	-0.61%	-0.07%	-0.36%	-0.32%
M-EP	-4.32%	-0.50%	-0.17%	-3.85%	-0.20%
LU	-2.75%	-0.82%	-0.15%	-2.51%	-0.70%
W-RD	22.91%	65.18%	4.43%	21.02%	51.08%
MM-RD	-20.21%	-6.08%	-3.10%	-19.30%	-3.10%
F-RD	-70.04%	-49.57%	-40.57%	-56.75%	-13.76%
ESS	-4.73%	-1.94%	-0.30%	-4.21%	-0.81%

The electricity supplier switch improved the environmental performance of the assessed dairy products in no more than 5% for all the cases. The best environmental performance improvement is for the processed cow milk products (~5% for cheese and ~4% for yoghurt) since the use of hydro powered electricity reduced its GWP scores by ~30% for the cheese and ~26% for the yoghurt. The cheese and yoghurt obtained from sheep milk reported environmental performance improvements of ~2% and ~1% respectively; while the goat milk cheese had improvement of less than 1%.

As presented in the results of these thesis, there are many other energy related improvement options that can be implemented towards more energy efficient dairy systems. These improvements were identified after executing energy audits to nine different small dairy systems and later suggested to each of them by taking as basis their energy efficiency, environmental and economic benefits. Moreover, for each of the systems energy related baseline Key Performance Indicators (KPI) were obtained.

Therefore, if the KPIs of the artisan dairy systems that are now being analysed (Table 5.17) are similar to the KPIs of the systems analysed as part of this thesis results, the artisan dairy systems could evaluate the implementation of the previously proposed energy efficiency improvements.

Table 5.17: Energy and production parameters and Key Performance Indicators (KPI) for the assessed artisan cow, sheep and goat dairy systems.

Livestock		**Consumed energy (GWh)**				**Processed raw milk (tons)**	**Production (tons)**	**KPI**	
Type	**Heads**	**Electricity**	**Diesel**	**Natural Gas**	**Total**			**kWh/kg processed raw milk**	**kWh/kg product**
Cow	90	235.24	63.36	-	298.60	115.10	44.76	2.59	6.67
Sheep	359	12.40	7.63	2.00	22.03	42.57	8.60	0.52	2.56
Goat	117	2.59	0.53	-	3.13	14.69	1.58	0.21	1.98

The KPI used for this collation is the electricity consumption and processed raw milk KPI ($KPI_{Energy/kgPRM}$) since the amount of processed raw milk is a common and indispensable input for dairy systems despite its size; and because most of the energy in the systems is used to transform raw milk to a final dairy product. Most of the raw milk processed by the artisan dairy systems is to produces cheese (77% for cow cheese, 95% for sheep cheese and 100% for goat cheese) hence, their KPIs are only compared between systems that produce cheese regardless the type of raw milk. This excludes the yoghurt, pasteurized milk and ice-cream systems analysed in this thesis results.

The $KPI_{Energy/kgPRM}$ collation process shows that the cow milk artisanal dairy system is more likely to improve its energy efficiency by replacing fluorescent and halogen lamps with LED lamps and by implementing an energy management or a consumption monitoring system. However, since this artisanal system processes more raw milk and thus, produces more dairy products than the system (DF1) for which these improvements were originally suggested in this thesis results, it is possible that implementing a solar photovoltaic installation or a solar thermal installation to produce electricity and hot-water is feasible. Thus, the decision-maker shall further assess the implementation of these improvements in the cow milk artisanal system since they have proven to reduce energy related costs and emissions.

Based on this thesis results, the best option to improve the energy efficiency of the sheep artisanal dairy system is the implementation of an energy management or a consumption monitoring system. However, similarly to the cow milk system, the sheep milk dairy system also processes more raw milk and produce more final dairy products than the system (DF9) for which this improvement was originally suggested.

Therefore, the replacement of the natural gas or diesel combustion boiler for a biomass boiler is likely to be a feasible improvement since the sheep milk dairy system could be capable to cover the investing costs and enjoy its benefits.

The goat milk tractional dairy system processes less raw milk and produces even less cheeses than the system (DF9) to which its $\mathrm{KPI}_{\mathrm{Energy/kgPRM}}$ is being related in this thesis results. Thus, the implementation of other improvements than an energy management or a consumption monitoring system could be not possible due to the high investment cots. However, if it is the case, the possibility of using LED lamps instead of fluorescent and halogen lamps shall be explored by the decision-maker since implementing this improvement requires the least amount of investment.

Cheese whey management

All the assessed artisanal dairy systems produce cheese and inevitably generate cheese whey. The following paragraphs present and discuss the implications of managing the cheese whey inside or outside of the systems as a waste or coproduct.

- **Cheese whey management inside of the system**

When managed inside of the system as waste, the cheese whey could be used as livestock feed, as natural fertilizer, as fuel for an anaerobic digestor (AD) or even, directly mixed with the slurry tank content. Whichever the case, the cheese whey DM allocated impacts will remain in the system boundaries and will be affecting the cheeses' environmental performance.

Nonetheless, it could be argued that using the waste cheese whey in the systems boundaries for livestock feeding and soil fertilizing purposes benefits the artisanal dairy systems since these practices promote a circular economy model. This argument is valid at some extent from a circular economy perspective because the cheese whey will pass from being considered a waste to be considered a nutrient supply for crops and animals; and thus, it helps to close the dairy systems' waste and nutrient loops and enhance their circularity performance.

However, as shown in the results of this thesis, if the decision-maker decides to keep the cheese whey in the systems boundaries, more benefits will be obtained from an environmental and circular economy perspective by using it as a feeding input for AD.

An AD would not only assist on closing the systems' waste and nutrients loops but it would also allow to close the energy loop and bring environmental credits to the artisanal systems. The biogas produced by the AD will avoid the consumption of natural gas and electricity from the network and the AD digestate will avoid the use of mineral fertilizers to produce crops or animal feed. Nonetheless, a further assessment shall be done to define the environmental and circularity benefits of strictly using the cheese whey as a livestock dietary complement.

According to Mostafa Imeni et al. (2019) an AD would be an economically viable heat & power recovery process for dairy systems with a minimum of 126 cow heads, 7512 sheep heads or 1054 goat heads. Thus, despite its circular economy and environmental benefits, implementing an AD on artisanal dairy systems seems to be not economically feasible due to its livestock herds sizes (Table 5.17).

Another option is to manage the cheese whey inside of the system to produce revalorized finished products such as ricotta cheese or whey protein powder; which could be later offered in the market. Through the on-site revalorisation of the cheese whey, its DM content will now be part of a new individual product and will improve the environmental performance of the produced cheeses.

Moreover, it will help to the circular economy performance of the artisan systems since it will pass from being a waste to be an ingredient; and also, would bring economic benefits since the cheese whey products can be offered to the market. Therefore, this practice could have a greater impact on the process of reaching more sustainable dairy systems.

Currently, over 50% of the cheese whey produced by the sheep and goat systems is managed inside the system as waste and used to feed livestock and as fertilizers. The other reaming sheep and goat cheese whey shares and the total of the cow cheese whey are managed out of the system. The cow cheese whey is fully managed outside the system as a coproduct (Table 5.18).

Table 5.18: Total cow, sheep and goat cheese whey production and its respective shares managed inside and outside the artisan dairy systems as waste or finished product/coproduct.

Total cheese whey production		**Inside management**			**Outside management**	
Milk type	**Amount (m³/y)**	**Waste**		**Finished product**	**Waste**	**Coproduct**
		Feeding	**Fertilization**			**Input to external system**
Cow	55.37	0%	0%	0%	0%	100%
Sheep	34.02	37%	20%	0%	0%	43%
Goat	8.26	80%	0%	0%	0%	20%

As shown in Table 5.19, considerable improvements on the environmental performance of the sheep and goat cheeses could be obtained if these artisan dairy systems decide to fully mange the produced cheese whey inside the system to produce revalorized finished products. The environmental performance of the sheep and goat cheeses improved around 20% and 30% respectively. The improvements are coherent with the amount of DM exiting the processing facility as sheep (23% of the total processed DM) and goat (31% the total processed DM) cheese whey and that is now part of the new revalorized products.

The cow cheese results in Table 5.19 do not show any environmental improvements since the current outside management has already improved the cow cheese performance to its maximum. However, on contrary to an outside management, the inside cheese whey management to produce a finished product would enhance the system's economic benefits and circular economy performance. A further discussion will be done in the following outside management section.

Nonetheless, a more specific analysis should be done to determine, the net economic impact of fully revalorizing the cheese whey inside the artisan dairy systems. For instance, a Life Cycle Costing Assessment together with a marketing assessment could provide economic specific outcomes of the benefits and feasibility of revalorizing the cheese whey inside the artisan dairy systems.

Table 5.19: General baseline variations of the characterized impact scores and the Environmental Single Score (ESS) results of the cheeses produced with sheep and goat milk when their respective cheese whey production is manged inside the system and revalorized as finished product.

Impact category	Baseline variations		
	Cow milk cheese	Sheep milk cheese	Goat milk cheese
GWP	0.0%	-19.6%	-28.9%
ODP	0.0%	-14.4%	-30.0%
FETP	0.0%	-19.9%	-29.3%
HTP-C	0.0%	-19.8%	-29.2%
HTP-NC	0.0%	-19.9%	-29.2%
PMFP	0.0%	-19.9%	-29.2%
IRP	0.0%	-19.3%	-26.8%
POCP	0.0%	-19.8%	-29.0%
AP	0.0%	-19.8%	-29.1%
T-EP	0.0%	-19.8%	-29.2%
F-EP	0.0%	-19.6%	-29.1%
M-EP	0.0%	-20.0%	-29.1%
LU	0.0%	-19.9%	-29.2%
W-RD	0.0%	-22.2%	-29.2%
MM-RD	0.0%	-19.0%	-27.9%
F-RD	0.0%	-17.9%	-25.5%
ESS	0.0%	-19.8%	-29.1%

- **Cheese whey management outside of the system**

When managed outside of the system as waste, the cheese whey would be sent to a waste management plant; thus, the cheese whey production and waste management impacts would be assigned to the determinant product (cheese) affecting its environmental performance; and additionally, this option will not generate any economic benefit to the artisan dairy system. In fact, the outside management of the produced cheese whey as waste is very likely to generate extra costs to the artisan dairy systems; therefore, it should be avoided.

However, when managed as a coproduct outside of the system, it would be become an input to other production systems. The outside management of the cheese whey as coproduct would improve the environmental performance of the artisan cheeses since the cheese whey environmental burdens will be assigned to the coproduct (raw cheese whey). Nonetheless, this practice would not bring a substantial economic benefit to the artisan dairy producers and would neither improve their systems circular economy performance.

For instance, the assessed artisan cow dairy system already manages all its produced cheese whey outside the system as a nutrient input for other agricultural system. Reason why, the cow milk cheese environmental performance has already improved to its maximum and thus, it does not present any improvements when managing it inside the system (Table 5.19). However, this practice does not generate a substantial economic benefit for the cow milk system since the revenue that could be obtained from the raw cheese whey is very marginal in comparation to the economic benefits of a revalorized finished product. In fact, some artisan dairy systems give away the cheese whey free to other systems as a raw material or nutrient.

The outside management of the cheese whey is a tempting option for artisan dairy producers due to its simplicity. However, doing it without a competitive economic benefit should be avoided since it will be overlooking the economic sustainability of the artisan dairy products and affecting its overall sustainability.

5.3 Ecolabeling and environmental declarations using CalcPEF$_{\text{Dairy}}$ Tool.

This section presents the experience of the externally verifying the CalcPEF$_{\text{Dairy}}$ v1.0. tool compliance with the Product Environmental Footprint Category Rules for Dairy Products (PEFCR-D) Version 1.0 (EDA, 2018). And also, the experience of using it in an external verification process to determine the Carbon Footprint (ISO 14067, 2018) and Product Environmental Footprint (EDA, 2018) for the market available *Ermesenda cheese* produced by Formatgeria Mas D'Eroles

As result of these verifications processes, the external audit party (DNV GL Business Assurance España S.L.U.) issued a PEFCR-D conformity declaration for the CalcPEF$_{\text{Dairy}}$ v1.0. tool (Annex D). While, for the Ermesenda cheese, , the audit party issued a Carbon Footprint (ISO 14067, 2018) and PEF conformity declaration; and granted the use of a carbon footprint verification label (ISO 14025, 2010) for the product.

The verifications were carried out as part of this thesis and in the "CalcPEF$_{Dairy}$ Demonstrative Project" financed by the Catalan Government and European Agricultural Fund for Rural Development. Information regarding the verification processes experience is presented below. However, due to the confidentiality clauses of the study, some sensitive data is not disclosed.

5.3.1 CalcPEFDairy v1.0. Tool verification process

The CalcPEF$_{Dairy}$ tool started to be developed in 2017 in the framework of this thesis as part of the INNOTRANSLACT project financed by EU through the Interreg POCTEFA call and in the framework of the OPTIMISM project co-financed by the Catalan Government and the EU H2020 research and innovation funds. In march 2020, after a six-month process, the CalcPEFDairy v1.0. Tool compliance with the PEFCR-D was verified and a conformity declaration (Annex D).was issued by the auditors (DNV-GL)

The objective of this verification was to generate an independent professional judgement about the information and data contained on the CalcPEF$_{Dairy}$ tool against the data and requirements stated in the following references.

- Product Environmental Footprint Category Rules for Dairy Products (PEFCR-D) Version 1.0.
- Product Environmental Footprint Category Rules Guidance Version 6.3 – May 2018 - Chapter 8 Verification and validation of EF studies, reports, and communication vehicles.
- ISO/TS 14071:2014 (Environmental Management – Life Cycle Assessment – Critical review processes and reviewer competencies)

5.3.1.1 Methodology of the verification process and outcomes

The verification process was carried out in two stages. The first stage was carried out at the offices of DNV-GL; where a documentary review of specific guidelines and standards that CalcPEF$_{Dairy}$ follows was done. Once the review was completed, DNV-GL used and explored the tool features to contrast the tool's functionality and performance with the reviewed literature. DNV-GL also assessed the tool from user experience perspective. As result of this first verification stage DNV-GL reported a series of preliminary findings to the developers.

The developers assessed the findings and made the respective improvements or changes in the tool. Once all the preliminary findings were overcome, DNV-GL visited the BETA TC installations in Vic (Catalonia-Spain) where CalcPEF$_{Dairy}$ was developed and the second verification stage started.

At the second verification stage, the developers disclosed all the tool's technical and coding aspects; and DNV-GL collated the tool's coding scripts with the previously reviews guidelines and standards. DNV-GL also interviewed the tool's developers regarding the developing process.

Then, the tool's performance and application were verified and validated by DNV-GL on a real case study. The Ermesenda cheese produced by the Formageria Mas D'Eroles was selected as case study for these purposes; and a field visit to case study installations was done.

On field, the case study model and LCI data was verified; and later, added in the CalcPEF$_{\text{Dairy}}$ tool. Then, the audit party verified transition of the LCI data into LCIA characterized results for a sample of data flows. At the end of the field visit, the audit team summited a consolidated final list of findings to the developers. Finally, once all the findings were overcome by the developers and reviewed by DNV-GL a verified CalcPEF$_{\text{Dairy}}$ tool v1.0 was consolidated.

During the verification process, DNV-GL did not find evidence to suppose that the CalcPEF$_{\text{Dairy}}$ v1.0 tool developed by BETA TC of the University of Vic- Central university of Catalunya, does not meet the requirements indicated in the scope of verification, according to Product Environmental Footprint Category Rules for Dairy Products Version 1.0. Thus, a conformity declaration for the CalcPEF$_{\text{Dairy}}$ v1.0. tool was issued (Annex D).

5.3.2 Ermesenda cheese verification process

The Ermesenda cheese is produced by Formageria Mas D'Eroles; an artisan cheese producer facility located in Adrall Alt Urgell – Catalunya (Spain) that started its operations in 2001. The Ermesenda cheese was selected for the verification since it is the best-selling cheese for Mas D'Eroles. In 2019, the Ermesenda cheese represented 40% in weight of the total sales.

Figure 5.6: Site visit to Formageria Mas D'Eroles: Salvador Maura (Manager, left) and Daniel Egas (BETA TC team and author of this thesis, right)

5.3.2.1 Description of production process

The first stage considered in the Ermesenda production cycle is the transport and reception of the raw milk since Mas D'Eroles does not produces raw milk on-site (Figure 5.7).

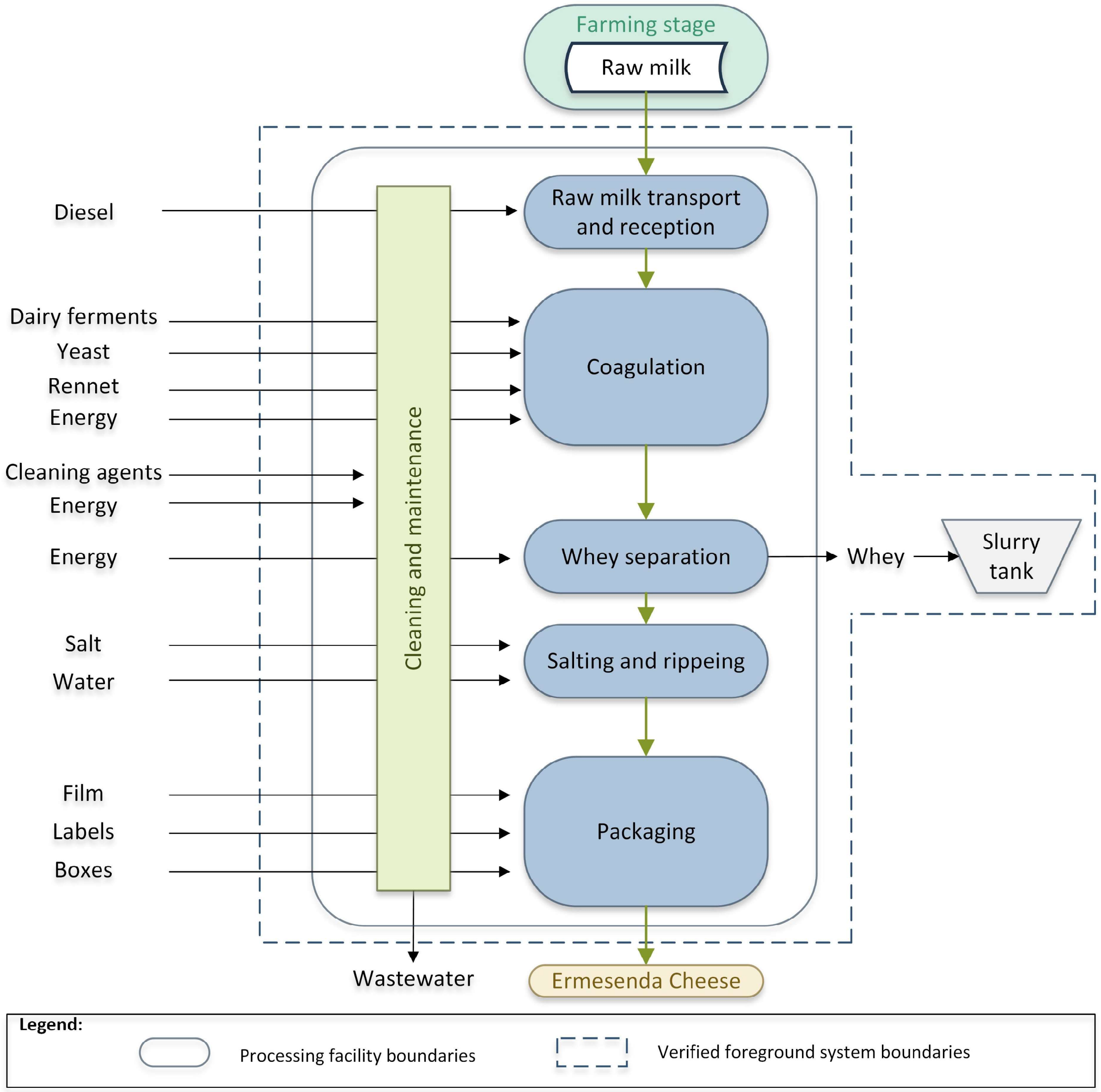


Figure 5.7: Process diagram for Ermesenda cheese: Processing facility and verified foreground system boundaries

The production of raw milk (farming stage) is carried out in an ecologically certified livestock farm, located 9 km from cheese processing facility. The raw milk is collected in the farm right after being milked and it is not refrigerated during transport therefore, it is still warm when arrives to the processing facility and subsequent heating to reach the working temperature (~33 °C) is not often required. This collection characteristics are possible given the proximity between the farm and the processing facility; and also, because the raw milk is collected and processed on a daily basis.

Figure 5.8: Raw milk collection at the dairy farm

To produce 1 kg of Ermesenda cheese, an average of 8.84 L of cow's milk must be processed. A total of 500 L of Milk are collected daily in a container trailer with a capacity of 1000 L, coupled to a van. Once the milk is in the processing facility, it is pumped into a 500 L capacity heated tank. This thermal energy is obtained from diesel combustion in a boiler.

Figure 5.9: Raw milk reception and pumping process from the container trailer to the heated tank.

After pumping the raw milk in the tank, the ferments (15 g / 500 L of milk) and the yeast (3 g / 500 L of milk) are added. At this point, a temperature control of the raw milk is carried out since it shall be in a working temperature of around 33 °C before starting the coagulation process to obtain the cheese curds. Occasionally, in the winter months, the raw milk is heated until reaching the desired working temperature.

Once the milk reaches the desired working temperature, the rennet is added at a ratio of 25 ml / 100 L of milk and the coagulation process that takes around 45 minutes starts. After this time, the cheese curd and whey are obtained, and the cutting process is carried out with blades coupled to two mixers on the top of the heated tank. The cutting process takes around 10 minutes and from, it medium to small sized curds are obtained. While this occurs, the cheese whey is mixed and heated together with the curd grains until reaching 38 ° C to promote the separation of the curd and before draining.

Figure 5.10: Raw milk coagulation process: Heated tank with the two mixers on its top for cutting

The draining step separates the cheese whey from the curt and it is mostly done in the tank; for every 500 L of milk an average of 450 L of whey are produced.

Figure 5.11: Draining process: separation of cheese whey and the Ermesenda cheese curds

After the draining, the cheese curd grains are placed in cheese sifter moulds so the remaining whey can drain by tumbling for 20 minutes. At the end of this step, the cheese dough is pressed for 4 to 5 hours. A progressive pressing is carried out, increasing the pressure to a maximum of 2 bars.

Figure 5.12: Cheese Moulding process: the Ermesenda cheese curds are placed in moulds

Figure 5.13: Cheese pressing process: Moulds with curds in the pressing machine

Once the pressed cheese is obtained, the salting step starts to help the formation of the cheese crust. The pressed cheeses are left in the salting tank for 24 hours and from there they pass to the airing room where they stay for 4 days.

Figure 5.14: Salting process: Salting bath where the Ermesenda cheese wheels are submerged

Upon entering the ripening chamber, a first cheese wash is carried out with a solution of water and salt. The cheeses are washed with this solution once a week for 4 weeks, after which the washing is carried out at intervals of 15 days. The cheeses remain in the ripening room for a total of 45 days at 11 °C.

Figure 5.15: Ripening process: Ripening chamber where the Ermesenda cheese wheels are placed

After completing its time in the ripening room, the Ermesenda cheese is labelled, packaged, and it is finally ready to be sent to the consumer.

Figure 5.16: Ermesenda cheese labelling and packaging area.

Figure 5.17: Ermesenda Cheese(final product for sale)

5.3.2.2 Verification objective

The verification was carried out by DNV-GL and its objective was to assess the degree of conformity, implementation and effectiveness of the Carbon Footprint and Product Environmental Footprint guidelines for the environmental assessment of the Ermesenda cheese production in 2019. Thus, the verification process contrasted the calculation procedures and results against the requirements established in the following reference standards:

- ISO 14067: 2018 "Greenhouse gases - Carbon footprint of products —Requirements and guidelines for quantification"
- Product Environmental Footprint Category Rules for Dairy Products (PEFCR-D) Version 1.0.
- Product Environmental Footprint Category Rules Guidance Version 6.3 – May 2018 - Chapter 8 Verification and validation of EF studies, reports, and communication vehicles.

5.3.2.3 Methodology of the verification process

The verification methodology followed by DNV-GL was adapted to the criteria established in ISO 14067:2018 and in the PEFCR-D. The verification process included a prior documentary review and a visit to the cheese processing facility (Formageria Mas D'Eroles), in order to verify:

- The limits chosen for the functional unit.
- Data management system and data collection process for the period considered in the verification (year 2019)
- Validity and adequacy of the applied data sources (primary and secondary data, as well as databases)
- The calculation process itself based on the data collected and by using the CalcPEF$_{\text{Dairy}}$v1.0 tool developed as part of this thesis.
- The data management system for monitoring the system and the presentation of evidence of improvement and environmental performance
- Contrast the modelled system with the real processing system

Temporality

The verification was carried out for the production of Ermesenda cheese of the year 2019 (from January 1st to December 31st).

Functional unit and reference flow

The Carbon Footprint and PEF results were verified for the functional unit (FU) defined as: *10g DM of packaged Ermesenda cheese consumed at home as final product without cooking or further transformation.*

The product is presented to the consumer as a piece of wheel-type cheese (Figure 5.18), 25 cm in diameter and 2.8 kg in weight, packaged and labelled, with a preferred consumption period of no more than 6 months after the cheese was shipped.

Figure 5.18: Ermesenda wheel-type cheese

The reference flow is 1 kg of Ermesenda cheese. Therefore, the quantitative results obtained for the verification process are calculated in relation to 1 kg of Ermesenda cheese and will later be transformed to the FU (10 gDM) by means of the dry matter content of each product made in the cheese processing facility.

Verified system boundaries

The Ermesenda cheese production system (from cradle-to-grave) was modelled in the CalcPEF$_{\text{Dairy}}$ v1.0 Tool and thus, the model inputs and outcomes were verified on-site by DNV-GL. The cheese processing activities presented in Table 5.20 along with the cheese whey storage were considered and modelled as foreground system since the decision-maker has control over them. While, the activities that are part of the remaining upstream and downstream life-cycle stages are modelled as background systems by using PEF compliant datasets because the decision-maker has no control over them.

Table 5.20: Ermesenda cheese processing activities

Processing phase	**Included activities**
Raw milk transport and reception	- Farm to processing facility transport - Reception and pumping
Coagulation	- Use of yeast and dairy ferments - Heating and stirring - Curd production
Whey separation	- Cutting - Filtering - Pressing
Salting and ripening	- Brine bath - Ripening in a small chamber - Ripening in a big chamber - Periodic cheese washing
Cleaning and maintenance	- Cleaning and maintenance of processing equipment - Cleaning and maintenance of the facility
Packaging	- Packaging

As shown in Figure 5.7, the raw milk production stage is out of the modelled and verified foreground system since Mas D'eroles has no control over its activities and emissions. However, the emissions generated by the cheese whey during its storage period in a slurry tank (belonging to a farm near the cheese factory), are included within the foreground system limits. On the contrary, the emissions resulting from the application of the slurry tank content on the cultivation fields are not included in the system, since this input corresponds to other agricultural production chain. Thus, these emissions are not attributable to the production of Ermesenda cheese.

Verification of the systems' data

The verification of the systems Life Cycle Inventory (LCI) data is a relevant stage in the verification process since it is the basis for determining the assessed systems emissions. First, DNV-GL interviewed the facility manager to know more about the corporate tools used to collect and trace data regarding the consumed supplies. Then, the LCI data (company specific primary data and secondary data) was collated against documented evidences and primary records (invoices, work reports, etc.) that were provided and verified on-site. Finally, the verified LCI data was contrasted with the CalcPEFDairy v1.0 tool inputs to ensure that the data used for Life Cycle Inventory Analysis (LCIA) step reflects the facility's reality.

Verification of the system's emissions

Once the LCI data in the CalcPEFDairy v1.0 tool was verified, the calculation procedures to obtain the system's emissions with the CalcPEF$_{\text{Dairy}}$ v1.0 Tool were assessed. DNV-GL verified the transition of the LCI data into LCIA characterized results for a sample of data flows. During this step, the tool's performance and compliance with the PEFCR-D was assessed in deep as part of its specific verification process (Section 5.3.1).

5.3.2.4 Verification outcomes

Based on the verification process, the audit party has concluded that the emissions reported by FORMATGERIA MAS D'EROLES are a faithful representation of the emissions of the functional unit. Thus, a Carbon Footprint (ISO 14067, 2018) and PEF (EDA, 2018) conformity declaration was issued for the Ermesenda cheese. This declaration reports the total Carbon Footprint score and the PEF environmental single score per FU of ermesenda cheese.

DNV-GL also granted the use of a Carbon Footprint Eco-label (ISO 14025, 2010) for the Ermesenda cheese (Figure 5.19). However, it did not grant the use of a PEF compliant Eco-label since its issue is still not regulated by the EC.

Figure 5.19: Carbon foot print eco-label issued by DNV-GL and labelled Ermesenda cheese

Chapter 6: General conclusions and outlook

6.1 General conclusions

This thesis has developed a new IT tool and used other existing tools and techniques as part of a clear strategy to optimize the environmental sustainability of the dairy industry in compliance with the European Union Product Environmental Footprint (PEF) Methodology.

As part of this work, an approach to solve the mas balance conflict that arises when determining N emissions incompliance with the *Product Environmental Footprint Category Rules* for dairy products (PEFCR-D) was proposed. This N balanced approach showed that implementing the PEFCR-D in a non-balanced system underestimates the N emissions and redistributes the related N emissions between the manure management and manure application farm activities. Which could lead to the formulation of less accurate conclusions; and thus, the incorrect identification of hot-spots and the suggestion of not efficient improvements while executing the optimization strategy.

The proposed optimization strategy involves a continuous five stage environmental optimization process: (i) environmental assessment, (ii) identification and analysis of hot-spots, (iii) suggestion of improvements, (iv) implementation of improvements and (v) environmental communication

To implement the first two optimization stages and as response to the need for specialized IT tools that facilitate the practical implementation of PEF methods together with the LCA methodology, $\mathrm{CalcPEF_{Dairy}}$ tool was developed; and its compliance with the PEFCR-D was verified by an external auditor (DNV-GL). The performance and capabilities of $\mathrm{CalcPEF_{Dairy}}$ were presented in this thesis through the assessment of three average artisan dairy systems and its outcomes were discussed.

In this context the $\mathrm{CalcPEF_{Dairy}}$ was used to model and suggest possible improvement measures for the artisan dairy systems at a farming and processing facility level (third optimization stage). In the dairy farm, the modelled possible measures were enhancement of the manure management techniques, optimal manure application and revalorization and improvement of the feeding quality and its supplier. While, at the processing facility, energy consumption and cheese whey management improvements were modelled.

The modelling outcomes showed that the most efficient environmental performance of the artisan dairy systems and their products could be reached by managing the produced cheese whey inside the system to produce a revalorized finished product. This environmental performance benefits are due to the Dry Matter allocation criterion followed to assign the processing facility environment burdens to the dairy products and coproducts.

Additionally, the revalorisation of the cheese whey inside the artisan systems would help to the circular economy performance of the systems since the cheese whey will pass from being a waste to be an ingredient; and also, it would generate economic benefits because the cheese whey products can be offered to the market. Therefore, this practice could have a greater impact on the process of reaching more sustainable dairy systems.

The CalcPEF$_{\text{Dairy}}$ tool outcomes were proved to be reliable for the environmental assessment of dairy systems and for the identification of hot-spots but, the decision-maker often needs the support of other valid assessment tools or techniques to evaluate in-depth the identified hot-spots and suggest custom-made improvements. Thus, this thesis also explored the use of energy audits and circularity indicators as supporting tools to suggest custom-made improvements for dairy systems as part of the third optimization stage.

The outcomes from energetically auditing nine real dairy systems showed that there are common energy efficient improvements that could be implemented in any other dairy systems as longest they share similar characteristics and Key Performance Indicators. These identified common improvements go from the use of LED technology lamps to the generation of electricity through the installation of a solar photovoltaic plant; and they could generate environmental benefits and an economic return to the facilities for which its implementation is feasible.

While, Material Circularity performance Indicator (MCPI) and the Environmental Circularity Performance Indicator (ECPI) showed that an anaerobic digestor (AD) is capable to close the water, energy and nutrient circular economy loops in a large dairy system since it is an important circular economy solution for the treatment of dairy effluents. Therefore, if the conditions are favourable to implement the process, an AD could be a powerful improvement towards more sustainable for dairy systems.

The outcomes of these supporting tools suggested custom-made improvements for specific hot-spots. This additional information would allow the decision-maker to take a more informed decision regarding the implementation or not of the suggested improvements in the systems; and therefore, complete the fourth optimization stage.

Finally, CalcPEF$_{\text{Dairy}}$ was used to environmental assess the Ermesenda Cheese produced by Formatgeria Mas D'Eroles; and its outcomes passed an external verification process to obtain a PEF and Carbon Footprint conformity declaration (EDA, 2018; ISO 14067, 2018); moreover, the use of a carbon footprint eco-label (ISO 14025, 2010) for the assessed cheese was granted. This real experience showed the practical use of CalcPEF$_{\text{Dairy}}$ and demonstrated that its outcomes are valid to communicate the environmental performance of dairy products (fifth optimization stage).

This thesis has shown that a constant environmental assessment and improvement of dairy systems is possible through the use of specialised tools such as CalcPEFD$_{airy}$, energy audits and circular economy indicators. Which together are capable to identify and propose high impact improvement measures. It has also demonstrated the feasibility of properly communicating the environmental assessment outcomes as a marketing strategy through environmental declarations and eco-labels. Verified green credentials that give dairy producers the real possibility of increase their economic returns without affecting their system and products environmental sustainability. Thus, this thesis has helped on the optimization of the environmental sustainability of the dairy industry.

6.2 Future research needs

CalcPEF$_{\text{Dairy}}$ has proven to be a successful attempt to develop a PEF compliant IT tool for Dairy products; nonetheless, it can always be improved. For instance, a future version will seek to solve the data management limitations that Microsoft Excel imposes as a consequence of being the tool's host. In fact, it is expected that future CalcPEF$_{\text{Dairy}}$ versions use Python as unique data management host instead of the Excel VBA platform; and therefore, make feasible a straight forward implementation of a matrix based LCA calculation approach. These improvements will increase the tools stability and efficiency since CalcPEF$_{\text{Dairy}}$ will have the potential of directly manipulate the data from the EF reference packages without the need of exporting it to SQLite databases and then to excel sheets for its use.

In other hand, there is the need to improve the quantification of the emissions at the farming life-cycle stage in compliance the PEFCR-D since there are still gaps in the emission modelling guidelines. These gaps could jeopardise the final goal of having a verifiable universal "Ecolabel" to report the environmental performance of the dairy products to the different stakeholders and enhance the development of an EU green market.

Currently, the PEFCR-D compliant on-farm emission models are not capable to reflect to the best the reality of the assessed dairy farms and its technology and management improvements. Thus, future research lines shall focus on proposing feasible methodologies to generate custom-made calculation parameters and emission factors.

For instance, since the manure related activities and the livestock feeding have been identified as relevant environmental hot-spots of the dairy farm, the possibility of generating straight forward methodologies to calculate custom-made feed digestibility energy ratios (DE) and N emission factors should be further explored. These custom-made ratios and factors could encourage the continuous improvement of the animal feeding quality and of the manure management and application techniques since the efforts of implementing technological and management improvements will be reflected in a more environmentally efficient and competitive dairy product.

Additionally, future PEFCR-D versions should explore new phosphorus and heavy metals models or improve the existing ones. The current models do not reflect the reality of all the EU countries so, the PEFCR-D should provide more representative parameters and emission factors to estimate P and heavy metal emissions since they directly affect the toxicity related impact categories.

Finally, the uncertainty analysis of the results is part of the sensitivity check in compliance with the ISO 14044:2006; and it has the purpose of understanding the relations between the LCA model inputs and outputs. Currently, the uncertainty of the default calculation parameters and emission factors of the PEFCR-D on-farm emission models is the unknow or very high; for example, the N excretion rates proposed by the IPCC from which all the manure related N emissions are obtained has an uncertainty range of ±50%. Thus, future research should focus on a more in-depth assessment of the effect of the models input uncertainties on calculated emissions and reported impact categories' scores.

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Annexes

Annex - A

A-1: Reviewed literature for raw milk production and dairy processing systems

Table A 1: Reviewed LCA studies of raw milk production systems

Source	Country	Product	Functional Unit	System Boundaries	Assessed environmental impacts
Arsenault et al. (2009)	Canada	Raw milk	liters raw milk	Cradle to farm gate	GWP, AP, LU, EP, EnU, POCP, T-ETP, F-ETP, HTP, ODP, A-RD
Bartl et al. (2011)	Peru	Raw milk	kg ECM, animal, ha	Cradle to farm gate	GWP 20years, AP, EP
Basset-Mens et al. (2009)	New Zealand	Raw milk	kg FPCM, ha	Cradle to farm gate	GWP, AP, LU, EP, EnU
Battini et al. (2014)	Italy	Raw milk	kg FPCM	Cradle to farm gate	GWP, AP, LU, F-EP, M-EP, EnU, PMF, POCP
Bava et al. (2014b)	Italy	Raw milk	kg FPCM, ha	Cradle to farm gate	GWP, AP, LU, EP, EnU
Castanheira et al. (2010)	Portugal	Raw milk	liters raw milk	Cradle to farm gate	GWP, AP, EP, POCP, A-RD
Cederberg and Flysjö, (2004)	Sweden	Raw milk	kg ECM	Cradle to farm gate	A-RD, LU, GWP, AP, EP
Cederberg and Mattsson (2000)	Sweden	Raw milk	kg ECM	Cradle to farm gate	A-RD, LU, GWP, ODP, POCP, AP, EP
Chen and Corson (2014)	France	Raw milk	kg FPCM, ha	Cradle to farm gate	GWP, AP, EP
Guerci et al. (2013a)	Italy	Raw milk	kg ECM	Cradle to farm gate	EnU, LU, GWP, AP, EP
Guerci et al. (2013b)	Denmark, Germany, Italy	Raw milk	kg ECM	Cradle to farm gate	GWP, LUCf, AP, LU, EP, EnU, Biodiversity
Haas et al. (2001)	Germany	Raw milk	tons raw milk	Cradle to farm gate	A-RD, GWP, AP, EP, Biodiversity, animal husbandry
Iribarren et al. (2011)	Spain	Raw milk	liters raw milk	Cradle to farm gate	GWP, AP, LU, EP, EnU
Jan et al. (2012)	Switzerland	Raw milk	-*	Cradle to farm gate	GWP, AP, LU, EP, EnU, T-ETP, F-ETP, M-ETP, HTP
Kristensen et al. (2011)	Denmark	Raw milk	kg ECM	Cradle to farm gate	GWP, LU
Meul et al. (2014b)	Belgium	Raw milk	kg FPCM	Cradle to farm gate	GWP, LUC, AP, LU, EP, EnU
T.T.H. Nguyen et al. (2013a)	France	Raw milk	kg FPCM, live weight	Cradle to farm gate	GWP, LUC, AP, LU, EP, EnU
T.T.H. Nguyen et al. (2013b)	France	Raw milk	kg FPCM	Cradle to farm gate	GWP, LUCf, LU
O'Brien et al. (2012)	Ireland	Raw milk	kg FPCM, ha	Cradle to farm gate	GWP, LUCf, AP, LU, EP, EnU
Penati et al. (2013)	Italy	Raw milk	kg FPCM, ha	Cradle to farm gate	GWP, AP, LU, EP, EnU
Roer et al. (2013)	Norway	Raw milk	kg ECM, carcass	Cradle to farm gate	GWP, AP, LU, F-EP, M-EP, POCP, T-ETP, F-ETP, M-ETP, HTP, ODP, A-RD
Ross et al. (2014)	United Kingdom	Raw milk	kg ECM	Cradle to farm gate	GWP, LU
Sasu-Boakye et al. (2014)	Sweden	Raw milk	kg ECM	Cradle to farm gate	GWP, LUC, LU
Thomassen et al. (2008)	Netherlands	Raw milk	kg FPCM	Cradle to farm gate	A-RD, LU, GWP, AP, EP
Thomassen et al. (2009)	Netherlands	Raw milk	kg FPCM	Cradle to farm gate	GWP, AP, LU, EP, EnU

Table A 1(continued): Reviewed LCA studies of raw milk production systems

Source	Country	Product	Functional Unit	System Boundaries	Assessed environmental impacts
van der Werf et al. (2009b)	France	Raw milk	kg FPCM, ha, €	Cradle to farm gate	GWP, AP, LU, EP, EnU, T-ETP
Yan et al. (2013a)	Ireland	Raw milk	kg ECM	Cradle to farm gate	GWP, AP
Yan et al. (2013b)	Ireland	Raw milk	kg ECM	Cradle to farm gate	GWP, LU
Zehetmeier et al. (2014)	Germany	Raw milk	kg FPCM	Cradle to farm gate	GWP, LU

Environmental Impacts:
Global Warming =GWP, Acidification (undefined) =AP, Terrestrial acidification =T-AP, Organic and inorganic particles =IO-P, Energy use =EnU, Ecotoxicity (undefined) =ETP, Freshwater Ecotoxicity =F-ETP, Marine Ecotoxicity =M-ETP, Terrestrial Ecotoxicity =T-ETP, Eutrophication (not specified) =EP, Freshwater Eutrophication =F-EP, Marine Eutrophication =M-EP, Terrestrial eutrophication =T-EP, Human Toxicity (undefined) =HTP, Human toxicity, cancer =HT-C, Human toxicity, non-cancer =HT-NC, Ionising radiation =IRP, Land use =LU, Land use change =LUC, Ozone depletion =ODP, Particulate matter formation =PMF, Photochemical oxidants formation =POCP, Abiotic resource depletion =A-RD, Mineral resource depletion =M-RD, Fossil resource depletion =F-RD, Mineral, fossil and renewable resource depletion =MFRD, Water resource depletion =W-RD, Toxicity (sum of human-terrestrial-fresh water, and marine toxicity) =TP, Waste produced (W) =W

Table A 2: Reviewed LCA studies of dairy processing systems

Source	Country	Product	Functional Unit	System Boundaries	Assessed environmental impacts
Bacenetti et al. (2018)	Italy	Whey protein concentrate	ton	Cradle to gate	GWP, ODP, PMF, POCP, AP, F-EP, T-EP, M-EP, MFRD
Bava et al.(Bava et al., 2018)	Italy	Cheese (Grana Padano)	kg	Cradle to gate	GWP, ODP, PMF, POCP, T-AP, T-EP, F-EP, M-EP, F-ETP, M-RD, F-RD
Berlin et al. (2008)	Sweden	Milk, cheese and yoghurt	kg	Cradle to grave	GWP, EP, EnU, POCP
Canellada et al. (2018)	Spain	Cheese	kg	Cradle to retail stores	GWP, ODP, T-AP, F-EP, M-EP, HTP, POCP, PMF, T-ETP, F-ETP, M-ETP, IRP, LU, LU, LUC, W-RD, M-RD, F-RD
Dalla Riva et al. (2017)	Italy	Cheese (Mozzarella)	kg	Cradle to grave	GWP, EnU, ODP, LU, T-AP, W-RD, F-EP, M-EP, HTP, ETP, POCP
Dalla Riva et al. (2018)	Italy	Cheese (Asiago PDO)	kg	Farm gate to plant gate	GWP, ODP, T-AP, F-EP, TP, POCP, LU, W-RD, EnU
Depping et al. (2017)	Denmark, Germany, Italy	Milk concentrate and milk powder	kg	Cradle to grave	EnU, GWP, EP, AP
Djekic et al. (2014)	Serbia	Ultra-high temperature (UHT) milk, yoghurt, cream, butter and cheese	kg	Cradle to grave	GWP, AP, EP, ODP, POCP, HTP
Doublet et al. (2013)	Romania	Pasteurised milk, sour cream, natural yoghurt, curd, butter, cream cheese, fresh cheese, soft cheese and semi-soft cheese	kg	Cradle to gate	GWP, EP, AP, HTP, ETP, LU, A-RD, W-RD
Fantin et al. (2012)	Italy	Milk	litre	Cradle to grave	GWP, ODP, POCP, AP, EP, W
Finnegan et al. (2017)	Republic of Ireland	Milk powder and butter	kg	Farm gate to plant gate	GWP, EnU, AP, F-EP, M-EP, W-RD
González-García et al.(2013c)	Portugal	Yoghurt	ton	Cradle to grave	A-RD, AP, EP, GWP, ODP, LU, POCP, EnU
González-García et al.(2013d)	Spain	Cheese (San Simon da Costa)	ton	Cradle to grave	A-RD, AP, EP, GWP, ODP, LU, POCP, EnU
González-García et al. (2013b)	Portugal	Milk	kg ECM	Cradle to gate	A-RD, AP, EP, GWP, ODP, HTP, F-ETP, M-ETP, T-ETP, POCP, EnU
González-García et al. (2013a)	Portugal	Cheese	kg	Cradle to gate	A-RD, AP, EP, GWP, ODP, LU, POCP, EnU
Heller and Keoleian (2011)	USA	Milk	unit of packaged fluid milk	Cradle to grave	A-RD, GWP, ODP, HTP, POCP, AP, EP
Høgaas Eide (2002)	Norway	Milk	kg	Cradle to retail stores	GWP, ODP, AP, EP, POCP, A-RD
Hospido et al. (2003)	Spain	Milk	litre	Cradle to gate	GWP, ODP, HTP, PMF, IRP, POCP, AP, T-EP, F-EP, M-EP, F-ETP, LU, W-RD, A-RD, EnU
Keller et al. (2016)	(-*)	UHT milk, cream, concentrated milk, yoghurt	kg	Cradle to grave	GWP, EnU, W-RD, M-EP, F-EP, POCP, HTP, ETP
Kim et al. (2013)	USA	Cheese (Cheddar and Mozzarela) and whey	ton of dry matter	Cradle to grave	EnU, W-RD, GWP, F-EP, M-EP, POCP, ETP

Table A 2 (continued): Reviewed LCA studies of dairy processing systems

Source	Country	Product	Functional Unit	System Boundaries	Assessed environmental impacts
Kim et al. (2014)	USA	Cheese (Cheddar and Mozzarella)	-	Cradle to grave	GWP, AP
Meneses et al. (2012)	Spain	Milk	litre	Cradle to gate	GWP, ODP, T-AP, F-EP, M-EP, HTP, POCP, PMF, T-ETP, F-ETP, M-ETP, IRP, LU, LUC, W-RD, M-RD, F-RD
Mondello et al. (2018)	Italy	Cheese (Pecorino)	kg	Cradle to grave	HTP-C, IO-P, GWP, ODP, ETP, AP, EP, LU, M-RD
Nigri et al. (2014)	Brazil	Cheese (Minas)	kg	Cradle to gate	EnU, GWP, EP, AP, POCP
Nilsson et al. (2010)	UK, Germany, France	Margarine and butter	kg	Cradle to gate	A-RD, GWP, ODP, HTP, F-ETP, M-ETP, T-ETP, POCP, AP, EP
Palmieri et al. (2017)	Italy	Cheese (Mozzarella)	g	Cradle to gate	HTP-C, HTP-NC, IRP, ODP, F-ETP, T-ETP, LU, T-AP, F-EP, GWP, EnU, M-RD
Rafiee et al. (2016)	Iran	Milk	ton	Cradle to gate	GWP, ODP, T-AP, F-EP, POCP, PMF, W-RD, F-RD
Santos Jr. et al. (2017)	Brazil	Cheese	kg	Cradle to gate	GWP, EnU
Tan et al. (2011)	USA	Milk	-	Cradle to-retail stores	GWP, AP, EP, POCP, A-RD, HTP, F-ETP, M-ETP, T-ETP
Vagnoni et al. (2017)	Italy	Cheese (Pecorino)	kg	Cradle to-retail stores	GWP, LU, EnU
van Middelaar et al. (2011)	Netherlands	Cheese (semi-hard)	kg	Cradle to gate	GWP, W-RD
Vasilaki et al. (2016)	Spain	Yoghurt (different types)	kg	Farm gate to plant gate	EnU, GWP
Yan and Holden (2018)	Republic of Ireland	Milk powder and butter	kg of dry matter	Cradle to gate	GWP, EnU

Environmental Impacts:
Global Warming =GWP, Acidification (undefined) =AP, Terrestrial acidification =T-AP, Organic and inorganic particles =IO-P, Energy use =EnU, Ecotoxicity (undefined) =ETP, Freshwater Ecotoxicity =F-ETP, Marine Ecotoxicity =M-ETP, Terrestrial Ecotoxicity =T-ETP, Eutrophication (not specified) =EP, Freshwater Eutrophication =F-EP, Marine Eutrophication =M-EP, Terrestrial eutrophication =T-EP, Human Toxicity (undefined) =HTP, Human toxicity, cancer =HT-C, Human toxicity, non-cancer =HT-NC, Ionising radiation =IRP, Land use =LU, Land use change =LUC, Ozone depletion =ODP, Particulate matter formation =PMF, Photochemical oxidants formation =POCP, Abiotic resource depletion =A-RD, Mineral resource depletion =M-RD, Fossil resource depletion =F-RD, Mineral, fossil and renewable resource depletion =MFRD, Water resource depletion =W-RD, Toxicity (sum of human-terrestrial-fresh water, and marine toxicity) =TP, Waste produced (W) =W

Annex - B

B-1: Equations to implement the proposed IPCC and EMEP/EEA harmonisation approach for on-farm N emissions.

This annex's material presents the four implementation phases of the proposed approach and it content should be read together with both the IPCC and the EMEP/EEA guidelines. For readability of the approach, the same abbreviations used in both guidelines were incorporated whenever was possible.

First phase: Additional N flows and independent application of the IPCC and EMEP/EEA.

This phase independently applies both IPCC and EMEP/EEA methodologies and the resulting emissions are reported as final emissions of the PEFCR-D non-N balanced approach (PEFCR-D$_{(NB)}$). It includes additional N inputs and outputs.

At manure management (MM), if the raw milk is also processed in the farm, wastes from processing such as wastewater (N_{WW}) and waste whey (N_{Wwhey}) are mixed with excrements in the slurry tank a liquid manure management system (MMS). These additional liquid sources of N and TAN affect the emissions from the IPCC and EMEP/EEA. In the IPCC guideline, these extra N loads are allocated by the population of the livestock sub-category T (Equation B.2) and included as part of the N in the liquid MMS as presented in Equation B.1.

$$N_{MS\,(T,Liquid)} = \left(AAP_{(T)} \times N_{ex\,(T)} \times MS_{(T,Liquid)}\right) + \left[\left(N_{WW} + N_{Wwhey}\right) \times AF_{Livestock\,(T)}\right] \qquad \textit{(Equation B.1)}$$

Where:

$N_{MS\,(T,\,Liquid)}$: Total N excreted from a livestock subcategory T entering a liquid manure management system (kg N/year)
$AAP_{(T)}$: Annual average population in the livestock subcategory T (heads)
$N_{ex(T)}$: Total nitrogen excreted by a livestock category T (kg N/year)
$MS_{(T,\,liquid)}$: Fraction of the total nitrogen excreted by a livestock category T that enters a Liquid manure management system (dimensionless)
N_{WW}: Wastewater nitrogen entering the liquid storage (kg N/year)
N_{Wwhey}: Waste whey nitrogen entering the liquid storage (kg N/year)
$AF_{Livestock\,(T)}$: Allocation factor for the livestock subcategory T (dimensionless)

$$AF_{Livestock\,(T)} = \frac{AAP_{(T)} \times W_{(T)}}{\sum_{(T)} AAP_{(T)} \times W_{(T)}} \qquad \textit{(Equation B.2)}$$

Where:

$AF_{Livestock\,(T)}$: Allocation factor for the livestock subcategory T (dimensionless)
$AAP_{(T)}$: Annual average population in the livestock subcategory T (heads)
W= Live weight or Tipical animal mass for a livestock subcategory T (kg/heads)

The other IPCC MMS do not consider additional N sources (Equation B.3).

$$N_{MS\,(T,S)} = \left(AAP_{(T)} + N_{ex\,(T)} + MS_{(T,S)}\right) \qquad \textit{(Equation B.3)}$$

Where:
$N_{MS\ (T,\ S)}$: Total N excreted from a livestock subcategory T entering an S manure management system (kg N/year)
$AAP_{(T)}$: Annual average population in the livestock subcategory T (heads)
$N_{ex(T)}$: Total nitrogen excreted by a livestock category T (kg N/year)
$MS_{\ (T,\ S)}$: fraction of the total nitrogen excreted by a livestock category T that enters a manure management system S (dimensionless)

Regarding the EMEP/EEA, these additional N sources during MM will be allocated and added to the original mass of stored slurry TAN and N ($m_{storage\_slurry\_TAN}$ and $m_{storage\_slurry\_N}$ respectively) as shown in Equation B.4 and Equation B.5. The EMEP/EEA original masses of stored solid manure TAN ($m_{storage\_soild\_TAN}$) and N ($m_{storage\_solid\_N}$) are not affected. It is considered a 7.5% TAN proportion (Carvalho et al., 2013) for mixed wastewater and whey from the production of cheese at the dairy farm.

$$m^{*}_{storge\_slurry\_TAN} = m_{storage\_slurry\_TAN} + \left[\left(TAN_{WW} + TAN_{Wwhey}\right) \times AF_{Livestock\ (T)}\right]$$

(Equation B.4)

Where:
$m^{*}_{storage\_slurry\_TAN}$: Modified EMEP/EEA mass of TAN at liquid storage (kg N-TAN/year)
$m_{storage\_slurry\_TAN}$: Original EMEP/EEA mass of TAN at storage (kg N-TAN/year)
TAN_{WW}: Wastewater nitrogen as TAN entering the liquid storage (kg N-TAN/year)
TAN_{Wwhey}: Waste whey nitrogen as TAN entering the liquid storage (kg N-TAN/year)
$AF_{Livestock\ (T)}$: Allocation factor for the livestock subcategory T (dimensionless)

$$m^{*}_{storge\_slurry\_N} = m_{storage\_slurry\_N} + \left[\left(N_{WW} + N_{Wwhey}\right) \times AF_{Livestock\ (T)}\right]$$

(Equation B.5)

Where:
$m^{*}_{storage\_slurry\_N}$: Modified EMEP/EEA mass of N at liquid storage (kg N/year)
$m_{storage\_slurry\_N}$: Original EMEP/EEA mass of N at solid storage (kg N/year)
N_{WW}: Wastewater nitrogen entering the liquid storage (kg N/year)
N_{Wwhey}: Waste whey nitrogen entering the liquid storage (kg N/year)
$AF_{Livestock\ (T)}$: Allocation factor for the livestock subcategory T (dimensionless)

At this point the additional N flows entering the system during MM are considered in both IPCC and EMEP/EEA guidelines.

At **application**, a fraction or all the manure that exits MM could be sold as organic fertiliser but also, some could be bought from other farms and mixed with the onsite manure. Moreover, N sources such a compost, sludges (from domestic wastewater treatment facilities in the farm) and waste whey (from the cheese production if it is the case) could also be directly applied to the soil. Therefore, all these extra N loads are allocated and included in the IPCC and EMEP/EEA guidelines as follows.

The IPCC includes N loads from the manure inputs and outputs when calculating the N animal manure fraction (F^{*}_{AM}, Equation B.6), the sludge inputs (N_{sludge}) will be added to the sewage fraction ($F_{SEW,}$ Equation B.7), the compost ($N_{compost}$) to the total compost N applied fraction ($F_{COMP,}$ Equation B.8) and the directly applied waste whey (N_{whey_app}) to the amount of other organic amendments fraction ($F_{OOA,}$

Equation B.9). All these fractions are part of the total organic nitrogen applied to soil (F_{ON}) and will be allocated according to each a livestock subcategory (T).

$$F^{*}_{AM} = F_{AM} + \left[\left(\left(N_{solid\_manure-IN} + N_{liquid\_manure-IN}\right) - \left(N_{solid\_manure-OUT} + N_{liquid\_manure-OUT}\right)\right) \times AF_{Livestock\ (T)}\right] \quad \text{(Equation B.6)}$$

Where:
F^{*}_{AM}: Coordinated Animal manure N fraction for application (kg N/year)
F_{AM}: IPCC Animal manure N fraction for application (kg N/year)
$N_{solid\_manure-IN}$: Extra solid manure entering the system, manure bought (kg N/year)
$N_{liquid\_manure-IN}$: Extra liquid manure exiting the system, manure bought (kg N/year)
$N_{solid\_manure-OUT}$: Onsite produced solid manure exiting the system, manure sold (kg N/year)
$N_{liquid\_manure-OUT}$: Onsite produced liquid manure exiting the system, manure sold (kg N/year)
$AF_{Livestock\ (T)}$: Allocation factor for the livestock subcategory T (dimensionless)

$$F_{SEW} = N_{sludge} \times AF_{Livestock\ (T)} \quad \text{(Equation B.7)}$$

Where:
F_{SEW}: IPCC N sewage fraction (kg N/year)
N_{sludge}: N from sludge added to the system (kg N/year)
$AF_{Livestock\ (T)}$: Allocation factor for the livestock subcategory T (dimensionless)

$$F_{COMP} = N_{compost} \times AF_{Livestock\ (T)} \quad \text{(Equation B.8)}$$

Where:
F_{COMP}: IPCC N sewage fraction (kg N/year)
$N_{compost}$: N from compost added to the system (kg N/year)
$AF_{Livestock\ (T)}$: Allocation factor for the livestock subcategory T (dimensionless)

$$F_{OOA} = N_{whey\_app} \times AF_{Livestock\ (T)} \quad \text{(Equation B.9)}$$

Where:
F_{OOA}: IPCC fraction of N from other organic amendments (kg N/year)
N_{whey_app}: N from cheese whey applied to soil (kg N/year)
$AF_{Livestock\ (T)}$: Allocation factor for the livestock subcategory T (dimensionless)

Regarding the EMEP/EEA, all the extra N that enters or exits the system at application is allocated to the respective N and TAN solid (Equation B.10 and Equation B.11) and liquid (Equation B.12 and Equation B.13) fractions.

$$NetExtra_{SolidTAN-IN} = \left[\left(TAN_{compost} + TAN_{Solid\_manure-IN} - TAN_{Solid\_manure-OUT}\right) \times AF_{Livestock\ (T)}\right] \quad \text{(Equation B.10)}$$

Where:
$NetExtra_{SolidTAN-IN}$: Net amount of TAN from solid sources entering the system (kg N-TAN/year)
$TAN_{compost}$: TAN fraction from compost (kg N-TAN/year)
$TAN_{Solid\_manure-IN}$: TAN fraction from solid manure that enters the system, manure bought (kg N-TAN/year)
$TAN_{Solid\_manure-OUT}$: TAN fraction from onsite produced solid manure that exits the system, manure sold (kg N-TAN/year)
$AF_{Livestock\ (T)}$: Allocation factor for the livestock subcategory T (dimensionless)

$$NetExtra_{SolidN-IN} = \left[\left(N_{compost} + N_{Solid\_manure-IN} - N_{Solid\_manure-OUT}\right) \times AF_{Livestock\ (T)}\right]$$ (Equation B.11)

Where:
NetExtra$_{SolidN\text{-}IN}$: Net amount of N from solid sources entering the system (kg N/year)
N$_{compost}$: N fraction from compost (kg N/year)
N$_{Solid\_manure\text{-}IN}$: N fraction from solid manure that enters the system, manure bought (kg N/year)
N$_{Solid\_manure\text{-}OUT}$: N fraction from onsite produced solid manure that exits the system, manure sold (kg N/year)
AF $_{Livestock\ (T)}$: Allocation factor for the livestock subcategory T (dimensionless)

$$NetExtra_{LiquidTAN-IN} = \left[\left(TAN_{sludge} + TAN_{whey\_app} + TAN_{Liquid\_manure-IN} - TAN_{Liquid\_manure-OUT}\right) \times AF_{Livestock\ (T)}\right]$$ (Equation B.12)

Where:
NetExtra$_{LiquidTAN\text{-}IN}$: Net amount of TAN from liquid sources entering the system (kg N-TAN/year)
TAN$_{sludge}$: TAN fraction from sludge (kg N-TAN/year)
TAN$_{whey\_app}$: TAN fraction from cheese whey applied to soil (kg N-TAN/year)
TAN$_{Liquid\_manure\text{-}IN}$: TAN fraction from liquid manure that enters the system, manure bought (kg N-TAN/year)
TAN$_{Liquid\_manure\text{-}OUT}$: TAN fraction from onsite produced liquid manure that exits the system, manure sold (kg N-TAN/year)
AF $_{Livestock\ (T)}$: Allocation factor for the livestock subcategory T (dimensionless)

$$NetExtra_{LiquidN-IN} = \left[\left(N_{sludge} + N_{whey\_app} + N_{Liquid\_manure-IN} - N_{Liquid\_manure-OUT}\right) \times AF_{Livestock\ (T)}\right]$$ (Equation B.13)

Where:
NetExtra$_{LiquidN\text{-}IN}$: Net amount of N from liquid sources entering the system (kg N/year)
N$_{sludge}$: N fraction from sludge (kg N/year)
N$_{whey\_app}$: N fraction from cheese whey applied to soil (kg N/year)
N$_{Liquid\_manure\text{-}IN}$: N fraction from liquid manure that enters the system, manure bought (kg N/year)
N$_{Liquid\_manure\text{-}OUT}$: N fraction from onsite produced liquid manure that exits the system, manure sold (kg N/year)
AF $_{Livestock\ (T)}$: Allocation factor for the livestock subcategory T (dimensionless)

The net amount of extra N and TAN affecting the system at application are considered in the respective EMEP/EEA masses of solid manure ($m_{applic\_solid\_TAN}$ and $m_{applic\_solid\_N}$) and slurry ($m_{applic\_slurry\_TAN}$ and $m_{applic\_slurry\_N}$), as shown in Equation B.14 to Equation B.17).

$$m^{*}_{applic\_solid\_TAN} = m_{applic\_solid\_TAN} + NetExtra_{SolidTAN-IN}$$ (Equation B.14)

Where:
m*$_{applic\_solid\_TAN}$: Modified EMEP/EEA mass of solid TAN applied to soil (kg N-TAN/year)
m$_{applic\_solid\_TAN}$: EMEP/EEA mass of solid TAN applied to soil (kg N-TAN/year)
NetExtra$_{SolidTAN\text{-}IN}$: Net amount of TAN from solid sources entering the system (kg N-TAN/year)

$$m^{*}_{applic\_solid\_N} = m_{applic\_solid\_N} + NetExtra_{SolidN-IN}$$ (Equation B.15)

Where:
$m^*_{applic\_solid\_N}$: Modified EMEP/EEA mass of solid N applied to soil (kg N/year)
$m_{applic\_solid\_N}$: EMEP/EEA mass of solid N applied to soil (kg N/year)
$NetExtra_{SolidN\text{-}IN}$: Net amount of N from solid sources entering the system (kg N/year)

$$m^*_{applic\_slurry\_TAN} = m_{applic\_slurry\_TAN} + NetExtra_{LiquidTAN-IN} \tag{Equation B.16}$$

Where:
$m^*_{applic\_slurry\_TAN}$: Modified EMEP/EEA mass of liquid/slurry TAN applied to soil (kg N-TAN/year)
$m_{applic\_slurry\_TAN}$: EMEP/EEA mass of liquid/slurry TAN applied to soil (kg N-TAN/year)
$NetExtra_{LiquidTAN\text{-}IN}$: Net amount of TAN from liquid sources entering the system (kg N-TAN/year)

$$m^*_{applic\_slurry\_N} = m_{applic\_slurry\_N} + NetExtra_{LiquidN-IN} \tag{Equation B.17}$$

Where:
$m^*_{applic\_slurry\_N}$: Modified EMEP/EEA mass of liquid/slurry N applied to soil (kg N/year)
$m_{applic\_slurry\_N}$: EMEP/EEA mass of liquid/slurry N applied to soil (kg N/year)
$NetExtra_{LiquidN\text{-}IN}$: Net amount of N from liquid sources entering the system (kg N/year)

Once the additional N sources have been added to the dairy system, the IPCC and EMEP/EEA are independently applied following their respective guidelines. Their results are reported as part of the PEFCR-D$_{(NB)}$ approach. At this point, none of the guidelines N flows are harmonised, and they report different emissions at same dairy farm stages. The independent PEFCR-D$_{(NB)}$ outcomes are the start point for the implementation of the proposed approach to reach a N balanced system and report N emissions as stated in the PEFCR-D framework (PEFCR-D$_{(B)}$).

Second phase: Balancing the housing and holding dairy farm stage.

The harmonisation between IPCC and EMEP/EAA guidelines start at the **second phase**, once the independent IPCC and EMEP/EAA results are obtained from Phase 1. This second phase focusses on balancing N outputs from Housing and Holding (H&H) stage.

The total NH_3 emissions (Equation B.18) determined at H&H with the EMEP/EEA arise from the TAN fractions of N_{ex} in yards and buildings.

$$E_{H\&H} = N - NH_{3_{(Y)}} + N - NH_{3_{(B)}} \tag{Equation B.18}$$

Where:
$E_{H\&H}$: Total EMEP/EEA housing & holding areas N-NH_3 emissions (kg N/year)
N-$NH_{3(Y)}$: EMEP/EEA N-NH_3 emissions at yards (kg N/year)
N-$NH_{3(B)}$: EMEP/EEA N-NH_3 emissions at buildings (kg N/year)

The $E_{H\&H}$ will be used to determine the IPCC Indirect N_2O emissions due to N volatilisation (I_V-N_2O) as presented in Equation B.19. The IPCC default emission factor for N_2O emissions from atmospheric deposition ($EF_4 = 0.01$) is used assuming that all the N is volatilized as ammonia (NH_3). Meanwhile, the

Direct N_2O (D-N_2O) emissions of this farm stage will be reported together with the MM direct emissions following the IPCC guideline.

$$I_{V,H\&H} - (N - N_2O) = E_{H\&H} \times EF_4^* \qquad \textit{(Equation B.19)}$$

Where:
$I_{V,\,H\&H}$-(N-N_2O): Total coordinated IPCC indirect N-N_2O emissions from volatile N at housing & holding areas (kg N/year)
$E_{H\&H}$: Total EMEP/EEA housing & holding areas N-NH_3 emissions (kg N/year)
$EF*_4$: IPCC emission factor for N volatilization and re-deposition (0.010kg N-N_2O/ kg N-NH_3) assuming NH_3 emissions only

Third phase: Balancing the manure management dairy farm stage

To balance the N flow entering MM ($N^*_{MS(T,\,S)}$), the EMEP/EEA $E_{H\&H}$ emissions are subtracted from the N entering each IPCC S manure management system ($N_{MS(T,\,S)}$) including the liquid MMS (S=liquid), as presented in Equation B.20.

$$N^*_{MS\,(T,S)} = N_{MS\,(T,S)} - \left(\frac{E_{H\&H} \times MS_{(T,S)}}{1 - MS_{(T,Grazing)}}\right) \qquad \textit{(Equation B.20)}$$

Where:
$N*_{MS(T,\,S)}$: IPCC coordinated total N excreted from a livestock subcategory T entering an S manure management system (kg N/year)
$N_{MS\,(T,\,S)}$: Total N excreted from a livestock subcategory T entering an S manure management system (kg N/year)
$E_{H\&H}$: Total EMEP/EEA housing & holding areas N-NH_3 emissions (kg N/year)
$MS_{(T,\,S)}$: fraction of the total nitrogen excreted by a livestock category T that enters a manure management system S (dimensionless)
$MS_{(T,\,grazing)}$: Fraction of the total nitrogen excreted by a livestock category T during grazing (dimensionless)

From $N^*_{MS(S)}$, D-N_2O emissions will be calculated (Equation B.21) by applying its corresponding IPCC emission factor ($EF_{3(S)}$).

$$D_{MS} - (N - N_2O) = \sum\nolimits_S N^*_{MS\,(S)} \times EF_{3(S)} \qquad \textit{(Equation B.21)}$$

Where:
D_{MS}-(N-N_2O): Total coordinated IPCC direct N-N_2O emissions from all manure management systems (kg N/year)
$N*_{MS(T,\,S)}$: IPCC coordinated total N excreted from a livestock subcategory T entering an S manure management system (kg N/year)
$EF_{3(S)}$: IPCC emission factor for direct N2O emissions from the manure management system S (kg N-N_2O/ kg N in S)

Since the PEFCR-D states that all the D-N_2O and NO_3^- emissions must be determined with the IPCC, the approach sets as equal the EMEP/EEA and IPCC D-N_2O emissions at MM (Equation B.22); which was previously determined as result of Equation B.21.

$$E^*_{storage\_N2O} = D_{MS} - (N - N_2O) \qquad \text{(Equation B.22)}$$

Where:
$E^*_{storage\_N2O}$: Total modified EMEP/EEA direct N-N_2O emissions at storage (kg N/year)
D_{MS}-(N-N2O): Total coordinated IPCC direct N-N_2O emissions from the manure management systems (kg N/year). From Equation B.21.

Since the EMEP/EEA only determines D-N_2O emissions at MM, the EMEP/EEA downstream N flow (from MM to application) will be affected by Equation B.22. Hence, the N difference between the EMEP/EEA and the IPCC D-N_2O emissions is calculated ($(N\text{-}N_2O)_{relocated}$, Equation B.23)to determine the total quantity of N that should be relocated among the solid and slurry N and TAN flows entering application.

$$(N - N_2O)_{relocated} = E_{storage\_N2O} - (N - N_2O)_{D-MS} \qquad \text{(Equation B.23)}$$

Where:
$(N\text{-}N_2O)_{relocated}$: N to be relocated at application from the manure management direct N-N_2O emissions (kg N/year)
$E_{storage\_N2O}$: Total EMEP/EEA direct N-N_2O emissions at storage (kg N/year)
$(N\text{-}N2O)_{D\text{-}MS}$: Total coordinated IPCC direct N-N_2O emissions from the manure management systems (kg N/year)

Then a general allocation based on the stored N as slurry ($m^*_{storage\_slurry\_N}$) and solid manure ($m_{storage\_solid\_N}$) is done (Equation B.24 and Equation B.25) to determine the $(N\text{-}N_2O)_{relocated}$ fraction that corresponds to the EMEP/EEA masses of N applied as a slurry and solid manure ($Coordfrac_{Slurry\_N}$ and $Coordfrac_{Solid\_N}$ respectively),

$$Coordfrac_{Slurry\_N} = (N - N_2O)_{relocated} \times \left[\frac{m^*_{storge\_slurry\_N}}{\left(m^*_{storge\_slurry\_N} + m_{storage\_solid\_N}\right)}\right] \qquad \text{(Equation B.24)}$$

Where:
$Coordfrac_{Slurry\_N}$: Coordination fraction to relocate slurry/liquid N in the EMEP/EEA
$(N\text{-}N_2O)_{relocated}$: N to be relocated at application from the manure management direct N-N_2O emissions (kg N/year)
$m^*_{storage\_slurry\_N}$: Modified EMEP/EEA mass of N at liquid storage (kg N/year)
$m_{storage\_solid\_N}$: EMEP/EEA mass of N at solid storage (kg N/year)

$$Coordfrac_{Solid\_N} = (N - N_2O)_{relocated} \times \left[\frac{m_{storage\_solid\_N}}{\left(m^*_{storge\_slurry\_N} + m_{storage\_solid\_N}\right)}\right] \qquad \text{(Equation B.25)}$$

Where:
$Coordfrac_{Solid\_N}$: Coordination fraction to relocate solid N in the EMEP/EEA
$(N\text{-}N_2O)_{relocated}$: N to be relocated at application from the manure management direct N-N_2O emissions (kg N/year)
$m^*_{storage\_slurry\_N}$: Modified EMEP/EEA mass of N at liquid storage (kg N/year)
$m_{storage\_solid\_N}$: EMEP/EEA mass of N at solid storage (kg N/year)

From the $Coordfrac_{Slurry\_N}$ and $Coordfrac_{Solid\_N}$, the fractions that correspond to the masses of TAN applied as slurry and solid manure are determined ($Coordfrac_{Slurry\_TAN}$ and $Coordfrac_{Solid\_TAN}$). The $Coordfrac_{Solid\_TAN}$ is defined by the TAN content of manure ($ContTAN_{manure}$) because manure is the only source of N in the solid fraction (Equation B.26). However, the $\mathrm{Coordfrac}_{\mathrm{Slurry\_TAN}}$ requires extra considerations due to the different N sources and TAN proportions that it involves. As stated before this approach considers that the IPCC liquid MMS or EMEP/EEA slurry storage could have extra N inputs from wastewater and waste whey ($\mathrm{N}_{\mathrm{WW}} + \mathrm{N}_{\mathrm{Wwhey}}$) which have a different TAN content ($\mathrm{ContTAN}_{\mathrm{WW\text{-}whey}}$) than the manure. Therefore, the $\mathrm{Coordfrac}_{\mathrm{Slurry\_N}}$ is allocated between them; based on the N content of the wastewater (N_{WW}), waste whey ($\mathrm{N}_{\mathrm{Wwhey}}$) and the slurry N at storage ($\mathrm{m}^*\mathrm{storage}_{\mathrm{\_slurry\_N}}$) as presented in Equation B.27.

$$Coordfrac_{Solid\_TAN} = Coordfrac_{Solid\_N} \times ContTAN_{manure} \qquad \text{(Equation B.26)}$$

Where:
$\mathrm{Coordfrac}_{\mathrm{Solid\_TAN}}$: Coordination fraction to relocate Solid TAN in the EMEP/EEA
$\mathrm{Coordfrac}_{\mathrm{Solid\_N}}$: Coordination fraction to relocate solid N in the EMEP/EEA
$\mathrm{ContTAN}_{\mathrm{manure}}$: TAN content in manure (kg N-TAN/kg N)

$$\begin{aligned} Coordfrac_{Slurry_{TAN}} &\\ &= Coordfrac_{Slurry_N} \\ &\times \left\{ \left[\frac{(N_{WW} + N_{Wwhe}\ )}{m^*_{storge_{slurr}\ _N}} \times\ AF_{Livestock\ (T)} \times ContTAN_{WW-Whey} \right] \right. \\ &+ \left[\left(1 - \left(\frac{(N_{WW} + N_{Wwhe}\ )}{m^*_{storge_{slur}\ _N}} \times\ AF_{Livestock\ (T)} \right) \right) \right. \\ &\left. \left. \times ContTAN_{manure} \right] \right\} \end{aligned} \qquad \text{(Equation B.27)}$$

Where:
$\mathrm{Coordfrac}_{\mathrm{Slurry\_TAN}}$: Coordination fraction to relocate slurry/liquid TAN in the EMEP/EEA
$\mathrm{Coordfrac}_{\mathrm{Slurry\_N}}$: Coordination fraction to relocate slurry/liquid N in the EMEP/EEA
N_{WW}: Wastewater nitrogen entering the liquid storage (kg N/year)
$\mathrm{N}_{\mathrm{Wwhey}}$: Waste whey nitrogen entering the liquid storage (kg N/year)
$\mathrm{m}^*_{\mathrm{storage\_slurry\_N}}$: Modified EMEP/EEA mass of N at liquid storage (kg N/year)
$\mathrm{AF}_{\mathrm{Livestock\ (T)}}$: Allocation factor for the livestock subcategory T (dimensionless)
$\mathrm{ContTAN}_{\mathrm{WW\text{-}Whey}}$: TAN content in cheese production wastewater and whey (kg N-TAN/kg N)
$\mathrm{ContTAN}_{\mathrm{manure}}$: TAN content in manure (kg N-TAN/kg N)

The EMEP/EEA TAN and N masses applied to the soil as solid manure ($\mathrm{m}^*_{\mathrm{applic\_solid\_TAN}}$ and $\mathrm{m}^*_{\mathrm{applic\_solid\_N}}$) and slurry ($\mathrm{m}^*_{\mathrm{applic\_slurry\_TAN}}$ and $\mathrm{m}^*_{\mathrm{applic\_slurry\_N}}$) that were calculated at the first phase are recalculated to include the Coordinated fractions of TAN and N as a slurry or solid manure (Equation B.28 to Equation B.31).

$$m^{**}_{applic\_slurry\_TAN} = m^{*}_{applic\_slurry\_TAN} + Coordfrac_{Slurry\_TAN} \qquad \text{(Equation B.28)}$$

Where:
$\mathrm{m}^{**}_{\mathrm{applic\_slurry\_TAN}}$: Coordinated EMEP/EEA mass of liquid/slurry TAN applied to soil (kg N-TAN/year)

$m^*_{applic\_slurry\_TAN}$: Modified EMEP/EEA mass of liquid/slurry TAN applied to soil (kg N-TAN/year)
$Coordfrac_{Slurry\_TAN}$: Coordination fraction to relocate slurry/liquid TAN in the EMEP/EEA

$$m^{**}_{applic\_slurry\_N} = m^{*}_{applic\_slurry\_N} + Coordfrac_{Slurry\_N} \quad \text{(Equation B.29)}$$

Where:
$m^{**}_{applic\_slurry\_N}$: Coordinated EMEP/EEA mass of liquid/slurry N applied to soil (kg N/year)
$m^*_{applic\_slurry\_N}$: Modified EMEP/EEA mass of liquid/slurry N applied to soil (kg N/year)
$Coordfrac_{Slurry\_N}$: Coordination fraction to relocate slurry/liquid N in the EMEP/EEA

$$m^{**}_{applic\_solid\_TAN} = m^{*}_{applic\_solid\_TAN} + Coordfrac_{Solid\_TAN} \quad \text{(Equation B.30)}$$

Where:
$m^{**}_{applic\_solid\_TAN}$: Coordinated EMEP/EEA mass of solid TAN applied to soil (kg N-TAN/year)
$m^*_{applic\_solid\_TAN}$: Modified EMEP/EEA mass of solid TAN applied to soil (kg N-TAN/year)
$Coordfrac_{Solid\_TAN}$: Coordination fraction to relocate Solid TAN in the EMEP/EEA

$$m^{**}_{applic\_solid\_N} = m^{*}_{applic\_solid\_N} + Coordfrac_{Solid\_N} \quad \text{(Equation B.31)}$$

Where:
$m^{**}_{applic\_solid\_N}$: Coordinated EMEP/EEA mass of solid N applied to soil (kg N/year)
$m^*_{applic\_solid\_N}$: Modified EMEP/EEA mass of solid N applied to soil (kg N/year)
$Coordfrac_{Solid\_N}$: Coordination fraction to relocate solid N in the EMEP/EEA

The volatilised N emissions (NH_3, NO_X and N_2) at MM are determined with the EMEP/EEA. However, since D-N_2O emissions are also determined by the EMEP/EEA at MM, from the total MM emissions calculated with the EMEP/EEA ($E_{storage\_gas}$) the EMEP/EEA D-N_2O emissions ($E_{storage\ N2O}$) will be subtracted. The remaining N will be considered as the IPCC total volatilized N arising from the MMS ($N_{volatilization\text{-}MMS}$, Equation B.32) from which the IPCC will determine I_V-N_2O during MM (Equation B.33).

$$N_{volatilization-MS} = E_{storage\_gas} - E_{storage\_N2O} \quad \text{(Equation B.32)}$$

Where:
$N_{volatilization\text{-}MS}$: IPCC coordinated total N volatilized (N-NH_3, N-NO_X and N-N_2) at the manure management systems (Kg N/year)
$E_{storage\_gas}$: Total EMEP/EEA gaseous emissions (N-NH_3, N-NO_X, N-N_2 and direct N-N_2O) at storage (kg N/year)
$E_{storage\_N2O}$: Total EMEP/EEA direct N-N_2O emissions at storage (kg N/year)

$$I_{V-MS} - (N - N_2O) = N_{volatilization-MS} \times EF_4 \quad \text{(Equation B.33)}$$

Where:
$I_{V\text{-}MS}$-(N-N_2O): Total coordinated IPCC indirect N-N_2O emissions in the manure management systems (kg N/year)
$N_{volatilization\text{-}MS}$: IPCC coordinated total N volatilized (N-NH_3, N-NO_X and N-N_2) at the manure management systems (Kg N/year)
EF_4: IPCC emission factor for N volatilization and re-deposition (0.010kg N-N_2O/ kg (N-NH_3+N-NO_X) volatilized)

When the manure exits MM, the amount of N from bedding calculated by the EMEP/EEA is added. It is estimated by a straw N content of 4g per kg (EMEP/EEA, 2016a). Since the total mass of bedding is used by all the livestock subcategories in the dairy farm, the total N from bedding is allocated to each livestock subcategory T (Equation B.34). The calculated EMEP/EEA $m_{bedding\text{-}N\ (T)}$ substitutes the IPCC $N_{beddingMS}$ value.

$$m_{bedding-N\ (T)} = m_{straw} \times N_{straw} \times AF_{Livestock\ (T)}$$ *(Equation B.34)*

Where:
$m_{bedding\text{-}N(T)}$: Coordinated IPCC N from bedding for a livestock subcategory T (kg N/year)
m_{straw}: Total mass of straw used in the dairy farm for animal bedding (kg straw/year)
N_{straw}: N content of straw (4 g N/kg straw)
$AF_{Livestock\ (T)}$: Allocation factor for the livestock subcategory T (dimensionless)

At this point the volatilized N emissions and the flows at MM before application have been harmonized. Hence the N flow entering application are the same for the IPCC and EMEP/EEA

Fourth phase: Balancing the Application dairy farm stage

Moving forward, IPCC emissions at application arise from three main N flows: the application of synthetic fertilizers (F_{SN}), manure directly deposited by grazing animals (F_{PRP}) and from the application of other organic N sources which involve the managed manure (F_{ON}). I_V-N_2O emissions are calculated from the volatilised N fraction of each of the flows. Hence, the approach recalculates the IPCC volatilized N fractions ($Frac^*_{GasF}$, $Frac^*_{GasM\_ON}$ and $Frac^*_{GasM\_PRP}$) that correspond to each of the three N flows as a function of their respective EMEP/EEA emissions at application (E_{fert_gas}, $E_{grazing\_gas}$ and $E^*_{applic\_gas}$). Consequently, three harmonized volatilized N fractions at application are obtained (Equation B.35 to Equation B.37); which are within the uncertainty range of the default IPCC fractions.

$$Frac^*_{GasM\_ON} = \frac{E^*_{applic\_gas}}{F_{ON}}$$ *(Equation B.35)*

Where:
$Frac^*_{GasM\_ON}$: IPCC coordinated fraction of applied organic N fertiliser materials (dimensionless)
E_{applic_gas}: Total EMEP/EEA gaseous emissions (N-NH_3 and N-NO_X) from the application of organic/manure N (kg N/year)
F_{ON}: IPCC fraction of organic N applied to soil (kg N/year)

$$Frac^*_{GasF} = \frac{E_{fert\_gas}}{F_{SN}}$$ *(Equation B.36)*

Where:
$Frac^*_{GasF}$: IPCC coordinated fraction of synthetic fertiliser N that volatilizes at application (dimensionless)
E_{fert_gas}: Total EMEP/EEA gaseous emissions (N-NH_3 and N-NO_X) from the application of synthetic N fertilisers (kg N/year)
F_{SN}: IPCC fraction of synthetic N fertilisers applied to soil (kg N/year)

$$Frac^{*}_{GasM\_PRP} = \frac{E_{grazing\_gas}}{F_{PRP}}$$ (Equation B.37)

Where:
$Frac^{*}_{GasM\_PRP}$: IPCC coordinated fraction of N applied to the soil during grazing (dimensionless)
$E_{grazing\_gas}$: Total EMEP/EEA gaseous emissions (N-NH_3 and N-NO_X) from the N application during grazing (kg N/year)
F_{PRP}: IPCC fraction of N applied by the livestock at pastures, ranges or paddock (kg N/year)

However, Since the third phase corrected the EMEP/EEA TAN and N masses applied to the soil as solid manure ($m^{*}_{applic\_solid\_TAN}$ and $m^{*}_{applic\_solid\_N}$) and slurry ($m^{*}_{applic\_slurry\_TAN}$ and $m^{*}_{applic\_slurry\_N}$), the EMEP/EEA total coordinated gaseous emissions (N-NH_3 and N-NO_X) from the application of organic sources and manure N ($E^{*}_{applic\_gas}$) must be adjusted (Equation B.38 to Equation B.40) before recalculating the $Frac^{*}_{GasM\_ON}$ (Equation B.35).

$$\begin{aligned} E^{*}_{appli\_NH3} = &\left(m^{**}_{applic\_slurry\_TAN} \times EF_{applic\_slurry}\right) \\ &+ \left(m^{**}_{applic\_solid\_TAN} \times EF_{applic\_solid}\right) \end{aligned}$$ (Equation B.38)

Where:
$E^{*}_{applic\_NH3}$: EMEP/EEA Total coordinated N-NH_3 emissions from application (kg N)
$m^{**}_{applic\_solid\_TAN}$: Coordinated EMEP/EEA mass of TAN applied to soil from solid manure (kg N-TAN/year)
$m^{**}_{applic\_slurry\_TAN}$: Coordinated EMEP/EEA mass of TAN applied to soil from slurry/liquid manure (kg N-TAN/year)
EF_{applic_slurry}: EMEP/EEA N-NH_3 emission factor for the application of slurry /liquid manure (N-TAN proportion)
EF_{applic_solid}: EMEP/EEA N-NH_3 emission factor for the application of solid manure (N-TAN proportion)

$$E^{*}_{appli\_NO} = \left(m^{**}_{applic\_slurry\_N} + m^{**}_{applic\_solid\_N}\right) \times EF_{applic\_NO}$$ (Equation B.39)

Where:
$E^{*}_{applic\_NO}$: EMEP/EEA Total coordinated N-NO emissions from application (kg N)
$m^{**}_{applic\_solid\_N}$: Coordinated EMEP/EEA mass of N applied to soil from solid manure (kg N/year)
$m^{**}_{applic\_slurry\_N}$: Coordinated EMEP/EEA mass of N applied to soil from slurry/liquid manure (kg N/year)
EF_{applic_slurry}: EMEP/EEA N-NO emission factor for the application of slurry /liquid manure (kg N-NO/ kg N)
EF_{applic_solid}: EMEP/EEA N-NO emission factor for the application of solid manure (kg N-NO/ kg N)

$$E^{*}_{applic\_gas} = E^{*}_{appli\_NH3} + E^{*}_{appli\_NO}$$ (Equation B.40)

Where:
$E^{*}_{applic\_gas}$: EMEP/EEA total coordinated gaseous emissions (N-NH_3 and N-NO_X) from the application of organic/manure N (kg N/year)
$E^{*}_{applic\_NH3}$: EMEP/EEA Total coordinated N-NH_3 emissions from application (kg N)
$E^{*}_{applic\_NO}$: EMEP/EEA Total coordinated N-NO emissions from application (kg N)

Once the gaseous fractions are obtained, they are used to determine the IPCC I_V-N_2O emissions at application as presented in Equation B.41).

$$I_{V-applic} - (N - N_2O) = \left[(F_{SN} \times Frac^*_{GasF}) + (F_{ON} \times Frac^*_{GasM\_ON}) + (F_{PRP} \times Frac^*_{GasM\_PRP})\right] \times EF_4 \quad \textit{(Equation B.41)}$$

Where:
$I_{V\text{-applic}}$-(N-N_2O): Total coordinated IPCC indirect N-N_2O emissions from N application (kg N/year)
F_{SN}: IPCC fraction of synthetic N fertilisers applied to soil (kg N/year)
Frac*$_{GasF}$: IPCC coordinated fraction of synthetic fertiliser N that volatilizes at application (dimensionless)
F_{ON}: IPCC fraction of organic N applied to soil (kg N/year)
Frac*$_{GasM\_ON}$: IPCC coordinated fraction of applied organic N fertiliser materials (dimensionless)
F_{PRP}: IPCC fraction of N applied by the livestock at pastures, ranges or paddock (kg N/year)
Frac*$_{GasM\_PRP}$: IPCC coordinated fraction of N applied to the soil during grazing (dimensionless)
EF_4: IPCC emission factor for N volatilization and re-deposition (0.010kg N-N_2O/ kg (N-NH_3+N-NO_X) volatilized)

The new masses of applied N to soil as slurry ($m^{**}_{applic\_slurry\_N}$) and solid manure ($m^*_{applic\_solid\_N}$) are used to determine the EMEP/EEA manure application N-N_2O and N-NO_3 emissions (E_{applic_N2O} and $E_{applicM\_NO3}$ respectively) with Equation B.42 and Equation B.4.3 by applying the given IPCC emission factors.

$$E_{\text{applic\_D\_}N2O} = \left(m^{**}_{applic\_solid\_N} + m^{**}_{applic\_slurry\_N}\right) \times EF_1 \quad \textit{(Equation B.42)}$$

Where:
$E_{applic\_D\_N2O}$: Total coordinated EMEP/EEA direct N-N_2O emissions at application (kg N/year)
$m^{**}_{applic\_solid\_N}$: Coordinated EMEP/EEA mass of solid N applied to soil (kg N/year)
$m^{**}_{applic\_slurry\_N}$: Coordinated EMEP/EEA mass of liquid/slurry N applied to soil (kg N/year)
EF_1: IPCC emission factor for direct N2O emissions from mineral fertilisers, organic amendments and crop residues, and N mineralised from mineral soil because of loss of soil carbon (kg N-N_2O/kg N)

$$E_{\text{applicM\_}NO3} = \left(m^{**}_{applic\_solid\_N} + m^{**}_{applic\_slurry\_N}\right) \times Frac_{Leach-H} \quad \textit{(Equation B.43)}$$

Where:
$E_{applicM\_NO3}$: Total coordinated EMEP/EEA N-NO_3 emissions at application (kg N/year)
$m^{**}_{applic\_solid\_N}$: Coordinated EMEP/EEA mass of solid N applied to soil (kg N/year)
$m^{**}_{applic\_slurry\_N}$: Coordinated EMEP/EEA mass of liquid/slurry N applied to soil (kg N/year)
$Frac_{Leach\text{-}H}$: IPCC fraction of N losses by leeching/runoff (kg N/kg N additions or depositions by grazing animals)

Moreover, N-N_2O and N-NO_3 emissions from grazing (E_{graz_NO3} and E_{graz_NO3}) and the application of N fertilisers (E_{graz_N2O} and E_{fert_NO3}) are calculated from its N content (m_{fert_N} and m_{graz_N} respectively) with Equation B.44 to Equation B.47 by also applying the given IPCC emission factors.

$$E_{\text{graz\_D\_}N2O} = m_{\text{graz\_}N} \times EF_{3\_prp}$$ *(Equation B.44)*

Where:
$E_{graz\_D\_N2O}$: Total coordinated EMEP/EEA direct N-N_2O emissions during grazing (kg N-N_2O /year)
m_{graz_N}= mass of N excreted during grazing (kg N/year)
EF_{3_prp}: IPCC emission factor for direct N_2O emissions from pasture, range and padock (kg N-N_2O/kg N)

$$E_{\text{fert\_D\_}N2O} = m_{\text{fert\_}N} \times EF_1$$ *(Equation B.45)*

Where:
$E_{fert\_D\_N2O}$: Total coordinated EMEP/EEA direct N-N_2O emissions from N synthetic fertilisers application (kg N/year)
m_{fert_N}= mass of N from synthetic fertilisers application (kg N/year)
EF_1: IPCC emission factor for direct N2O emissions from mineral fertilisers, organic amendments and crop residues, and N mineralised from mineral soil because of loss of soil carbon (kg N-N_2O/kg N)

$$E_{\text{fert\_}NO3} = m_{\text{fert\_}N} \times Frac_{Leach-H}$$ *(Equation B.46)*

Where:
E_{fert_NO3}: Total coordinated EMEP/EEA N-NO_3 emissions from N synthetic fertilisers application (kg N/year)
m_{fert_N}= mass of N from synthetic fertilisers application (kg N/year)
$Frac_{Leach-H}$: IPCC fraction of N losses by leaching/runoff (kg N/kg N additions or depositions by grazing animals)

$$E_{\text{graz\_}NO3} = m_{\text{graz\_}N} \times Frac_{Leach-H}$$ *(Equation B.47)*

Where:
E_{graz_NO3}: Total coordinated EMEP/EEA N-NO_3 emissions during grazing (kg N/year)
m_{graz_N}= mass of N excreted during grazing (kg N/year)
$Frac_{Leach-H}$: IPCC fraction of N losses by leaching/runoff (kg N/kg N additions or depositions by grazing animals)

Additionally, N-NO_3 emissions from crop residues (F_{CR}) and mineral soils (F_{SOM}) are also included in the EMEP/EEA N flow by using (Equation B.48).

$$E_{\text{applicN\_}NO3} = (F_{CR} + F_{SOM}) \times Frac_{LEach-H}$$ *(Equation B.48)*

Where:
$E_{applicN\_NO3}$: Total coordinated EMEP/EEA N-NO3 emissions from other organic N sources (kg N/year)
F_{CR}: IPCC fraction of N from crop residues (kg N/year)
F_{SOM}: IPCC fraction of N from mineral soils (kg N/year)
$Frac_{Leach-H}$: IPCC fraction of N losses by leaching/runoff (kg N/kg N additions or depositions by grazing animals)

Annex - C

C-1: Life cycle Inventory for cow milk artisan dairy system

Table C 1:Global life cycle inventory for the cow milk artisan system

Flow	Amount	Unit	Transport
Inputs			
Livestock feeding			
Pasture	8.06	ha	-
Alfalfa (produced at farm)	15,434.32	kg	-
Barley (produced at farm)	20,947.07	kg	-
Maize (corn grain) production; ,technology mix,at farm, ES	210,114.46	kg	T
Soybean protein concentrate; ,from crushing (extraction with solvent),at plant, ES	4,253.67	kg	T
Animal meal from rendering (beef); ,technology mix, production mix,at plant, EU+28	134,134.80	kg	T
Fertilizers			
Managed manure (produced in at farm)	1,122,266.0	kg	-
Animal bedding			
Straw (produced at farm)	54,337.70	kg	-
Packaging materials			
Paper bag,Kraft Pulping Process, pulp pressing and drying,production mix, at plant,uncoated Kraft Paper, EU-28+EFTA	8.42	kg	V
Plastic bag, PE,raw material production, plastic extrusion,production mix, at plant,thickness: 0.03mm, grammage: 0.0283 kg/m2, EU-28+EFTA	27.09	kg	V
	0.77	m2	-
Chemicals			
Nitric acid production,technology mix,production mix, at plant,100% active substance, RER	9.57	kg	V
At farm	1.91	kg	-
At processing	7.66	kg	-
Sodium hydroxide production,technology mix,production mix, at plant,100% active substance, RER	6.38	kg	V
At farm	1.28	kg	-
At processing	5.11	kg	-
Energy			
Electricity grid mix 1kV-60kV,AC, technology mix,consumption mix, to consumer,1kV - 60kV, ES	235,236.80	kWh	-
At farm	51,752.10	kWh	-
At processing	183,484.71	kWh	-
Diesel mix at refinery,from crude oil,production mix, at refinery,10 ppm sulphur, 7.23 wt.% bio components, EU-28+3	5,306.56	kg	T
At farm	4,245.25	kg	-
At processing	1,061.31	kg	-
Water			
Tap water,technology mix,at user,per m3 water, EU-28+3	4,227.18	m3	-
At farm	2,345.02	m3	-
For Irrigation	703.51	m3	-
For animal trough	1,641.51	m3	-
At processing	1,882.16	m3	-
For cleaning and others	1,882.16	m3	-

Table C 1 (continued):Global life cycle inventory for the cow milk artisan system

Flow	Amount	Unit	Transport
Inputs			
Processing ingredients			
Lactic ferments	0.54	kg	V
Rennet	7.96	kg	V
Sodium chloride powder production,technology mix,production mix, at plant,100% active substance, RER	68.15	kg	V
Raw milk (1.035kg/l. Fat= 4%, protein=3.3%, DM=12.3%)	11,5095.19	kg	-
Outputs			
Wastes			
Wastewater to slurry tank (0.08 kgN/m3, 0.015kg P/m3, 0.75 g COD/L)	1,882.16	m3	-
Sales (out of the system)			
Cheese whey livestock feeding (6.8%DM, 1.039kg/l)	55.37	m3	-
	0.00	€	-
Raw milk (1.035kg/l. Fat= 8.31%, protein=5.77%, DM=12.3%)	262,134.36	kg	-
	25,1648.99	€	-
Adult livestock	7,223.17	kg	-
	14,446.34	€	-
Young livestock (>1 year)	1,458.58	kg	-
	2,917.16	€	-
Cheese (70%DM)	14,319.13	kg	-
Yoghurt (12%DM)	30,437.62	kg	-

T= Articulated lorry transport, Euro 4, Total weight >32 t (64%),diesel driven, Euro 4, cargo,consumption mix, to consumer,more than 32t gross weight / 24,7t payload capacity, EU-28+3. Distance: 50km
V= Articulated lorry transport, Euro 3, Total weight <7.5 t (UR=20%), consumption mix, to consumer, diesel driven, Euro 3, cargo, up to 7,5t gross weight / 3,3t payload capacity Distance: 20km

Table C 2: Recipes for cow milk dairy products

Ingredient	Unit (/kg product)	Dairy product	
		Cheese	Yoghurt
Dairy ferments	kg	3.75E-05	-
Rennet	kg	5.56E-04	-
Sodium chloride	kg	4.76E-03	-
Raw milk (Fat= 8.31%, protein=5.77%, DM=12.3%)	kg	6.21E+00	8.60E-01
Paper bag	kg	1.88E-04	1.88E-04
Plastic bag -PE	kg	6.05E-04	6.05E-04
	m2	2.14E-02	2.14E-02
Dry matter content (DM)	%	70	12.2

Table C 3: Dairy livestock and raw milk properties.

Property	Unit	Livestock		
		High-production dairy cow	Young dairy cow	Heifers
Number of heads	Heads	45	31	14
Average weight	kg/head	600	600	125
Milk production yield	kg/head*day	22.97	0	0
Fat content	%	3.3	0	0
Protein content	%	4.0	0	0
Avg. daily weight gain in the sub-category population	kg/day	0	0.5	0.5
Livestock permanence in the farm	days	365	365	30

Table C 4: Percentage of the livestock yearly activity and feeding situation in the dairy farm.

Livestock's activity/feeding situation	Share (%)
Stall	87
Grazing large areas (open range land or hilly terrain)	13

Table C 5: Percentage of manure produced annually that is managed by system type.

System type	Share (%)
Pasture/range/paddock	13
Deep bedding	37
Liquid/slurry	50

Table C 6: Other dairy farm parameters

Parameter	Unit	Amount
Annual average temperature	˚C	20
Area used by livestock for natural grazing	ha	8.06
Area of land where the managed manure and/or fertilizers are applied	ha	7.25
Feed digestibility (DE)	%	72.5

C-2: Life cycle Inventory for sheep milk artisan dairy system

Table C 7:Global life cycle inventory for the sheep milk artisan system

Flow Inputs			Amount	Unit	Transport
Livestock feeding					
Pasture			7.20	ha	-
Alfalfa (produced at farm)			15,373.92	kg	-
Barley (produced at farm)			8,152.54	kg	-
Lima beans (produced at farm)			1,716.33	kg	-
Fertilizers					
Phosphate rock,as P2O5,at mine,per kg P2O5, EU-28+3			241.32	kg	T
Managed manure (produced in at farm)			812,471.9	kg	-
Animal bedding					
Hay,production mix, dried,at farm,per kg dry matter, EU-28+3			5,731.42	kg DM	T
Barley straw,production mix,at farm,per kg straw, EU-28+3			7,633.55	kg DM	T
Packaging materials					
Paper bag,Kraft Pulping Process, pulp pressing and drying,production mix, at plant,uncoated Kraft Paper, EU-28+EFTA			16.12	kg	V
Corrugated box, uncoated,Kraft Pulping Process, pulp pressing and drying,production mix, at plant,280 g/m2, R1=88%, EU-28+EFTA			6.29	kg	V
Plastic bag, PE,raw material production, plastic extrusion,production mix, at plant,thickness: 0.03mm, grammage: 0.0283 kg/m2, EU-28+EFTA			36.17	kg	V
			1,278.20	m2	-
Plastic film , PE wrap,raw material production, plastic extrusion,production mix, at plant,thickness: 25 µm, grammage: 0,023575 kg/m2, EU-28+EFTA			8.94	kg	V
			379.12	m2	
Chemicals					
Nitric acid production,technology mix,production mix, at plant,100% active substance, RER			10.73	kg	V
	At farm		2.15	kg	-
	At processing		8.58	kg	-
Isopropanol production,technology mix,production mix, at plant,100% active substance, RER			9.62	kg	V
	At farm		1.92	kg	-
	At processing		7.69	kg	-
Energy					
Electricity grid mix 1kV-60kV,AC, technology mix,consumption mix, to consumer,1kV - 60kV, ES			12,396.75	kWh	-
	At farm		2,727.29	kWh	-
	At processing		9,669.47	kWh	-
Diesel mix at refinery,from crude oil,production mix, at refinery,10 ppm sulphur, 7.23 wt.% bio components, EU-28+3			798.52	kg	T
	At farm		638.81	kg	-
	At processing		159.70	kg	-
Thermal energy from natural gas,technology mix regarding firing and flue gas cleaning,production mix, at heat plant,MJ, 100% efficiency, EU-28+3			2,004.86	kWh	-
	At farm		400.97	kWh	-
	At processing		1,603.88	kWh	-
Water					
Tap water,technology mix,at user,per m3 water, EU-28+3			916.42	m3	-
	At farm		373.10	m3	-
		For Irrigation	111.93	m3	-
		For animal trough	261.17	m3	-
	At processing		543.32	m3	-
		For cleaning and others	543.32	m3	-

Table C 7 (continued):Global life cycle inventory for the sheep milk artisan system

Flow	Amount	Unit	Transport
Inputs			
Processing ingredients			
Lactic ferments	0.62	kg	V
Rennet	9.96	kg	V
Sodium chloride powder production,technology mix,production mix, at plant,100% active substance, RER	100.44	kg	V
Raw milk (1.035kg/l. Fat= 8.31%, protein=5.77%, DM=12.3%)	42,574.86	kg	-
Outputs			
Wastes			
Cheese whey for on-site livestock feeding	12.64	m3	-
Cheese whey for on-site fertilizing	6.83	m3	-
Wastewater to slurry tank (0.08 kgN/m3, 0.015kg P/m3, 0.75 g COD/L)	543.32	m3	-
Sales (out of the system)			
Cheese whey livestock feeding (6.8%DM, 1.039kg/l)	14.56	m3	-
	0.00	€	-
livestock manure	68,452.33	kg	-
	2,053.57	€	-
Raw milk (1.035kg/l. Fat= 8.31%, protein=5.77%, DM=12.3%)	1,835.05	kg	-
	1,761.65	€	-
Adult livestock	1,892.13	kg	-
	5,676.38	€	-
Young livestock (>1 year)	1,242.16	kg	-
	3,726.47	€	-
Cheese (75%DM)	6,021.58	kg	-
Yoghurt (5%DM)	2,582.26	kg	-

T= Articulated lorry transport, Euro 4, Total weight >32 t (64%),diesel driven, Euro 4, cargo,consumption mix, to consumer,more than 32t gross weight / 24,7t payload capacity, EU-28+3. Distance: 50km

V= Articulated lorry transport, Euro 3, Total weight <7.5 t (UR=20%), consumption mix, to consumer, diesel driven, Euro 3, cargo, up to 7,5t gross weight / 3,3t payload capacity Distance: 20km

Table C 8: Recipes for sheep milk dairy products

Ingredient	Unit (/kg product)	Dairy product	
		Cheese	Yoghurt
Dairy ferments	kg	1.04E-04	-
Rennet	kg	1.65E-03	-
Sodium chloride	kg	1.67E-02	-
Raw milk (Fat= 8.31%, protein=5.77%, DM=12.3%)	kg	6.70E+00	8.60E-01
Paper bag	kg	6.24E-03	-
Corrugated carton	kg	1.41E-03	2.58E-04
Plastic bag -PE	kg	8.08E-03	1.49E-03
	m2	2.86E-01	5.25E-02
Plastic film-PE wrapping	kg	2.42E-03	4.45E-04
	m2	1.03E-01	1.89E-02
DM	%	75	5

Table C 9: Dairy livestock and raw milk properties.

Property	Unit	Livestock		
		Mature ewes	**Young ewes**	**Lambs**
Number of heads	Heads	211	51	97
Average weight	kg/head	40	40	12.33
Milk production yield	kg/head*day	0.6	0	0
Fat content	%	8.31	0	0
Protein content	%	5.77	0	0
Livestock permanence in the farm	days	365	365	30

Table C 10: Percentage of the livestock yearly activity and feeding situation in the dairy farm.

Livestock's activity/feeding situation	Share (%)
Housing	50
Grazing flat pasture	25
Grazing hilly pasture	25

Table C 11: Percentage of manure produced annually that is managed by system type.

System type	Share (%)
Pasture/range/paddock	50
Deep bedding	43
Liquid/slurry	7

Table C 12: Other dairy farm parameters

Parameter	Unit	Amount
Annual average temperature	˚C	20
Area used by livestock for natural grazing	ha	7.20
Area of land where the managed manure and/or fertilizers are applied	ha	4.58
Average annual production of wool per sheep	kg/yr	5
Live bodyweight at weaning	kg	12.33
Live bodyweight at 1-year old or at slaughter if slaughtered prior to 1 year of age	kg	12.33
Number of lambs born in a year	Heads	97
Number of pregnant ewes in a year	Heads	97
Feed digestibility (DE)	%	60

C-3: Life cycle Inventory for goat milk artisan dairy system

Table C 13:Global life cycle inventory for the goat milk artisan system

Flow	Amount	Unit	Transport
Inputs			
Livestock feeding			
Pasture	1.50	ha	-
Hay (produced at farm)	7,102.88	kg	-
Fescue (produced at farm)	11,505.01	kg	-
Green pea (produced at farm)	1,075.57	kg	-
Maize (corn grain) production; ,technology mix,at farm, ES	5,583.19	kg	T
Sodium chloride powder production,technology mix,production mix, at plant,100% active substance, RER	35.85	kg	T
Fertilizers			
Managed manure (produced in at farm)	2,696.09	kg	-
Animal bedding			
Hay,production mix, dried,at farm,per kg dry matter, EU-28+3	5,731.42	kg DM	T
Packaging materials			
Paper bag,Kraft Pulping Process, pulp pressing and drying,production mix, at plant,uncoated Kraft Paper, EU-28+EFTA	0.72	kg	V
Plastic bag, PE,raw material production, plastic extrusion,production mix, at plant,thickness: 0.03mm, grammage: 0.0283 kg/m2, EU-28+EFTA	18.00	kg	V
	0.51	m2	-
Chemicals			
Nitric acid production,technology mix,production mix, at plant,100% active substance, RER	10.76	kg	V
At farm	2.15	kg	-
At processing	8.60	kg	-
Sodium hydroxide production,technology mix,production mix, at plant,100% active substance, RER	12.91	kg	V
At farm	2.58	kg	-
At processing	10.33	kg	-
Calcium chloride production,technology mix,production mix, at plant,100% active substance, RER	12.55	kg	V
At farm	2.51	kg	-
At processing	10.04	kg	-
Energy			
Electricity grid mix 1kV-60kV,AC, technology mix,consumption mix, to consumer,1kV - 60kV, ES	2,591.80	kWh	-
At farm	570.20	kWh	-
At processing	2,021.60	kWh	-
Diesel mix at refinery,from crude oil,production mix, at refinery,10 ppm sulphur, 7.23 wt.% bio components, EU-28+3	44.74	kg	T
At farm	35.79	kg	-
At processing	8.95	kg	-
Water			
Tap water,technology mix,at user,per m3 water, EU-28+3	199.24	m3	-
	111.27	m3	-
For Irrigation	33.38	m3	-
For animal trough	77.89	m3	-
	87.97	m3	-
For cleaning and others	87.97	m3	-
Processing ingredients			
Lactic ferments	0.45	kg	V
Rennet	5.95	kg	V
Sodium chloride powder production,technology mix,production mix, at plant,100% active substance, RER	35.85	kg	V
Raw milk (1.035kg/l. Fat= 4.1%, protein=3.6%, DM=12.3%)	14,694.41	kg	-

Table C 13 (continued):Global life cycle inventory for the goat milk artisan system

Flow	Transport	Flow	Amount
Outputs			
Wastes			
Cheese whey for on-site livestock feeding	12.64	m3	-
Wastewater to municipal WWTP (0.75 g COD/L)	543.32	m3	-
Sales (out of the system)			
Cheese whey livestock feeding (6.8%DM, 1.039kg/l)	1.62	m3	-
	0.00	€	-
livestock manure	4,716.66	kg	-
	141.51	€	-
Adult livestock	556.37	kg	-
	1,669.10	€	-
Young livestock (>1 year)	281.84	kg	-
	845.53	€	-
Cheese (65%DM)	1,577.50	kg	-

T= Articulated lorry transport, Euro 4, Total weight >32 t (64%),diesel driven, Euro 4, cargo,consumption mix, to consumer,more than 32t gross weight / 24,7t payload capacity, EU-28+3. Distance: 50km

V= Articulated lorry transport, Euro 3, Total weight <7.5 t (UR=20%), consumption mix, to consumer, diesel driven, Euro 3, cargo, up to 7,5t gross weight / 3,3t payload capacity Distance: 20km

Table C 14: Recipes for goat milk dairy products

Ingredient	Unit (/kg product)	Dairy product
		Cheese
Dairy ferments	kg	2.85E-04
Rennet	kg	3.77E-03
Sodium chloride (kg)	kg	2.27E-02
Raw milk (1.035kg/l. Fat= 4.1%, protein=3.6%, DM=12.3%)	kg	9.32E+00
Paper bag	kg	4.55E-04
Plastic bag -PE	kg	1.14E-02
	m2	4.03E-01
DM	%	65

Table C 15: Dairy livestock and raw milk properties.

Property	Unit	Livestock		
		Mature goats	Young goats	kids
Number of heads	Heads	57	36	24
Average weight	kg/head	50	50	6
Milk production yield	kg/head*day	0.71	-	-
Fat content	%	4.1	-	-
Protein content	%	3.6	-	-
Livestock permanence in the farm	days	365	365	30

Table C 16: Percentage of the livestock yearly activity and feeding situation in the dairy farm.

Livestock's activity/feeding situation	Share (%)
Housing	77
Grazing flat pasture	11.5
Grazing hilly pasture	11.5

Table C 17: Percentage of manure produced annually that is managed by system type.

System type	Share (%)
Pasture/range/paddock	23
Composting (static pile)	9
Deep bedding	68

Table C 18: Other dairy farm parameters

Parameter	Unit	Amount
Annual average temperature	˚C	20
Area used by livestock for natural grazing	ha	1.50
Area of land where the managed manure and/or fertilizers are applied	ha	1.39
Average annual production of wool per sheep	kg/yr	6
Live bodyweight at weaning	kg	6
Live bodyweight at 1-year old or at slaughter if slaughtered prior to 1 year of age	kg	24
Number of lambs born in a year	Heads	24
Number of pregnant ewes in a year	Heads	60
Feed digestibility (DE)	%	20

Annex - D

D-1: Declaration of conformity for CalcPEF$_{\text{Dairy}}$ tool.

DNV·GL

DECLARATION OF CONFORMITY

Introduction

UNIVERSITAT DE VIC – BETA TECHNOLOGICAL CENTER, has comissioned DNV GL Business Assurance España S.L.U. to carry out alimited verification of the environmental profile tool CalcPEF_Dairy_V1.0

Verification Scope

Our limited review verified that the tool is based on PEFCR- Product Environmental Footprint Category Rules for Dairy Products Version 1.0

Verification Objective

The objective of this verification is to facilitate the interested parties an independent professional judgement about the information and data contained on the tool

Verification Criteria

The reference requirements for the verification of the tool were:

- Product Environmental Footprint Category Rules for Dairy Products Version 1.0).
- Guía Product Environmental Footprint Category 1 Rules Guidance 2 Version 6.3 – May 2018 - Chapter 8 Verification and validation of studies, reports, and communication vehicles
- ISO/TS 14071:2014 (Environmental Management – Life Cycle Assessment – Critical review processes and reviewer competencies)

As part of the verification process, DNV GL verification team:

- carried out interviews with relevant people in the organization responsible for developing the tool
- carried out interviews with relevant people in the organization regarding the technical aspects
- had access to specific documents, data and information that the organization made available
- carried out a previous documentary study of the CalcPEF_Dairy_V7.1.0 tool, the result of which was a series of preliminary findings
- carried out a visit to a cheese factory on February 19, 2020 to verify the correct application of the tool
- carried out a visit to the organization premises on February 20, 2020 to review the preliminary findings together with the developers
- carried out a subsequent remote follow-up for the final closure of all the findings for the tool revision 1.0 consolidation
- continuing with a report preparation and an internal technical review

DNV GL expressly disclaims any responsibility for decisions, investment or otherwise, based on this statement.

Opportunities for improvement and Findings

During the verification process, some areas for improvement and findings in the tool were detected, which were satisfactorily resolved, and which will serve as support for future developments of the tool.

Conclussion

Based on the above, in our opinion there is no evidence that leads us to suppose that the CalcPEF_Dairy_V1.0 tool developed by UNIVERSITAT DE VIC - BETA TECHNOLOGICAL CENTER, does not meet the requirements indicated in the scope of verification, according to PEFCR- Product Environmental Footprint Category Rules for Dairy Products Version 1.0

Place and Date:
Barcelona, 10.03.2020

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Juan Andrés Salido Villatoro
Technical Reviewer – Assurance Iberia

Despite being a relevant social and economic driver, the dairy industry is well known for its high consumption of natural resources and for generating large amounts of emissions that affect the quality of the environment. To accurately identify the origin and amount of emissions that trigger environmental impacts related to the dairy industry, Life Cycle Assessment (LCA) has been widely used. However, the LCA reliability has been jeopardized by an unclear consensus regarding its many methodological choices; which generate heterogenous and incompatible results. This has created confusion among stakeholders and led to the uncontrolled proliferation of green credentials (eco-labels) for products in Europe and around the world.

This thesis results shown that a constant environmental assessment and improvement of dairy systems is possible through the use of specialised tools such as CalcPEFDairy, energy audits and circular economy indicators; which together are capable to identify and propose high impact improvement measures. The results also demonstrate the feasibility of properly communicating the CalcPEFDairy environmental assessment outcomes as a marketing strategy since their quality and reliability is such that they can be used in an external verification process to obtain an environmental declaration and eco-label for a market available dairy product. This verified green credentials give dairy producers the real possibility of increasing their economic returns without affecting their system and products environmental sustainability.

Beta

tecnio catalonia
Fins a 31/12/2023

ACCIÓ
Generalitat de Catalunya

The present Thesis was carried out at the Technological Centre for the Biodiversity, Ecology, Environmental and Agri-food Technologies (BETA Tech. Centre) at the University of Vic – Central University of Catalonia (UVic-UCC),