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Development and testing of the Product Environmental Footprint Milk Tool: A comprehensive LCA tool for dairy products

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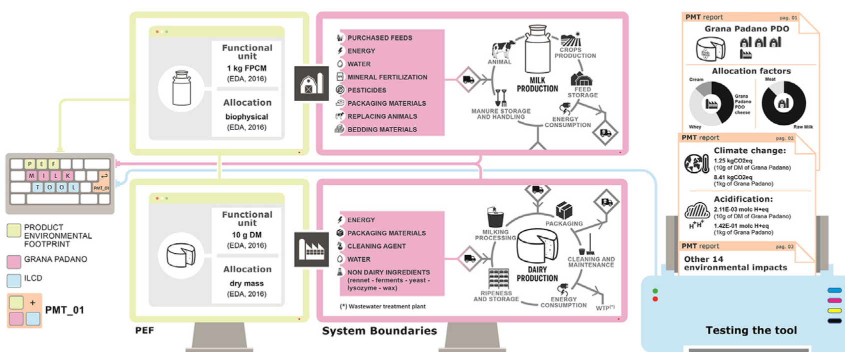
HIGHLIGHTS

- The paper describes the structure of the Product Environmental Footprint Milk Tool.
- The tool was developed on the bases of the Product Environmental Footprint rules.
- It assesses 16 environmental impact categories within the dairy production chain.
- Environmental impact of Grana Padano PDO cheese was evaluated for testing the tool.
- A scenario and a sensitive analysis were also included in the present study.

GRAPHICAL ABSTRACT



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ABSTRACT

The paper describes the general structure of the PMT_01 tool developed to assess the environmental impacts of different dairy products as Protected Designation of Origin (PDO) cheeses of Lombardy Region (Po Valley - Northern Italy) and High Quality fresh pasteurized milk in a cradle-to-distribution center gate approach.
Based on the PEF Product Environmental Footprint (PEF) methodology, the authors aim to provide a useful instrument for technicians and researchers in the evaluation of the environmental load of dairy products, allowing the process-hotspots identification through 16 different impact categories. The tool requires a modest amount of data that can be easily collected at the farms and at the dairies.
In order to test the tool's performance, the environmental impact of 10 g dry matter of Grana Padano PDO cheese was evaluated starting from the data of three different dairy farms used as “reference farming systems” and one dairy factory. A scenario and a sensitive analysis were also included in the study.
The main contribution to most of the environmental impact categories was related to the raw milk production while the dairy factory process affected significantly only a few impact categories.
The scenario analysis suggested that the anaerobic digestion could have a strong potential in the mitigation of the GHG emissions while the sensitive analysis confirmed that the choice of the allocation method at the dairy factory level is a key point in the methodological choices.
Despite the test of the tool was done only on three farms and one dairy factory, the results were consistent with those of recent studies. Even if some improvements in the tool functionalities are needed, we believe that in the future it could be easily applied on a wider sample of farms and dairies, and used to guide the stakeholders through a responsible environmental strategy.

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1. Introduction

Nowadays food retailers and consumers are more and more sensitive to the overall sustainability of animal products and, focusing their attention to the environmental aspects, they ask for foods with low impact (Ravaglia et al., 2018). Farming activities are considered to play an important role in depleting the Earth's resources and contributing significantly to Greenhouse Gas (GHG) emissions, to soil fertility and to biodiversity losses, to water scarcity and to the release of large amounts of nutrients and other pollutants that affect ecosystem quality (McMichael et al., 2007). Considering only the Global Warming Potential (GWP), the livestock sector accounts for approximately 14.5% of total human-induced emissions and the milk sector alone is contributing for the 20% (Gerber et al., 2013). Moreover the dairy sector affects the environmental sustainability in term of water resource depletion, freshwater eutrophication, marine eutrophication, freshwater ecotoxicity, land use, and acidification (Fantin et al., 2012).

Beside the strong environmental pressure of livestock production there is a world increasing demand of these products (Opio et al., 2011) and the big challenge of it will be to satisfy human needs without affect and compromise the ecosystem quality. Considering this scenario, in the last decades, many studies were performed to assess and analyze the environmental impacts of the dairy production in a life cycle approach. Life cycle assessment (LCA) (ISO, 2006a, 2006b) represents a reference method that helps in analyzing supply chains with the aim of achieving environmental sustainability objectives (Sala et al., 2017) and it consists in a comprehensive analysis that accounts the material and energy inputs and emissions associated with each stage of a product life cycle, from resource extraction trough processing to final use and disposal, for the assessment of the environmental load quantified on specific impact categories.

The LCA is now one of the leading methodologies for environmental metrics and it will potentially become a powerful strategic management and decision-making tool to make our society more sustainable and resource-efficient (Baldini et al., 2018).

Some of the studies were limited to the cradle-to-farm-gate system (Battini et al., 2016; Castanheira et al., 2010; Guerci et al., 2013a; Thomassen and De Boer, 2005) as it is well recognized that the biggest role in pollutant emissions is related to the raw milk production (Kim et al., 2013) but other works evaluated the environmental impact of specific dairy products (Bava et al., 2018; Berlin, 2002; Finnegan et al., 2017) in order to focus the attention on which steps of the entire process could be improved to have a more sustainable production.

Starting from this point, previous works have been already done in developing operational methods for the assessment of the environmental impacts of dairy activities: EDEN-E tool described by van der Werf et al. (2009) evaluated the potential impacts of 7 impact categories for 1000 kg of fat and protein corrected milk at the farm gate, Asselin-Balençon et al. (2013) developed a simplified model for the evaluation of the cradle to farm gate carbon footprint. The LatteGHG tool (Pirlo and Carè, 2013) was a simplified tool for the estimation of the carbon footprint of cow milk produced under typical conditions in Italy, and the Arla model (Dalgaard et al., 2014) assesses the farm-specific carbon footprint and Danish and Swedish national baselines for milk at the farm gate.

In our knowledge no model has been already developed for the assessment of the environmental impacts of dairy products in a full life cycle perspective, considering not only the primary production at the farm level but also the processing of the raw milk into the finished products. Moreover, many of the present tools were focused on the GHG emissions while the dairy production strongly affects also other environmental impact categories. A tool based on the cradle-to-distribution center-gate approach, able to assess different environmental impacts, might be the next step in the life cycle analysis applied to livestock production, because it can be used by technicians, extension personnel or researchers to evaluate the environmental performance of a specific product in its whole life cycle. The use of such operational tool might support the stakeholders and the decision makers for assessing and planning more environmental sustainable production solutions in a more complete approach compared to existing simplified LCA tools or commonly used software. As stated in the ISO/TS 14067 (ISO, 2013), action to minimize a single environmental impact can result in greater impacts arising from other environmental aspects (e.g. activities to reduce water pollution can result in increased GHG emissions from the life cycle of a product), in that way it is therefore important to have instruments covering not one or few impact categories but a large number of them.

The present study will explain how the PMT_01 tool was developed in order to assess the environmental impact of the dairy products in a “cradle to distribution center gate” approach. The tool included the Product Environmental Footprint (PEF) methodology based on “Recommendation 2013/179/EU” (European Commission, 2013) and the Product Environmental Footprint Category Rules (PEFCR) for dairy products (The European Dairy Association, 2016), and throughout life cycle assessment 16 environmental indicators were evaluated.

Actually the European certification schemes for dairy products have more than one reference document for the studies implementation, e.g. PCR 2013:18 Yoghurt, butter and cheese v.2 for The International EPD® System (Sessa, 2016), the Guidelines for the Carbon Footprinting of Dairy Products in the UK for Carbon Trust Footprint Label (DairyCo, 2010), etc. With a shared European methodology the European Commission aims to contrast the proliferation of environmental impact assessment methodologies (Ravaglia et al., 2018). The authors aim to provide the first reference tool for the sector based on the PEF, considering the reference methodology in the near future for LCA analyses in Europe, and to extend and ease the product environmental impact evaluation in Small and Medium Enterprises (SMEs), reducing time and cost for the implementation.

Moreover, in this study are reported the first results from the application of the PMT_01 in the assessment of the environmental impact of 10 g of dry matter of Grana Padano Cheese Protected Designation of Origin (PDO). A “scenario analysis” and a “sensitive analysis” were performed in order to compare respectively a farm with or without the anaerobic digestion (AD) of manure and different allocation choices for the finished products and by-products at the dairy factory.

2. Material and methods

2.1. Goal

The objective of this study was to present the PMT_01 tool, a comprehensive LCA instrument that aims to: a) analyze the environmental impacts of dairy products (i.e. hard and soft cheeses typical of the Po Valley – Norther Italy, High Quality milk; and Ultra High Temperature milk) according to PEF methodology; b) assess 16 different impact categories and determine the contribution of each stage of the dairy production chain (farms, dairies and distribution) on the environmental impact; c) support technicians and researchers in the evaluation of the environmental load of dairy products with the application of PEF methodology in SMEs.

In the presented work the PMT_01 methodology was described, moreover, in order to test a tool application: b) a case study of Grana Padano Protected Designation of Origin (PDO) cheese supply chain was analyzed; c) a scenario and a sensitive analysis were provided.

2.2. Scope

2.2.1. System boundaries

The tool was developed for a “cradle-to-distribution center-gate analysis”, the production system evaluated is shown in Fig. 1 and consists in two sub-systems: “Dairy Farm System” and “Dairy Factory System”. Both of the two sub-systems were divided in “Foreground Process” (FP) and “Background Process” (BP). According to PEF

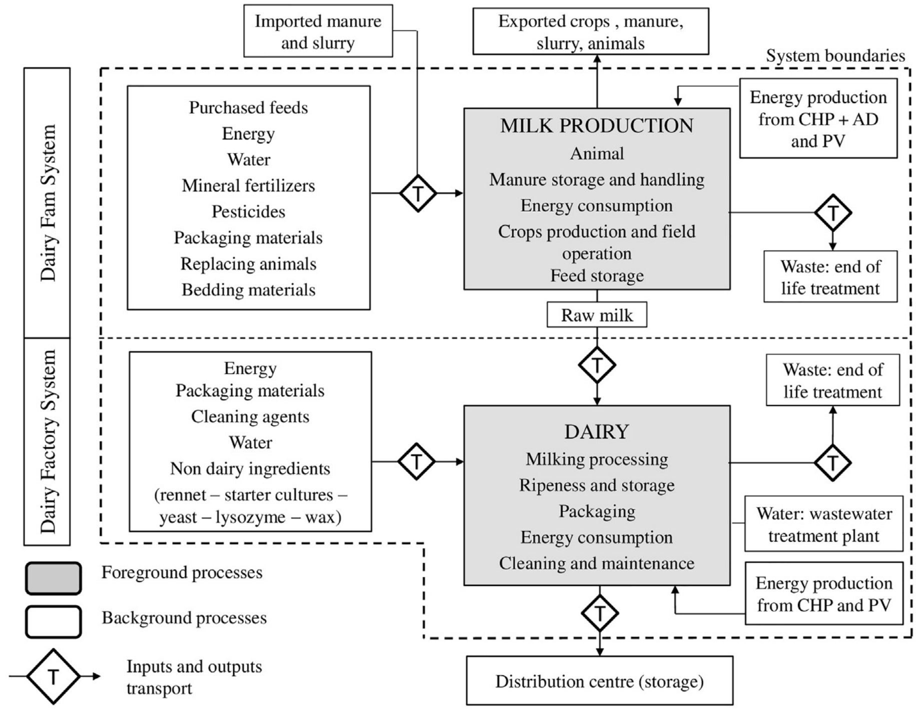

Fig. 1. System boundaries diagram for dairy products in PMT_01.

methodology, FP required company-specific datasets, while BP allowed, where appropriate, the use of secondary datasets. For the "Dairy Farm System" the FP were all the activities linked to the raw milk production at the farm level and the BP were related to all the most important production inputs, like purchased feeds, energy inputs, mineral fertilizers, pesticides, etc. Regarding the "Dairy Factory System" the FP were milk processing, packaging and transportation of the finished products from the dairy factory to the distribution centers, the BP were energy production, packaging materials, cleaning agents etc. Some less important inputs like medicines and cleaning agents used at the farms and rennet, lysozyme and starter cultures used in the dairy processing, were excluded from the analysis because the low amount consumed and lack of data concerning their production processes, their transport was however considered (Battini et al., 2016; Bava et al., 2018). The raw milk transportation from the farm to the dairies and the finished products transportation from the dairies to the distribution centers were evaluated as separate inputs from the other subsystems. The input and output processes represented in Fig. 1 as "out of the system boundaries" were included in the evaluation without take into account their environmental load, i.e. imported manure and slurry were considered as input of nitrogen and phosphorus for the farms crops production but the emission related to their production (storage and handling out of the system boundaries) were excluded (considered as residues, no economic value, with no upstream burden allocated).

The temporal coverage necessary for the analysis with the PMT_01 tool was a period of 1 year, for that reason all the data collected had to be referred to a "reference year". The model of LCA analysis was descriptive (attributional) (European Commission, 2013).

2.2.2. Allocation

The environmental impacts of the processes that involve multiple co-products, were allocated following the IDF rules (IDF, 2015): biophysical allocation was used for the production of raw milk and meat at the farm gate and dry mass content allocation was used for the processing of the finished dairy products and by-products. Allocation rule (100–0%) was used for electrical and thermal energy produced by the Combined Heat & Power (CHP) plant, this because the thermal energy produced was not used in the farm but only in the anaerobic digester. The digestate produced in the anaerobic digestion plant was considered as a residue and all the impact produced was attributed to biogas (Jungbluth et al., 2007).

Regarding "Background Process", when multiple co-products were originating from the production of the input, the choice was to accept what was proposed by the database used, and, in case of more than one allocation options, the worst-case scenario was considered. For the end-of-life-modelling was used the Cut-off approach proposed in Ecoinvent 3.4 database (Wernet et al., 2016).

Emissions related to the production and application of fertilizers and pesticides for crops production were allocated between self-consumed crops (for animal feeding) and sold crops in a linear way on the bases of the amount of each crop kept in the farm or sold. Emissions from energy consumption (i.e. diesel) for field management were not allocated as explained before to sold crops, because of difficult estimation, so the environmental load was charged precautionary on self-consumed crops entirely and consequently to milk and meat. The emissions related to renewable energy production sold (i.e. from CHP and photovoltaic plants to the national electricity network) were not allocated to raw milk, meat or dairy products.

2.2.3. Functional units

The functional units (FUs) used in the tool were: 1 kg of Fat and Protein Corrected Milk (FPCM) for raw milk (IDF, 2015), 10 g dry matter of packaged cheese, and 1000 ml of packaged liquid milk at the distribution center gate (The European Dairy Association, 2016).

2.3. Inventory analysis

The inventory analysis included in the tool was developed based on the inputs and the outputs for all the production stages. The main part of the data and information related to the inputs and to the outputs had to be collected directly on the farm with a dedicated check-list and at the dairy plant level. This step of the study is time

Table 1
Emissions estimated and methodology references for the Dairy Farm System.

Emissions	Methodology references
CH_4 - enteric fermentation	Tier 2 (IPCC, 2006)
CH_4 - manure storages	Tier 2 (IPCC, 2006)
N_2O - direct & indirect - manure storages	Tier 1–2 (IPCC, 2006)
N_2O - direct & indirect - fields fertilization[a]	Tier 1–2 (IPCC, 2006)
NH_3 - manure storages	Tier 2 (EEA, 2016)
NH_3 - fields fertilization[b]	Tier 2 (EEA, 2016)
NH_3 - pesticides application	Tier 2 (EEA, 2016)
NO_x - manure storages & grazing	Tier 2 (EEA, 2016)
NO_2 - fields fertilization[b]	Tier 2 (EEA, 2016)
NO_3 - fields fertilization[a]	Tier 1 (IPCC, 2006)
P - fields fertilization[b]	Emmenegger et al. (2009); Nemecek and Kagi (2007)
CO_2 - urea & carbonate limes fertilization	Tier 1 (IPCC, 2006)
NMVOC - animal housing, manure storages & animal grazing	Tier 2 (EEA, 2016)
NMVOC - manure spreading on fields	Tier 2 (EEA, 2016)
NMVOC - silage feeds	Tier 2 (EEA, 2016)
Water	(IDF, 2017; Truc, 1961)
Cu – Cd – Pd – Zn – Ni – Cr – Hg[b]	Freiermuth (2006)
PM 2.5	Tier 1 (EEA, 2016)

[a] Including emissions from: manure spreading, mineral fertilizers application, urine and dung inputs to grazed soils, crops residues and N fixed from N fixing crops.
[b] Including emissions from: manure spreading, mineral fertilizers application, urine and dung inputs to grazed soils.

consuming because it requires to interview the farmers, technicians and operators, and to check all the records necessary to complete the data collection.

The information that had to be collected for the estimation of the emissions from raw milk production are listed below:

Dairy farm system:
Foreground process:

- Herd management (n° of cows in milk, of dry cows and of replacing animals);
- Feeding management (rations composition, silage feeds storages);
- Housing management (type of animal housing, type of bedding);
- Manure management (type of manure and storage systems including anaerobic digestion);
- Crops production (crop land, type of crops, crops yield, fields operations, manure spreading);
- Energy consumption (electricity, diesel, liquefied petroleum gas).

Background process:

- Concentrate feed (compounds feed and raw materials) and purchased forages;
- Bedding materials (i.e. straw and sawmill);
- Mineral fertilizers (e.g. nitrogen (N), phosphorus (P), potassium (K), lime, etc.) and organic fertilizers (i.e. imported slurry and manure);
- Pesticides (if treatment is carried out or not);
- Replacing animals (i.e. purchased heifers and female calves);
- Infrastructure (milking parlor and dairy facility – useful life 30 years);
- Water (irrigation, drinking, and cleaning);
- Packaging materials (of the fertilizers and pesticides products, plastic materials used for silages);
- Energy carriers (i.e. diesel, natural gas, liquefied petroleum gas, electricity from national grid, electrical and thermal energy from CHP, electrical energy form photovoltaic plant, energy required for drying of grass);
- Treatment of slurry and manure in the AD plant;
- Transport (purchased concentrate feed and forages, manure and slurry imported, bedding materials, animals purchased, mineral fertilizers, pesticides, other materials).

Dairy farm system:
Outputs:

- Raw milk (quantity and composition);
- Meat (sold animals);
- Slurry/manure;
- Crops;
- Emissions.

Regarding the Dairy Factory System, some information about the process and the management are needed. The PMT_01 tool was developed on three types of dairy production: [1] cheese, hard and soft (hard cheeses like Grana Padano PDO cheese, Provolone Valpadana PDO cheese and Salva Cremasco PDO cheese and fresh and soft cheeses like Taleggio PDO cheese and Crescenza,); [2] High Quality milk; [3] Ultra High Temperature (UHT) milk. The PDO cheeses are typical of the Po Valley, Lombardy Region (Norther Italy) while Crescenza and HQ milk and UHT milk are normally produced in that geographical area.

Table 2
Processes and references for the Dairy Farm System.

Input	References	Activity data (input)
Milking equipment	Agribalyse v1.3	Area (m^2)
Purchased bedding materials	Agri-footprint v.4\Ecoinvent 3.4	Type and amount used (kg $year^{-1}$)
Purchased forages	Agri-footprint v.4\Ecoinvent 3.4	Type and amount used (kg $year^{-1}$)
Purchased concentrate feeds	Agri-footprint v.4\Ecoinvent 3.4	Type and amount used (kg $year^{-1}$)
Drying grains	Ecoinvent 3.4	amount of grains produced (kg $year^{-1}$)
Purchased milk powder	Agri-footprint v.4	Amount used (kg $year^{-1}$)
Purchased mineral fertilizers[a]	Agri-footprint v.4\Ecoinvent 3.4	Type and amount used (kg $year^{-1}$)
Purchased organic fertilizers	Agri-footprint v.4\Ecoinvent 3.4	Type and amount used (kg $year^{-1}$)
Purchased pesticides[a]	Ecoinvent 3.4	Estimated[c]
Drinking water	ELCD v3.2	Amount consumed (kg $year^{-1}$)
Wrapping materials used for silages	Ecoinvent 3.4	Amount used (kg $year^{-1}$)
Electricity[b]	Ecoinvent 3.4	Amount used (kWh $year^{-1}$)
Diesel	Agri-footprint v.4	Amount used (kg $year^{-1}$)
Natural gas for heat	USLCI\Ecoinvent 3.4	Amount used (liters and MJ $year^{-1}$)
Thermal energy from biogas plant	Ecoinvent 3.4	Amount used (kWh $year^{-1}$)
Transportations	Agri-footprint v.4\ELCD v3.2	km
Fields operations (from contractors)	References	Activity data (input)
Silages harvesting	Ecoinvent 3.4	ha $year^{-1}$
Grains harvesting	Ecoinvent 3.4	ha $year^{-1}$
Sowing	Ecoinvent 3.4	ha $year^{-1}$
Mowing	Ecoinvent 3.4	ha $year^{-1}$
Baling & bale loading	Ecoinvent 3.4	Unit
Manure spreading	Ecoinvent 3.4	Amount used (m^3 or kg $year^{-1}$)
Mineral fertilizing	Ecoinvent 3.4	ha $year^{-1}$
Pesticides application	Swiss Input Output database	Pesticides (type and amount used) (kg $year^{-1}$)
Irrigation	Ecoinvent 3.4	Amount of water consumed (m^3 $year^{-1}$)
Output	References	Activity data (input)
Solid waste (wrapping materials and packaging)	Ecoinvent 3.4	Automatically derived from related input data

[a] Packaging materials included (from Ecoinvent 3.4).
[b] Including electricity from photovoltaic or biogas plant.
[c] On the bases of the type of crops and crops management.

Dairy factory system
Foreground process:

- Water (mass and source of incoming water and mass and COD content of outgoing water);
- Type and mass loss of refrigerant gases (i.e. R407C, R404A, R507, R422D, R417B);
- Energy consumption (electricity, thermal);
- Mass and dry matter content of dairy products (i.e. raw milk in input and dairy co-products in outputs);
- Mass of chemicals used;
- Mass and type of solid waste produced;
- Mass and type of packaging used;
- Transports from the farms to dairies (type of truck used and km travelled).

Background process:

- Infrastructure (dairy construction – useful life 60 years);
- Raw milk (if purchased from the spot market);
- Non-dairy ingredients (i.e. sodium chloride);
- Cleaning agents production (i.e. sodium hydroxide and nitric acid);
- Gas mixtures for food use (e.g. nitrogen, oxygen, carbon dioxide, etc.);
- Primary, secondary, and tertiary packaging production (e.g. PET, PE, HDPE, core board, paper, corrugated board, packaging film, EUR-flat pallet – for pallets we considered a use of 20 times before their end of life);
- Other materials used (e.g. paper, lubricating oils, mixed plastics, iron and steel, etc.);
- Energy carriers (i.e. diesel, natural gas, liquefied petroleum gas, light fuel oil, electricity from national grid, electrical and thermal energy from CHP, electrical energy form photovoltaic plant);
- Input transportation (non-dairy ingredients, cleaning agents, packaging materials, other materials used);
- Transports of the wastes to the disposal centers;
- Transports of finished products from the dairies to the distribution centers.

Dairy factory system - outputs:

- Finished packaged products and co-products;
- Emissions.

The data inventories, for Dairy Farm System and Dairy Factory System, can be evaluated by the tool in compliance of the Data Requirements Rules reported in the PEFCR (The European Dairy Association, 2016).

2.4. Emissions estimation and impact assessment

All the data and the information collected were organized in two different types of dataset: one related to the Dairy Farm System and one related to Dairy Factory System. The dataset of the Dairy Farm System contained data of each individual farm included in the analysis: filling all the fields required by the dataset the tool automatically calculates the associated emissions related to 1 kg of FPCM for 16 impact categories. The weighted average impacts of the raw milk production based on the quantity of FPCM delivered by each farm to the dairies and all the data related to the milk processing at the factory level were then used for the calculation of the final results. The final environmental impact assessed for each product was expressed on 16 impact categories, following the ILCD 2011 Midpoint + (version 1.0.9, May 2016) – normalization/weighting set EU27 2010 equal weighting (Euorpoen Commission - Joint Research Centre, 2012): [1] climate change (CC) (time horizon of 100 years) using the characterization factors proposed by Myhre et al. (2013) in the IPCC Fifth Assessment Report; [2] ozone depletion (OD) (time horizon of 100 years); [3] human toxicity, non-cancer effects (HT – non-cancer effects); [4] human toxicity, cancer effects (HT - cancer effects); [5] particulate matter (PM); [6] ionizing radiation human health (IR-HH); [7] Ionizing radiation ecosystems (IR-E); [8] photochemical ozone formation (POF); [9] acidification (A); [10] terrestrial eutrophication (TE); [11] freshwater eutrophication (FE); [12] marine eutrophication (ME); [13] freshwater ecotoxicity (FWE); [14] land use (LU); [15] water resource depletion (WRD); [16] mineral, fossil & renewable resource depletion (MF & RRD). The ILCD 2011 Midpoint + was selected and used in compliance with the Recommendations for

Table 3
Processes and references for the Dairy Factory System.

Input	References	Activity data (input)
Dairy construction	Ecoinvent 3.4	Volume (m^3)
Milk delivered	–	Amount delivered (t $year^{-1}$)
Milk processed from member farms	PMT_01	Amount used per farm (t $year^{-1}$), fat and protein content per farm (g 100 g^{-1} or g 100 ml^{-1}) and the environmental footprint per farm (emissions estimated by the dairy farm system)
Milk processed from other farms (foreign)	Agri-footprint v.4	Amount used (t $year^{-1}$)
Main ingredients (sodium chloride, rennet, lysozyme, etc.)	Ecoinvent 3.4	Type and amount used (t $year^{-1}$)
Cleaning agents	Ecoinvent 3.4 and Agri-footprint v.4	Type and amount used (t $year^{-1}$)
Packaging materials (primary, secondary and tertiary)	Ecoinvent 3.4/Industry data 2.0	Type and amount used (kg $year^{-1}$)
Electricity[a]	Ecoinvent 3.4	Amount used (kWh $year^{-1}$)
Diesel	Agri –footprint v.4	Amount used (kg $year^{-1}$)
Natural gas for heat	USLCI\Ecoinvent 3.4	Amount used (liters and MJ $year^{-1}$)
Thermal energy from biogas plant	Ecoinvent 3.4	Amount used (kWh $year^{-1}$)
Light fuel oil	Ecoinvent 3.4	Amount used (MJ $year^{-1}$)
Refrigerant gases[b]	Ecoinvent 3.4	Amount used (kg $year^{-1}$)
Water	Ecoinvent 3.4	Source and amount of water consumed (m^3 $year^{-1}$)
Other materials	Ecoinvent 3.4	Automatically derived from solid waste
Transportations[c]	Ecoinvent 3.4	Type of truck used, European emission standards and distance (km)
Output	References	Activity data (input)
Factory products (cheeses, whey, cream, and milk)	–	Type and amount used (kg $year^{-1}$)
Solid waste (produced in factory)	Ecoinvent 3.4	Amount (kg $year^{-1}$) and waste scenario (% recycling, % incineration and % landfill)
Wastewater	Ecoinvent 3.4	Amount (m^3 $year^{-1}$) and BOD_5 or COD (mg/l)
Transportations	Ecoinvent 3.4\ELCD v3.2	Type of truck, European emission standards and distance (km)

[a] Including electricity from photovoltaic or biogas plant.
[b] Emissions in air of dispersed gas are included.
[c] Distance and tucks used for transporting cheese to distribution centers were assumed in the tool by the indications of PEFCR: 150 km and refrigerated truck, 7.5-16t, EURO 4, Allocation per mass.

Life Cycle Impact Assessment in the European context (European Commission - Joint Research Centre, 2011) and the report "Normalization method and data for Environmental Footprints" (Battini et al., 2014). The endpoint method was not used because not yet mature (Owsianiak et al., 2014).

In the Table 1 the information regarding the methodology used for the emissions estimation of the raw milk production at the Dairy Farm System are listed.

The estimation of emissions from other sources was done on the base of what proposed in different databases: Agribalyse v1.3 (Colomb et al., 2015), Agri-footprint v.4 (Blonk Agri-Footprint, 2017), Ecoinvent 3.4 (Wernet et al., 2016), ELCD v3.2 (European Commission - Joint Research Centre, 2017), Swiss Input Output database (Jungbluth et al., 2011), Industry data 2.0 (Plastics Europe, 2017), and USLCI (NREL, 2015). The details of the different processes and the activity data that had to be collected in the farms are listed in Table 2.

Regarding the Dairy Factory System, the emissions were estimated directly from the records provided by the factory. All the process related to the emissions assessment are listed in the Table 3.

2.5. Tool description and testing

PMT_01 is actually a IT-tool characterized by two connected sections: the first is dedicated to the Dairy Farming System and allows to calculate the PEF for raw milk, the second is dedicated to the Dairy Factory System and allows to calculate the PEF for drinking milk and cheese. The two sections have similar layouts organized on three levels: 1) user-friendly interface for data entry; 2) spreadsheets for data processing; 3) output with PEF results in graphical and tabular form. In the first level, the data entry interface was organized through masks those guide the cognitive process of data input; in the second level, the data were processed through the algorithms taken from the reference methodology. The third level provided the results (graphs and tables).

Table 4
Main characteristic, inputs and outputs of the three farms analyzed.

Characteristic	Units	Farm 1	Farm 2	Farm 3
Farm structure				
Dairy cows	Cows $farm^{-1}$ $year^{-1}$	27	230	140
Other cattle	Cows $farm^{-1}$ $year^{-1}$	28	280	188
Housing system (dairy cows)	–	Tight stall	Cubicles & full floor	Cubicles & slatted floor
Housing system (other cattle)	–	Deep litter	Slatted floor & deep litter	Slatted floor & deep litter
Manure management system	–	Solid manure	Liquid slurry, pit storage, anaerobic digester & solid manure	Pit storage & solid manure
Average productivity of cows	kg cow^{-1} day^{-1}	25.4	39.2	37.5
Farm land	ha	30	195	72.5
Permanent grassland	% of farm land	73.3%	0	27.6%
Corn silage[a]	% of farm land	0%	79.5%	55.2%
Days on grazing	days $year^{-1}$	0	0	0
N from slurry/manure/digestate	kg $farm^{-1}$ $year^{-1}$	1895	17,632	0
Inputs				
Purchased feed				
Corn silage	t $farm^{-1}$ $year^{-1}$	0	1314	0
Corn grains	t $farm^{-1}$ $year^{-1}$	50	400	300
Lucerne hay	t $farm^{-1}$ $year^{-1}$	10	0	110
Grass hay	t $farm^{-1}$ $year^{-1}$	10	150	0
Commercial feed	t $farm^{-1}$ $year^{-1}$	47	1027	280
Milk powder	t $farm^{-1}$ $year^{-1}$	1	9	0
Bedding material				
Straw	t $farm^{-1}$ $year^{-1}$	40	30	6
Sawdust	t $farm^{-1}$ $year^{-1}$	0	0	10
Purchased pesticides and fertilizers				
Pesticides	g ha^{-1} $year^{-1}$	0	2212	1534
Urea	kg ha^{-1} $year^{-1}$	0	30,000	12,000
NPK [13–13-19][b]	kg ha^{-1} $year^{-1}$	0	50,000	0
Energy consumption				
Diesel	kg $farm^{-1}$ $year^{-1}$	5239	44,532	15,582
Electricity	kWh $farm^{-1}$ $year^{-1}$	12,134	71,253	59,254
Electricity from co-generation	kWh $farm^{-1}$ $year^{-1}$	0	60,000	0
Electricity from photovoltaic plant	kWh $farm^{-1}$ $year^{-1}$	0	0	27,500
Other inputs				
Water for irrigation	m^3 $farm^{-1}$ $year^{-1}$	0	519,467	223,209
Water for livestock (watering and cleaning)	m^3 $farm^{-1}$ $year^{-1}$	1250	10,819	6916
Livestock purchase (live weight)	kg $farm^{-1}$ $year^{-1}$	0	0	0
Outputs				
Co-products				
Milk production	kg FPCM $farm^{-1}$ $year^{-1}$	208,164	2,708,437	1,641,494
Milk fat content	%	4.00	3.77	3.94
Milk protein content	%	3.25	3.48	3.56
Slurry/Manure/Digestate	m^3 $farm^{-1}$ $year^{-1}$	0	0	2966
Livestock sold (live weight)	kg ha^{-1} $year^{-1}$	4380	56,500	26,100
Wastes				
Polyethylene in municipal incineration	kg $farm^{-1}$ $year^{-1}$	733	3363	506
Polyethylene in landfill	kg $farm^{-1}$ $year^{-1}$	290	1330	200
Allocation				
Raw milk	%	87.3	87.4	90.4
Meat	%	12.7	12.6	9.6

[a] Considering second harvesting corn.
[b] Determined as average of other NPKs on the market.

An analysis on 10 g dry matter of packaged Grana Padano PDO cheese was done in order to test and to validate the tool. For this purpose, three farms and one dairy factory producing Grana Padano as main product were included in the study.

2.5.1. Dairy farms systems inventory

The three farms selected for the purpose of this study differed in herd size, housing systems, milk yield (kg milk cow^{-1} day^{-1}) manure management systems, home-grown crops and type and amount of production inputs. In Table 4 are reported the main characteristics of the farms analyzed. The reason why different farming systems were considered was to verify the capacity of the tool to cover a range of different situations as the variability in term of the farms size, farm management and production intensity is very high in the Lombardy Region.

2.5.2. Dairy factory systems inventory

The dairy factory analyzed in this study produced yearly 2853 tons of Grana Padano PDO cheese, 2954 tons of cream and 33,593 tons of whey.

The raw milk was daily collected, transported to the dairies and then processed for the production of Grana Padano.

2.5.2.1. Milk processing (Grana Padano production). After reception, the raw milk is heated to 40 °C for reactivation, then cooled to 10–12 °C and then skimmed with natural separation. After that the semi-skimmed milk is heated to 33–34 °C in 1 tons copper boilers, first the whey started is added then with a the liquid calf rennet and the lysozyme. After the curding phase, the curd is cut and cooked at a temperature around 55 °C then, during the curd extraction, the whey is aspirated and send to the separation line, the skimmed whey is cooled (at 15 °C) and sold, the cream is used or sold for other purpose (i.e. butter production). After the molding phase, the cheese was kept in a hot chamber for 24 h and then for 48 h in the cold chamber (13 °C and 85% of relative humidity), then it was sent to the saltwater tanks (at 11 °C salt saturated water). Afterwards the cheese was ripened with a minimum of 9 months (17 °C with 85% Relative Humidity). Storage silos and all the milk processing equipment were cleaned by Cleaning in Place (CiP) system using hot and cold water plus detergents: nitric acids, hydrochloric acids, and sodium hydroxide.

2.5.2.2. Products packaging. The cheese forms are cutted into 1 kg slices and packed with polymer envelope (polyethylene high density and polyamide) as shown in Table 5. Packaged and palletized cheese is stored in refrigerated cells and delivered to distribution centers located throughout Italy.

To calculate the inventory of 10 g of Grana Padano PDO cheese, data were weighted according to production volume of the dairy.

2.6. Scenario analysis and sensitive analysis

The scenario analysis was performed to test the ability of the tool to take into account some technical options along the dairy production chain that could improve the environmental performances of the finished products. In that case, we focused on the anaerobic digestion (AD) of manure. AD is recognized as an efficient strategy in the reduction of GHG emission at the farm level (Bacenetti et al., 2016; Battini et al., 2014; de Boer et al., 2011), for that reason the environmental impact of 1 kg of FPCM of Farm 2 was assessed not considering the AD.

AD and CHP scenario was modelled through the processes “Biogas {GLO}| market for | Cut-off, U” and “Electricity, high voltage {IT}| heat and power co-generation, biogas, gas engine | Cut-off, U” provide by Ecoinvent database (Wernet et al., 2016). Both processes were modified on the basis of the analyzed plants, through the following information collected on site: input substrates to the AD (i.e. energy crops and manure), transport of substrates used by the AD, % and N content of liquid and solid digestate produced; Low Heating Value (LHV) of biogas produced; size and electrical and thermal efficiency of the CHP plant. All other information were taken by default from the processes used. No additional data is required from users in addition to the electrical kWh produced and used in the farms to carry out the environmental assessment.

Regarding the sensitive analysis, it is well recognized that the allocation choice heavily affects the final results of a life cycle assessment (Flysjö et al., 2014; Guerci et al., 2014), so the Fat and Protein content Allocation (FP-A) and the Economic Allocation (E-A) were compared with the Dry Matter content Allocation (DM-A) implemented in the tool. FP-A was calculated considering the fat and protein content of the products and by-products at the dairy factory level (Bava et al., 2018) and the E-A considered the economic values of the products and by-products at the dairy factory level (Bava et al., 2018). More over the sensitive analysis was performed considering two different functional unit: 10 g of dry matter Grana Padano and 1 kg of Grana Padano as it is.

Table 5
Main characteristic, inputs and outputs of the dairy factory analyzed. Data refer to the production of Grana Padano.

Characteristic	Units	Dairy
Dairy structure		
Dairy construction (expected useful life 60 years)	m^3 $year^{-1}$	726
Dry matter		
Grana Padano PDO	%	67.5%
Whey	%	6.1%
Cream	%	22.3%
Inputs		
Main ingredients		
Raw milk	kg $year^{-1}$	39,154,356
Salt	kg $year^{-1}$	142,045
Rennet	kg $year^{-1}$	1712
Lysozyme	kg $year^{-1}$	970
Cleaning agents		
Nitric acid	kg $year^{-1}$	12,055
Sodium hydroxide	kg $year^{-1}$	464
Hydrochloric acid	kg $year^{-1}$	51,008
Carbon dioxide, liquid	kg $year^{-1}$	1724
Packaging		
Primary packaging – polymer bag	kg $year^{-1}$	34,241
Secondary packaging – Corrugated board	kg $year^{-1}$	107,002
Tertiary packaging – LDPE film	kg $year^{-1}$	1902
Tertiary packaging – EUR flat pallet	kg $year^{-1}$	118,891
Energy consumption		
Electricity	kWh $year^{-1}$	2,218,337
Natural gas	Nm^3 $year^{-1}$	186,146
Transport input materials	tkm $year^{-1}$	1,981,680
Refrigerant gases		
R407C	kg $year^{-1}$	13.9
R404A	kg $year^{-1}$	81.1
R507	kg $year^{-1}$	276
R417B	kg $year^{-1}$	27.8
Other inputs		
Underground water	m^3 $year^{-1}$	154,922
Outputs		
Co-products		
Grana Padano production	t $year^{-1}$	2853
Cream production	t $year^{-1}$	2638
Whey production	t $year^{-1}$	33,593
Wastes		
Mixed plastics	kg $year^{-1}$	29,476
Paper and cardboard	kg $year^{-1}$	2734
Bio-waste	kg $year^{-1}$	20,392
Muds	kg $year^{-1}$	843,483
Mineral oil	kg $year^{-1}$	121
Waste water	kg $year^{-1}$	490,048
Transport		
Transport Grana Padano with packaging	tkm $year^{-1}$	328,211
Transport wastes	tkm $year^{-1}$	26,886

Table 6
Impact assessment results per 10 g of DM of Grana Padano PDO.

Potential impact	Units	Characterization	Units	Normalization	Units	Weighted
CC	$kgCO_2$-eq.	1.25E-01	–	1.35E-05	μPt	9.03E-01
OD	kgCFC-11-eq.	3.74E-09	–	1.73E-07	μPt	1.16E-02
HT - non cancer effects	CTUh	1.10E-07	–	2.06E-04	μPt	1.37E + 01
HT - cancer effects	CTUh	2.08E-09	–	5.65E-05	μPt	3.77E + 00
PM	kg PM2.5-eq.	5.99E-05	–	1.58E-05	μPt	1.05E + 00
IR-HH	kBq U235-eq.	1.81E-03	–	1.60E-06	μPt	1.07E-01
IR-E	CTUe	2.05E-08	–	–	μPt	–
POF	kgNMVOC-eq.	4.43E-04	–	1.40E-05	μPt	9.32E-01
A	molc H^+-eq.	2.11E-03	–	4.45E-05	μPt	2.97E + 00
TE	molc N-eq.	9.15E-03	–	5.20E-05	μPt	3.46E + 00
FE	kgP-eq.	1.13E-05	–	7.61E-06	μPt	5.07E-01
ME	kgN-eq.	5.21E-04	–	3.09E-05	μPt	2.06E + 00
FWE	CTUe	7.28E-01	–	8.33E-05	μPt	5.56E + 00
LU	kgC deficit	8.28E-01	–	1.11E-05	μPt	7.38E-01
WRD	m3 water-eq.	1.26E-02	–	1.55E-04	μPt	1.03E + 01
MF & RRD	kgSb-eq.	1.04E-06	–	1.03E-05	μPt	6.84E-01

3. Results and discussion

3.1. Environmental impacts

Characterization, normalization and weighting results of 10 g of DM of Grana Padano PDO are shown in the Table 6. Normalization and weighting are optional steps of LCA, supporting the interpretation of the outcomes in order to better understand the relative significance of impact categories (Benini and Sala, 2016). Excluding toxicity-related impact categories, the effect of PM, A, TE, ME, and WRD cumulatively contributed to 80% of the total environmental impact (with the equal weighting approach, the weighting results were not different compared to the normalized impact scores). Considering that the emissions of toxic substances are currently incompletely covered in available normalization and weighting references, thus the related results were largely overestimated (Pizzol et al., 2017).

The weighting results of the entire life cycle, showed a contribution of the Dairy Farm System about the 96.9% confirming that the most relevant impact is related to this stage, followed by the Dairy Factory System (3.05%) composed by the dairy processing phase (2.20%), the packaging phase (0.41%), the raw milk collection phase (0.34%), and the transport of finished product phase (0.10%).

In the Fig. 2 are reported the characterization results of the different compartments for the selected functional unit.

As expected (and already mentioned for the weighting results) the main contribution to all the environmental impact categories was related to the raw milk production (Dairy Farm System) and it ranged from 99.0% for the FWE to 56.3% for the MF & RRD, except for the OD. Considering OD the Dairy Factory System played the most important role (49.2%) due mainly to the un-efficient refrigerant use (31.4% of the contribution) and to the energy consumption in term of electricity and methane burning for heat production that accounted respectively

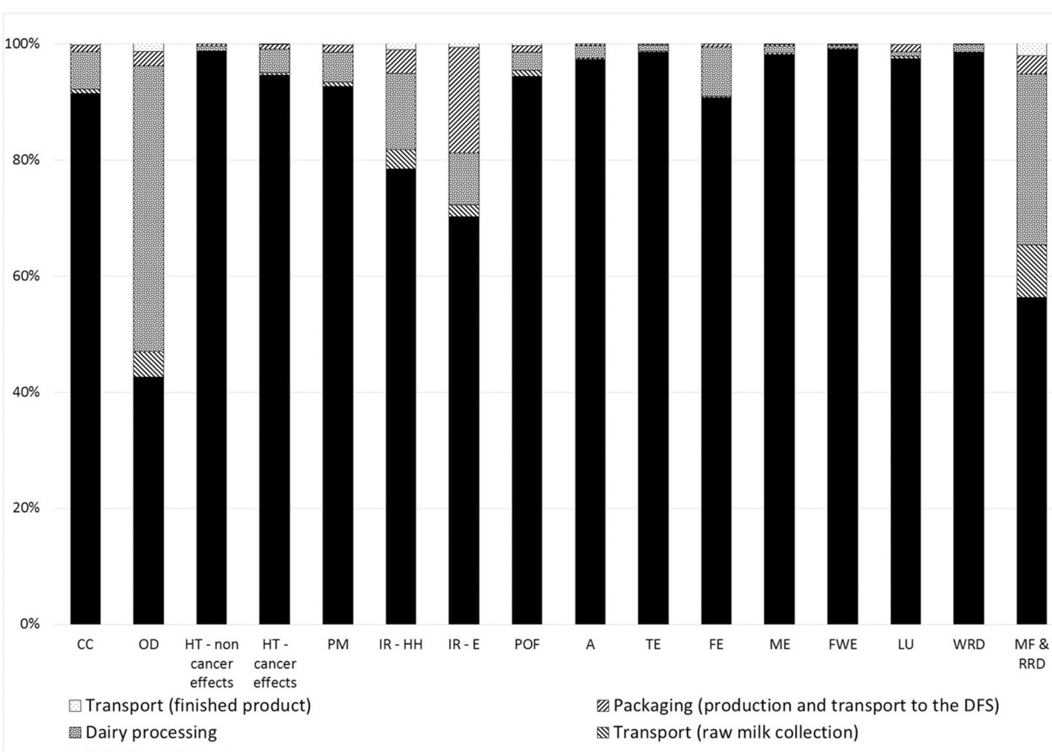

Fig. 2. Characterization results of the different compartments per 10 g of DM of Grana Padano PDO.

Table 7
Characterization results per 1 kg of FPCM produced by the farms analyzed.

Potential impact		Units	Total	Average[a]	Direct on-farm emissions	Bedding materials	Purchased feeds	Energy	Mineral fertilizers & pesticides	Packaging materials[b]	Water (irrigation and livestock)	Other emissions[c]
CC	FARM 1	$kgCO_2$-eq.	1.51E + 00	1.43E + 00	53.1%	4.3%	34.3%	6.5%	0.0%	1.3%	0.2%	0.1%
	FARM 2		1.37E + 00		42.0%	0.3%	46.1%	5.9%	2.2%	0.7%	2.5%	0.2%
	FARM 3		1.25E + 00		62.0%	0.1%	29.6%	4.5%	0.9%	0.2%	2.1%	0.7%
OD	FARM 1	kgCFC-11-eq.	1.30E-08	1.89E-08	0.0%	8.4%	63.1%	26.3%	0.0%	1.9%	0.3%	0.0%
	FARM 2		2.10E-08		0.0%	0.3%	67.7%	11.3%	12.0%	2.6%	6.1%	0.0%
	FARM 3		1.54E-08		0.0%	0.1%	63.0%	19.7%	10.1%	0.9%	6.1%	0.1%
HT - non cancer effects	FARM 1	CTUh	2.62E-06	1.11E-06	71.4%	13.3%	15.2%	0.1%	0.0%	0.0%	0.0%	0.0%
	FARM 2		1.61E-06		53.1%	1.3%	42.2%	1.9%	0.1%	0.0%	1.4%	0.0%
	FARM 3		5.17E-07		5.4%	1.3%	86.8%	3.1%	0.2%	0.0%	3.1%	0.0%
HT - cancer effects	FARM 1	CTUh	1.98E-08	2.29E-08	29.6%	20.1%	48.9%	0.8%	0.0%	0.5%	0.1%	0.0%
	FARM 2		3.04E-08		48.4%	0.8%	43.1%	1.6%	0.6%	0.2%	5.2%	0.0%
	FARM 3		1.11E-08		0.8%	0.7%	84.1%	2.9%	0.9%	0.2%	10.5%	0.1%
PM	FARM 1	kg PM2.5-eq.	8.21E-04	6.05E-04	73.5%	5.3%	15.2%	5.4%	0.0%	0.6%	0.0%	0.0%
	FARM 2		7.50E-04		61.3%	0.3%	24.8%	5.7%	3.8%	0.5%	3.5%	0.0%
	FARM 3		4.54E-04		51.1%	0.2%	33.7%	6.4%	4.0%	0.2%	4.2%	0.2%
IR-HH	FARM 1	kBq U235-eq.	1.10E-02	1.67E-02	0.0%	12.0%	64.7%	20.8%	0.0%	2.1%	0.3%	0.0%
	FARM 2		1.89E-02		0.0%	0.4%	80.4%	8.5%	5.6%	1.3%	3.7%	0.0%
	FARM 3		1.32E-02		0.0%	0.2%	78.9%	12.4%	4.0%	0.5%	3.9%	0.2%
IR-E	FARM 1	CTUe	1.16E-07	1.69E-07	0.0%	15.5%	65.3%	17.3%	0.0%	1.6%	0.3%	0.0%
	FARM 2		1.93E-07		0.0%	0.5%	82.4%	7.4%	5.8%	1.0%	2.9%	0.0%
	FARM 3		1.32E-07		0.0%	0.3%	81.9%	10.2%	3.9%	0.4%	3.2%	0.2%
POF	FARM 1	kgNMVOC-eq.	5.61E-03	5.41E-03	71.3%	3.2%	11.7%	12.6%	0.0%	0.8%	0.1%	0.3%
	FARM 2		5.54E-03		64.0%	0.2%	20.2%	10.4%	1.3%	0.5%	2.9%	0.4%
	FARM 3		3.70E-03		61.8%	0.1%	22.0%	10.4%	0.6%	0.2%	3.2%	1.7%
A	FARM 1	molc H^+-eq.	3.32E-02	2.17E-02	79.7%	5.0%	13.0%	2.1%	0.0%	0.1%	0.0%	0.0%
	FARM 2		2.82E-02		71.9%	0.3%	23.3%	3.1%	0.6%	0.1%	0.7%	0.1%
	FARM 3		1.56E-02		62.6%	0.2%	32.8%	2.7%	0.5%	0.1%	0.9%	0.3%
TE	FARM 1	molc N-eq.	1.48E-01	9.54E-02	80.4%	5.0%	12.5%	2.0%	0.0%	0.1%	0.0%	0.0%
	FARM 2		1.25E-01		73.3%	0.3%	22.4%	3.1%	0.4%	0.1%	0.3%	0.1%
	FARM 3		6.76E-02		64.5%	0.2%	31.7%	2.4%	0.3%	0.0%	0.5%	0.4%
FE	FARM 1	kgP-eq.	1.35E-04	1.19E-04	23.6%	29.5%	46.0%	0.8%	0.0%	0.1%	0.0%	0.0%
	FARM 2		1.35E-04		14.0%	1.7%	76.8%	2.5%	3.5%	0.1%	1.4%	0.0%
	FARM 3		9.16E-05		10.9%	0.9%	84.7%	1.4%	0.5%	0.0%	1.5%	0.0%
ME	FARM 1	kgN-eq.	1.57E-02	1.19E-02	74.5%	9.8%	14.1%	1.6%	0.0%	0.1%	0.0%	0.0%
	FARM 2		6.28E-03		13.0%	1.4%	79.2%	5.1%	0.4%	0.1%	0.6%	0.1%
	FARM 3		4.22E-03		8.2%	0.7%	86.5%	3.1%	0.2%	0.0%	0.6%	0.6%
FWE	FARM 1	CTUe	8.46E + 00	8.31E + 00	11.9%	59.5%	28.3%	0.1%	0.0%	0.2%	0.0%	0.0%
	FARM 2		9.98E + 00		48.1%	2.9%	47.8%	0.6%	0.2%	0.1%	0.4%	0.0%
	FARM 3		5.81E + 00		32.4%	1.7%	64.9%	0.3%	0.2%	0.0%	0.4%	0.1%
LU	FARM 1	kgC deficit	1.09E + 01	9.43E + 00	0.0%	25.9%	73.8%	0.2%	0.0%	0.1%	0.0%	0.0%
	FARM 2		1.10E + 01		0.0%	1.5%	93.6%	2.6%	0.2%	0.1%	2.0%	0.0%
	FARM 3		6.56E + 00		0.0%	0.8%	95.5%	0.9%	0.3%	0.0%	2.4%	0.0%
WRD	FARM 1	m3 water-eq.	3.58E-03	3.13E-01	0.0%	44.5%	22.7%	8.1%	0.0%	0.8%	23.8%	0.0%
	FARM 2		1.65E-01		0.0%	0.1%	11.1%	0.1%	0.1%	0.0%	88.7%	0.0%
	FARM 3		1.28E-01		0.0%	0.0%	15.9%	0.1%	0.0%	0.0%	83.9%	0.0%
MF & RRD	FARM 1	kgSb-eq.	3.85E-06	7.74E-06	0.0%	2.8%	84.3%	10.0%	0.0%	2.6%	0.2%	0.0%
	FARM 2		6.67E-06		0.0%	0.1%	26.9%	10.2%	13.7%	2.4%	46.6%	0.0%
	FARM 3		7.39E-06		0.0%	0.0%	39.0%	23.1%	6.5%	0.6%	30.8%	0.0%

[a] Average impact of incoming raw milk based on the average weighted according to kg of FPCM delivered by each farm.
[b] Packaging materials: includes their production and end-of-life.
[c] Other emissions: include transport and infrastructure.

for the 9.2% and 5.0% of the total impact for this category. Contribution to MF & RRD from the Dairy Factory System (29.6%) was mainly affected by the cheese-making process (21.4% of the total impact). Transportation of the raw milk from the farms to the dairy factory was significant for MF & RRD (9.0%), OD (4.4%), IR-HH and IR-E (3.3% and 2.1% respectively) and it suggested that a more efficient management of the raw milk collection could improve the environmental impact (Bava et al., 2018). On the contrary the transportation of the finished product was not relevant for the most environmental impact categories and it only slightly affected MF & RRD (2.1%), OD (1.4%) and IR-HH (1.0%), might point out that the logistic behind the distribution of the finished product to the retail points was already efficient. The packaging production was relevant only for IR-E (18.0% of the impact). Considering the CC, the emission from the Dairy Farm System highly affected the final results (91.4%) and this finding was in line with what shown by previous studies on Grana Padano (Bava et al., 2018; Guerci et al., 2016) and on other cheese productions (Berlin, 2002; González-García et al., 2013; Palmieri et al., 2017). In any case it is important to underline that all the comparisons between LCA studies has to be done carefully as many assumptions and methodological decisions can differ and consequently affect the final results. Despite the water consumption for producing animal food is a big issue, as the water footprint of any animal product is larger than the water footprint of crop products with equivalent nutritional value (Mekonnen and Hoekstra, 2012), not many studies have focused on this topic compared to other impact categories (i.e. carbon footprint). Our results showed that, despite the use of water in the dairy processes might be relevant (i.e. for cleaning end sanitization of the equipment), the Dairy Farms System was still main responsible for WRD due to the consumption of water for animal drinking, cleaning process and crop production as in the area where the three farms were located was very common to irrigate the crops fields during the summer period.

3.2. Dairy farm system emission

The Dairy Farm System was the principal responsible for the environmental impacts and the detailed results for 1 kg of FPCM at the farm's gate are reported in Table 7. The data show a certain degree of variability between the three farms, both in term of the total impacts and in term of the contribution of each single compartment to every environmental impact category.

Considering the average values, the CC estimated (1.43 kgCO_2-eq.) was in line to what found by Bava et al. (2018) but slightly higher compered to Guerci et al. (2013b). Bava et al. (2014) and Battini et al. (2016) who assessed the environmental impact of dairy farms located in the same region (Lombardy, Italy) of the present study. The results regarding the eutrophication potentials in term of ME and FE (1.19E-04 kgP-eq. and 1.19E-02 kgN-eq. respectively) agreed with the findings of Bava et al. (2018). Battini et al. (2016) and Roer et al. (Roer et al., 2013).

About the other impact categories, the results for POF (5.41E-03 kgNMVOC-eq.) was consistent with the findings of Bava et al. (2018) and Roer et al. (2013). PM, A, TE, MF & RRD and FEW were similar to those of Bava et al. (2018), while the value of OD was higher compared to the result of Bava et al. (2018) but in good agreement to the result of Roer et al. (2013).

The data in Table 7 show that CC, PM, POF, A and TE were heavily affected by direct on-farm emissions for all the three farms, while for the other impact categories the trend is different. Further investigations need to be done in order to understand the relation between the results obtained and the farm characteristics.

Considering only the direct on-farm emission, the Fig. 3 shows the contribution from the different sources: enteric fermentation mainly affected the direct GHG emission, the value found in the present study ranged from 55.4 to 68.0% and it was comparable to the findings of Battini et al. (2016). Fertilizers (organic and mineral) application for the production of home-grown feed covered about the 100% of direct emissions linked to HT - non cancer effects, HT - cancer effects and FE. Emissions from storage and use of silage feeds were significant only for POF and they affected the direct emission of this impact category from the 52.5 to 62.7%. Not surprisingly the PM, A, TE and ME direct emissions were heavily influenced by the nutrients management both in manure storages and handling and in the application of the fertilizers on the fields and similar findings were reported also in the recent study of Baldini et al. (2018). About the contribution to FWE direct emissions, pesticide application played the main role for farm 2 and farm 3 (88.3 and 99.1% respectively) while farm 1 did not used any pesticides.

3.3. Scenario and sensitive analysis

Supposing that the anaerobic digestion (AD) was not adopted in the manure management of Farm 2 the environmental impacts changed as shown in Fig. 4. Even if all the impact categories were affected, only seven of them had a variation of more than 10% compared to the reference scenario (anaerobic digestion in place).

The main negative effects were related to HT-non cancer effect, IR-HH. FE and CC, these impacts increased by 27.4%, 18.2%, 13.8% and 12.4% respectively while a reduction of the impact on FEW, ME and POF was observed to be 13.2%, 12.9% and 10.5% respectively. Regarding the CC, the introduction of the AD in the manure management system was confirmed to have a strong potential in the mitigation of GHG emissions (de Boer et al., 2011), but the effects on the other impact categories were not so clear if compared to the previous results of Bacenetti et al. (2016) and Battini et al. (2016).

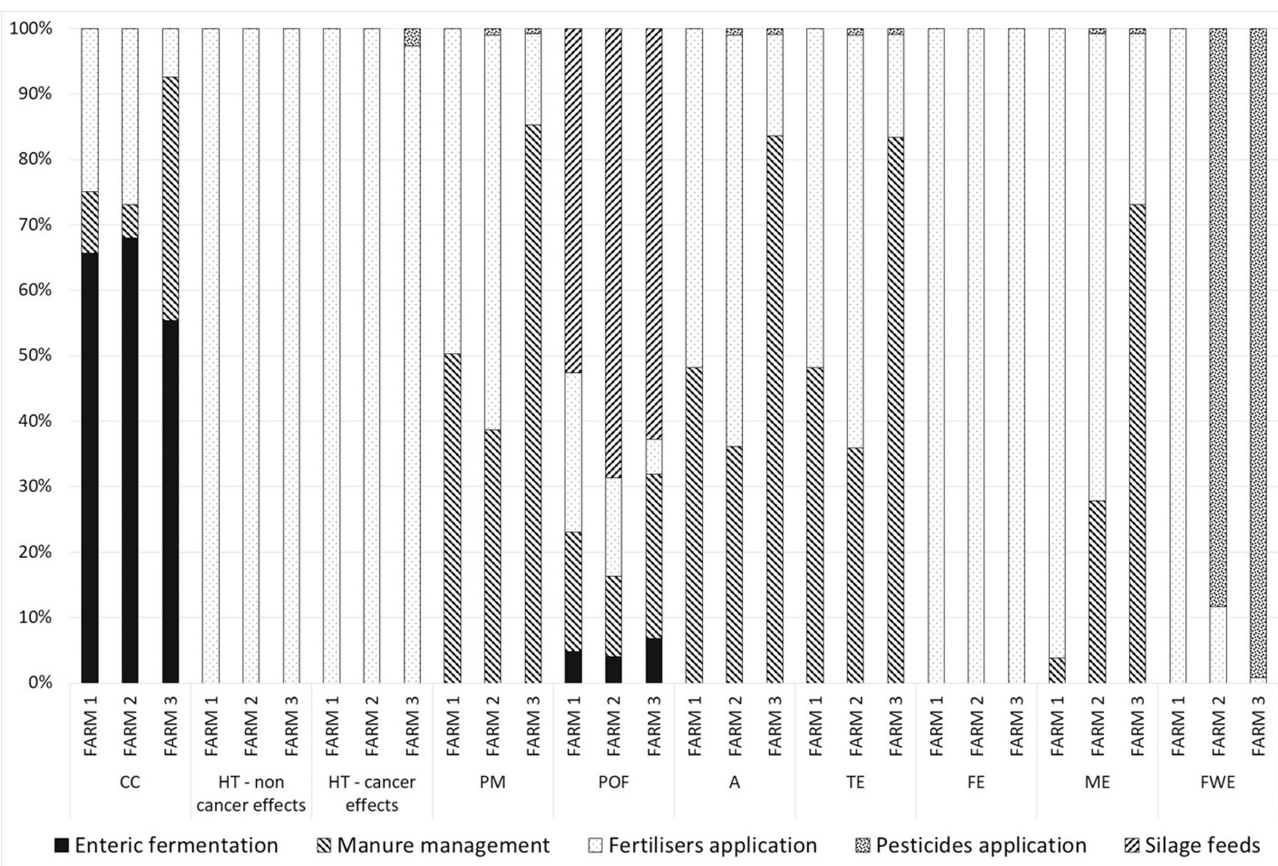

Fig. 3. Direct on-farm emission results per 1 kg of FPCM produced by the farms analyzed.

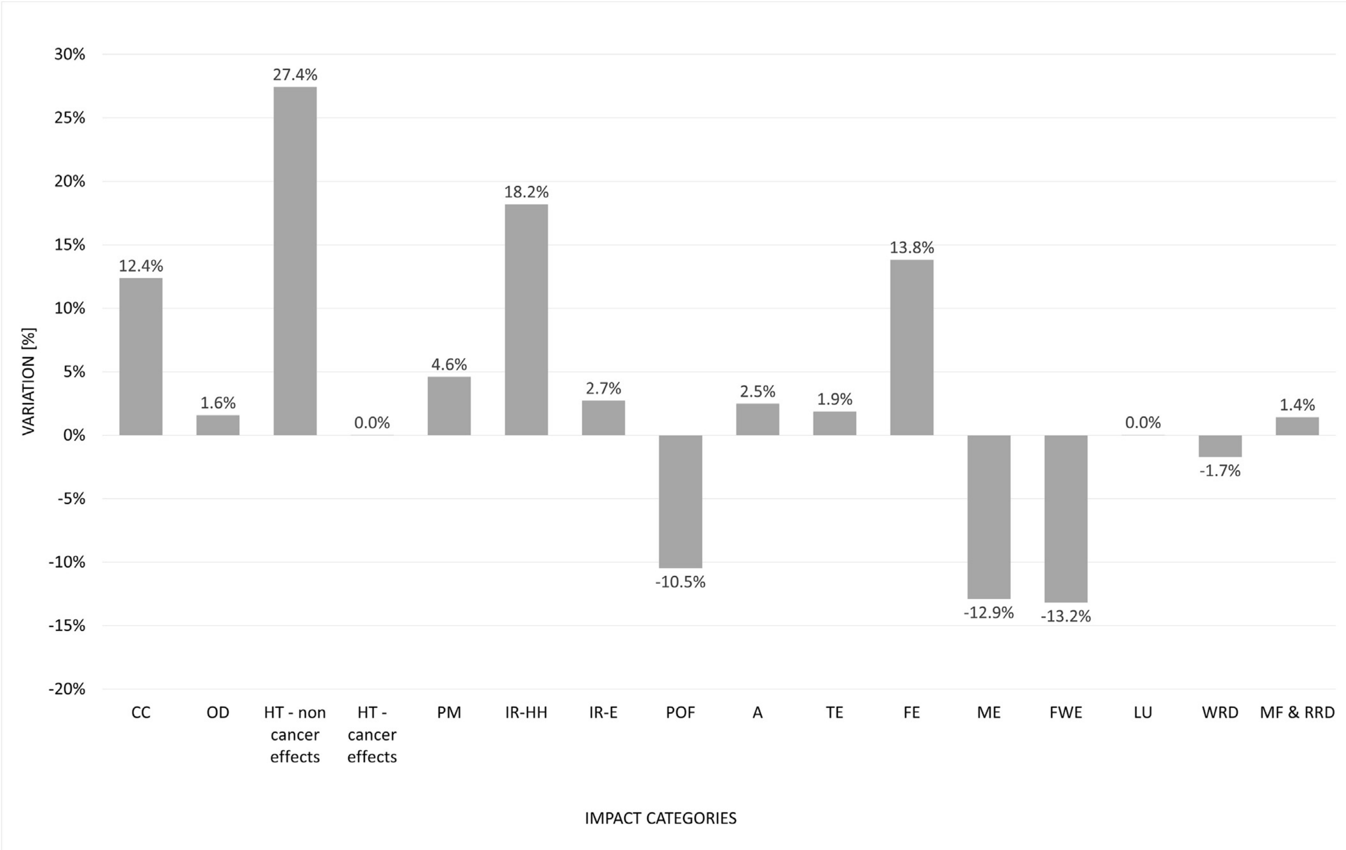

Fig. 4. Variation % of the environmental impacts for 1 kg of FPCM in farm 2 without anaerobic digestion plant (biogas).

The variations of the allocation factors obtained changing the allocation method for the products and the by-products at da dairy factory level, were in some cases significant (Fig. 5) and consequently they had a strong influence on the final results.

Economic allocation (E-A) factor for Grana Padano was 81.8%, higher compared to both the Dry Metter allocation (DM-A) factor (42.4%) and the Fat and Protein allocation (FP-A) factor (60.8%), while the E-A factor for whey showed a strong reduction compared to the other two co-

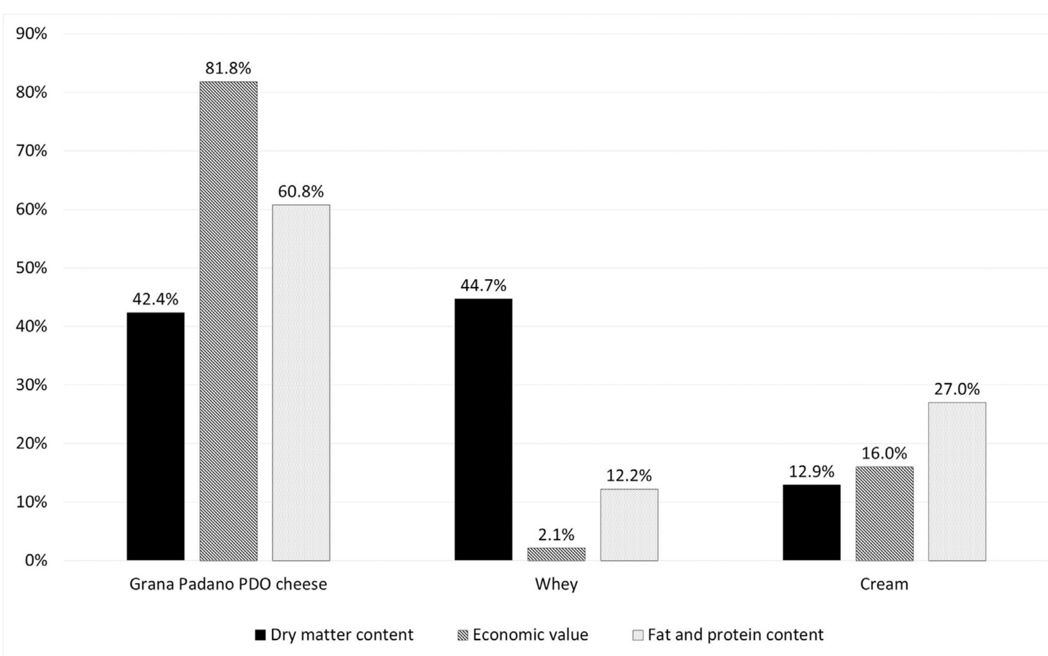

Fig. 5. Allocation factors (%) of Grana Padano and other products and by-products considering different allocation methods.

Table 8
Characterization results per 1 kg of Grana Padano PDO cheese considering three different type of allocations.

Potential impacts	Unit	Allocation DM	Allocation with economic value	Allocation Fat and Protein content
CC	$kgCO_2$-eq.	8.43E + 00	1.63E + 01	1.24E + 01
OD	kgCFC-11-eq.	2.53E-07	4.80E-07	3.48E-07
HT - non cancer effects	CTUh	7.41E-06	1.44E-05	1.10E-05
HT - cancer effects	CTUh	1.41E-07	2.73E-07	2.08E-07
PM	kg PM2.5-eq.	4.04E-03	7.82E-03	5.97E-03
IR-HH	kBq U235-eq.	1.22E-01	2.31E-01	1.76E-01
IR-E	CTUe	1.38E-06	2.44E-06	1.91E-06
POF	kgNMVOC-eq.	2.99E-02	5.79E-02	4.43E-02
A	molc H^+-eq.	1.42E-01	2.77E-01	2.12E-01
TE	molc N-eq.	6.17E-01	1.20E + 00	9.21E-01
FE	kgP-eq.	7.60E-04	1.48E-03	1.12E-03
ME	kgN-eq.	3.52E-02	6.85E-02	5.24E-02
FWE	CTUe	4.92E + 01	9.58E + 01	7.33E + 01
LU	kgC deficit	5.59E + 01	1.08E + 02	8.30E + 01
WRD	m3 water-eq.	8.49E-01	1.66E + 00	1.27E + 00
MF & RRD	kgSb-eq.	6.99E-05	1.30E-04	9.80E-05

products. The allocation factors for whey and cream calculated in this study were comparable to what found by Bava et al. (2018) as well as the economic allocation factor for Grana Padano. A limitation of the economic allocation approach is the variation of the market price that can change quickly and make difficult to compare the results of same products.

In Table 8 are reported the results obtained from the sensitive analysis for 1 kg of fresh matter Grana Padano PDO instead 10 g of dry matter. Even the variations of the results followed the same trend explained before, the data help to understand how the environmental burden of a specific product can be affected negatively or positively by the allocation system but also the choice of the functional unit might be relevant in expressing the final results.

For example, the CC for 1 kg of fresh matter Grana Padano is 16.3 $kgCO_2$-eq with the E-A factors, but just a half if the DM-A factor (8.43 $kgCO_2$-eq.) was used. Considering the values shown in Table 8, they are comparable to what found by Bava et al. (2018) for the most environmental impact categories (CC, PM, POF, A, TE, FE and MF & RRD). Taking into account the CC only, the result with the FP-A factor (12.4 $kgCO_2$-eq) were slightly lower compared to Guerci et al. (2016) but higher than González-García et al. (2013) who investigated the environmental impact of a Galician semi-hard PDO cheese choosing for no-allocation.

4. Conclusion

The results obtained, in term of potential impacts and contributions of the different compartments, were consistent with what found by previous studies considering both the environmental impacts of the finished product (Grana Padano PDO cheese) and the environmental impacts of the raw milk production. Even if the analysis was conducted only on a limited number of farms and on one dairy factory, the reliability of the tool in the estimation of the environmental impacts was supported by the fact that most of the findings agreed with recent works.

Regarding the Dairy Farm System, that mainly affects the environmental performance of the production of Grana Padano PDO cheese and the dairy products in general, the variation among the results of the farms analyzed were probably linked to the characteristics of the farms, but this aspect needs to be deeper investigated and to be supported with a study on a bigger sample of farms.

The starting point for further improvements in the tool development is to refine the capacity of the tool to compare the ability of the different farms and also the different dairy factories in using resources, highlighting how they can affect the environmental performances. In that way the effects of different management practices and technical innovation included in the system boundaries could be tested and the results obtained could be used to guide the stakeholders and the decision makers through more responsible environmental strategy.

Actually, the PMT_01 tool is a IT-tool tested on three Lombardy dairies, to which about 80 farms delivering raw milk. From a functional point of view, these first phases of experimentation showed a good usability of the tool with ample margins for improvement the IT infrastructure. Specifically, this test process highlighted the need to integrate PMT_01 with company management and accounting systems in order to automate data collection. PMT_01 is a tool consisting of dedicated interface linked with spreadsheet for PEF evaluation currently in the testing phase.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.08.142.

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