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Environmental hot-spots and improvement scenarios for Tuscan “Pecorino” cheese using Life Cycle Assessment

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ABSTRACT

The agricultural sector released about 5.4 Gt CO_2 eq in 2010, of which 57% was due to the livestock sector. Cattle are the main contributors (65%) to the livestock sector's emissions, while sheep and goats (small ruminants) are responsible for about 6.5%, corresponding to 475 million tonnes CO_2 eq. The Life Cycle Assessment method has been largely adopted to assess the environmental impacts connected to the livestock sector and to related products. Despite this, very few pieces of research are specifically addressed to analysis of the environmental performances of sheep cheese and, particularly, to the proposal of improvement strategies that may allow the reduction of environmental impacts. In this context, the Life Cycle Assessment method is applied in order to assess the environmental hot-spots of Tuscan “Pecorino” cheese (a traditional Italian dairy product obtained from sheep milk processing) and to evaluate potential improvement scenarios. The analysis follows a “cradle to gate” approach by including the processes related to sheep breeding (intensive system), milk transport and cheese production. The functional unit selected is 1 kg of “Pecorino” cheese, packaged at dairy farm gate and ready to be distributed. Focusing on Climate Change impacts, the results highlight that the total impacts related to the functional unit are 22.13 kg CO_2 eq. The environmental hot-spots are mainly connected to direct emissions from the sheep enteric fermentation and to the production of feed used in sheep breeding, as well as, to waste water treatment and electricity consumption during cheese production. The adoption of a different breeding system (from intensive to extensive) may represent a good improvement option for the reduction of environmental impacts related to the baseline system, as well as the utilisation of a photovoltaic system as an alternative energy source for production of the electricity used in the cheese production phase.

1. Introduction

Small ruminants (sheep and goat) are responsible for about 6.5% of greenhouse gas (GHG) emissions related to the livestock sector, corresponding to 475 million tonnes CO_2 equivalent (eq) (Gerber et al., 2013; Opio et al., 2013). Enteric fermentation and feed production largely dominate the sources of GHG emissions for small ruminants, accounting for 55% and 35% respectively (FAO, 2016). In 2011, sheep produced more than 8 million tonnes of milk, which corresponds approximately to 67 million tonnes CO_2 eq - excluding post-harvest emissions (Gerber et al., 2013). The heterogeneity of the small ruminant production systems (e.g. the wide range of agro-ecological zones; the diversity of systems, species and products; the secondary economic importance and low political weight of the Mediterranean and other European areas - de Rancourt et al., 2006) leads to difficulties in their environmental assessment. Because of this, few studies and guidelines have addressed the environmental load of the sheep sector, in particular when it is referred to cheese production. In this context, it is known that cheese production and dairy products can play a remarkable role in environmental impacts (de Vries and de Boer, 2010; Steinfeld et al., 2006).

The present research focuses on the production of Tuscan “Pecorino” cheese, which is a traditional Italian dairy product made by the processing of sheep milk. This type of cheese is very popular worldwide, principally due to the quality label “Protected

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Designation of Origin - PDO" (Lerma-García et al., 2010). PDO is a European scheme implemented for "agricultural products and foodstuffs which are produced, processed and prepared in a given geographical area using recognised know-how" (EU, 2012). According to the Italian Statistical Institute, sheep rearing is the second largest livestock system managed in Italy (7,148,534 units corresponding to about 32% of total livestock) after swine rearing (ISTAT, 2015). In 2015, 397,508 tonnes of sheep milk and 30,714 tonnes of pecorino cheese were produced in Italy (ISTAT, 2015).

Different Life Cycle Assessment (LCA) studies have focused on assessment of the environmental impacts related to sheep milk production and, in particular, to breeding processes (e.g. Atzori et al., 2013a; Atzori et al., 2013b; Vagnoni et al., 2015). On the contrary, only two studies regard assessment of the specific production of "Pecorino" cheese by including the cheese making processes in the analysis (Favilli et al., 2008; Conte et al., 2015).

Favilli at al. (2008) assessed the sustainable production of "Tuscan Pecorino PDO" in a geothermal district in which renewable energy sources were adopted. The analysis underscored that Global Warming related to 3.053 kg of "Pecorino" cheese was 47,299.64 g CO_2 eq and the highest impacts were connected to the milk production phase, which accounted for 92.49% of the Global Warming impacts.

Conte et al. (2015) analysed the "environmental indirect effects related to the different choices in the food packaging" by assessing the life cycle of sheep cheese from the production of milk to the cheese making and packaging processes. The study underscored that sheep breeding plays an important role with respect to the other phases (sheep breeding 86.2%, cheese-making 8.5%, transport 3.5%, milking 1.8%).

To the authors' knowledge, the scope of the previous LCA studies only extends to the identification of the environmental hot-spots connected to the production of "Pecorino" cheese and none of the LCA studies focus attention on the proposal of alternative and improvement strategies for processes related to the environmental hot-spots.

In this context, this study has two main goals. Firstly, a detailed study is performed of the environmental burden of Tuscan "Pecorino" cheese production made by the processing of sheep milk obtained in an intensive sheep breeding system, through implementation of the LCA method. This allows us to underscore the environmental hot-spots and to include detailed information related to the system considering the whole life cycle. The choice of assessing Tuscan "Pecorino" cheese production is connected to the importance of this product in Italy and worldwide. In addition, the study investigates a particular and specific type of sheep breeding. Indeed, there are very few companies that adopt an intensive sheep breeding system, in Italy (the choice of managing intensive sheep breeding is mainly related to specific traditions passed down for generations). Furthermore, because of the lack of information regarding the environmental impacts of this particular breeding system, a detailed analysis can add valuable information to the scientific literature. The second goal of this analysis is to quantify and compare potential improvement scenarios that use alternative practices for processes related to the environmental hot-spots of the baseline system. In this context, the study aims to improve the scientific literature related to this specific product, by proposing potential improvement options that may allow reduction of systemic environmental impacts.

This paper is structured as follows:

1. Introduction - summarizing the general aim of the paper and its structure;
2. Materials and methods - explaining the analysis framework applied;
3. Results and discussion - divided into: characterisation results, normalisation results, proposal for environmental improvement strategies, and sensitivity analysis;
4. Conclusions - summarizing the main findings of the paper.

2. Materials and method

The analysis starts with a detailed description of the production of Tuscan "Pecorino" cheese (baseline system) and assessment of the environmental hot-spots related to this system by applying the LCA method.

Secondly, a comparative LCA is implemented on the environmental hot-spots of the baseline system and potential improvement scenarios, in order to propose strategies that would improve the environmental performance of the system. The potential improvement scenarios are described in section 3.

Lastly, a sensitivity analysis is performed in order to evaluate the potential influences on results related to the inventory data.

Analyses are carried out by means of the LCA method. LCA is a standardized tool that allows analysis of the potential environmental impacts of a product, process or service throughout its whole life cycle, from raw material extraction and processing, through manufacturing, transport, use, reuse, recycling and final disposal (Guinée, 2002). LCA is structured in four iterative phases, in accordance with ISO standards: 1) goal and scope definition, 2) inventory analysis, 3) impact assessment, and 4) interpretation (ISO, 2006a; ISO, 2006b).

2.1. Goal and scope definition

The goals of this study are to define the environmental burden of Tuscan "Pecorino" cheese production through a hot-spot analysis and to analyse improvement scenarios for processes related to the identified environmental hot-spots. The scope is to propose a detailed picture of the environmental performance of the system as well as to propose improvement options/processes for the reduction of environmental impacts.

System boundaries related to "Pecorino" cheese production (baseline system) are based on a "cradle to gate" approach (Fig. 1) in which three different phases are considered: 1) breeding, 2) milk transport, and 3) cheese production. The agricultural aspects related to intensive sheep breeding and the resulting milk production are included in phase 1, while the transport of milk from farm to dairy factory and the processing of milk into "Pecorino" cheese are included in phases 2 and 3, respectively. System boundaries include all processes related to the system except for the rennet and starter culture used in cheese production (phase 3), because no specific information and data on these two products were available. Furthermore, system boundaries do not include the disposal of whey obtained in phase 3, which is partially sent to a feed factory in order to be treated and adopted for livestock feeding, and partly used to produce a different type of cheese called "Ricotta". These aspects are outside the scope of this analysis. Infrastructure, machinery and equipment are also included in the system boundaries and an average life time of 80, 15 and 5 years, respectively, is set to associate the environmental impacts to one year of "Pecorino" cheese production.

The hot-spot analysis (baseline system) and comparative LCAs (alternative scenarios) were carried out using the functional unit (FU) of *1 kg of "Pecorino" cheese, packaged at dairy farm gate and ready to be distributed*, as suggested by the International Dairy Federation (IDF, 2015). This FU was selected to better understand the environmental consequences related to the final product, since 1 kg represents the average weight of one "Pecorino" shape

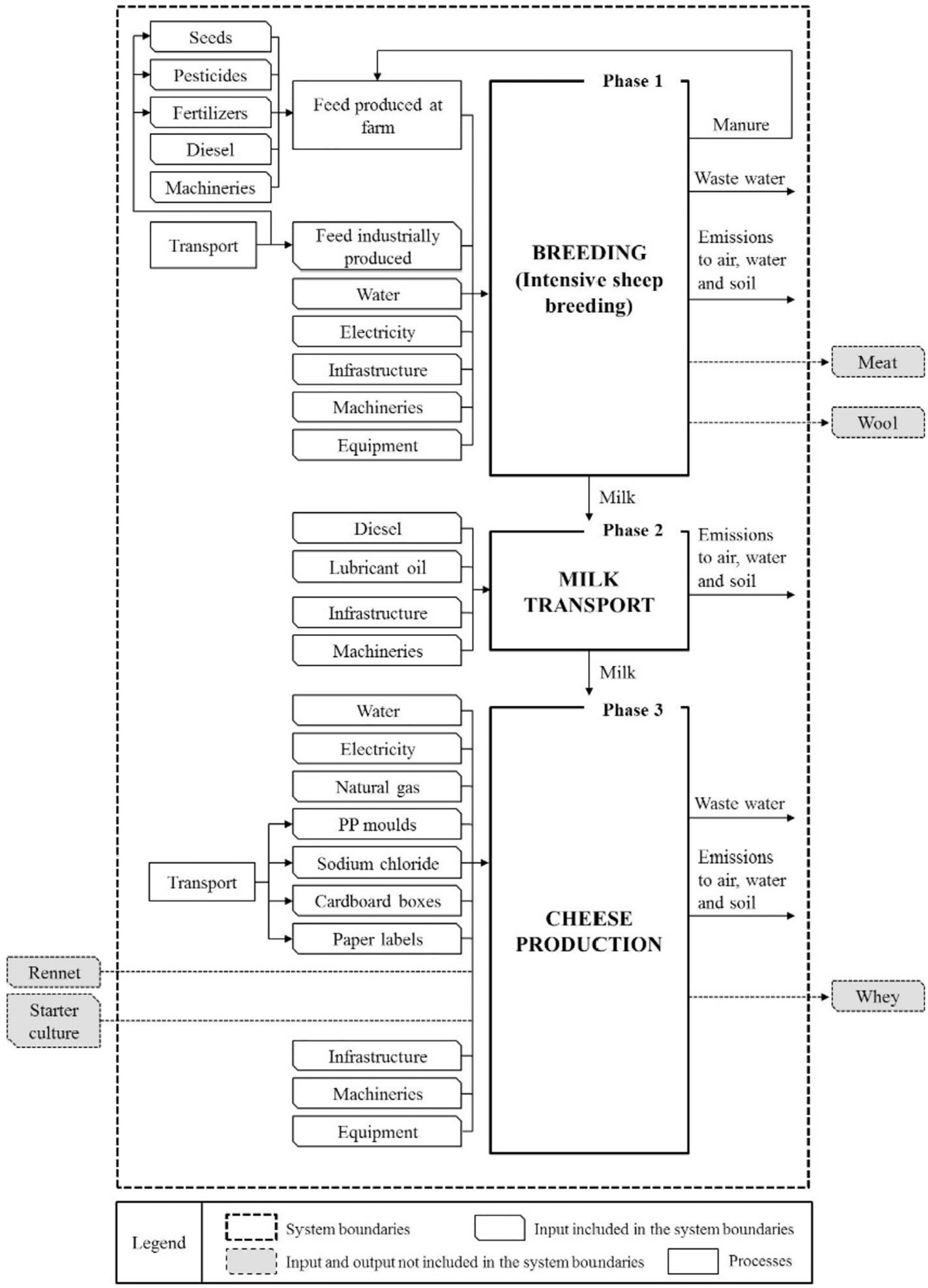

Fig. 1. System boundaries (baseline system).

distributed by the factory.

2.2. Inventory analysis

Inputs and outputs of the baseline system (Table 1) are related to the following three main phases, considering one year of production:

1) Breeding – in this phase sheep breeding, through an intensive system (700 livestock units – Sardinian breed), and milking are considered. The livestock is permanently housed in a shed (700 m^2) and, because of this, the sheep are mainly fed by means of industrially produced feed (hay, soy, corn, wheat, barley and oats) integrated with feed directly produced on farms (wheat, barley and oats). The feed (from farm and from industry) is stored in 8 fibreglass silos, except for hay, which is kept inside a barn (600 m^2). Milking is carried out twice daily in a milking room (80 m^2) using an automatic milking machine (24 modules). The milk is stored in 2 refrigerated stainless steel tanks with a capacity of 200 and 600 L, respectively;
2) Milk transport – in this phase the transport of milk, in refrigerated trucks, from the farm to the dairy factory is considered. Milk is sent to the dairy factory three times a week. The average

Table 1
Inventory data related to the functional unit of 1 kg of “Pecorino” cheese, packaged at dairy farm gate and ready to be distributed.

Phases	Input/Output		Unit	Amount	Data sources
1. Breeding	Intput	Seeds	kg	0.92	Primary data; Ecoinvent
		Pesticides	kg	0.0038	Primary data; Ecoinvent
		Fertilizers	kg	0.011	Primary data; Ecoinvent
		Diesel	kg	0.65	Primary data; Ecoinvent
		Feed produced at farm	kg	2,11	Primary data
		Wheat[a]	kg	2.79	Primary data; LCA Food DK
		Oat[a]	kg	0.53	Primary data; LCA Food DK
		Barley[a]	kg	1.12	Primary data; Ecoinvent
		Soy[a]	kg	1.47	Primary data; Ecoinvent
		Hay[a]	kg	14.74	Primary data; Ecoinvent
		Corn[a]	kg	0.59	Primary data; Ecoinvent
		Water	kg	30.79	Primary data; Ecoinvent
		Electricity	kWh	1.92	Primary data; Ecoinvent
		Infrastructures	kg	0.55	Primary and calculated data; Ecoinvent
		Machineries	kg	0.078	Primary and calculated data; Ecoinvent; ELCD
		Equipment	kg	0.0096	Primary and calculated data; Ecoinvent; ELCD
		Transport	kgkm	560	Primary data; Ecoinvent
	Output	Milk	kg	5.7	Primary data
		Manure	kg	5.4	Primary data
		Waste water	kg	30.2	Primary data; ELCD
	Emission to air	Carbon dioxide	kg	2.00E+00	Calculated data; Nemecek and Kägi, 2007
		Carbon monoxide	kg	2.30E-02	Calculated data; Nemecek and Kägi, 2007; IPCC, 2006;
		Ammonia	kg	7.67E-03	Calculated data; Nemecek and Kägi, 2007; Brentrup et al., 2000
		Nitrogen	kg	3.19E-03	Calculated data; Brentrup et al., 2000
		Nitrogen oxides	kg	2.68E-02	Calculated data; Nemecek and Kägi, 2007
		Dinitrogen monoxide	kg	4.95E-03	Calculated data; Nemecek and Kägi, 2007; IPCC, 2006; Brentrup et al., 2000
		Methane	kg	2.23E-01	Calculated data; Nemecek and Kägi, 2007
		Benzene	kg	4.66E-06	Calculated data; Nemecek and Kägi, 2007
		Benzo(a)pyrene	kg	1.91E-08	Calculated data; Nemecek and Kägi, 2007
		NMVOC	kg	5.11E-03	Calculated data; Nemecek and Kägi, 2007
		Cadmium	kg	6.38E-09	Calculated data; Nemecek and Kägi, 2007
		Chromium	kg	3.19E-08	Calculated data; Nemecek and Kägi, 2007
		Copper	kg	1.09E-06	Calculated data; Nemecek and Kägi, 2007
		Nickel	kg	4.47E-08	Calculated data; Nemecek and Kägi, 2007
		Selenium	kg	6.38E-09	Calculated data; Nemecek and Kägi, 2007
		Sulfur dioxide	kg	6.45E-04	Calculated data; Nemecek and Kägi, 2007
		Zinc	kg	6.38E-07	Calculated data; Nemecek and Kägi, 2007
		Thifensulfuron-methyl	kg	2.56E-07	Calculated data; EMEP/EEA, 2009
		Tibenuron-methyl	kg	1.28E-07	Calculated data; EMEP/EEA, 2009
		Cloquintocet-methyl	kg	2.33E-07	Calculated data; EMEP/EEA, 2009
	Emission to water	Thifensulfuron-methyl	kg	1.28E-07	Calculated data; Audsley et al., 2003
		Tibenuron-methyl	kg	6.42E-08	Calculated data; Audsley et al., 2003
		Cloquintocet-methyl	kg	2.33E-07	Calculated data; Audsley et al., 2003
	Emission to soil	Thifensulfuron-methyl	kg	1.28E-07	Calculated data; Audsley et al., 2003
		Tibenuron-methyl	kg	6.42E-08	Calculated data; Audsley et al., 2003
		Cloquintocet-methyl	kg	2.33E-07	Calculated data; Audsley et al., 2003
2. Milk Transport	Input	Transport	kgkm	114	Primary data; Ecoinvent
	Output	Milk	kg	5.7	Primary data
3. Cheese production	Input	Sodium chloride	g	4	Primary data; Ecoinvent
		Electricity	kWh	1.54	Primary data; Ecoinvent
		Natural gas	MJ	13.54	Primary data; Ecoinvent
		Water	kg	51.25	Primary data; Ecoinvent
		Moulds[b]	g	0.0012	Primary data; Ecoinvent
		Paper[b]	g	0.0032	Primary data; Ecoinvent
		Cardboard boxes[b]	g	0.06	Primary data; Ecoinvent
		Infrastructures	kg	0.086	Primary data; Ecoinvent
		Machineries	kg	0.0015	Primary and calculated data; Ecoinvent; ELCD
		Equipment	kg	0.004	Primary and calculated data; Ecoinvent; ELCD
		Transport	kgkm	0.00016	Primary data; Ecoinvent
	Output	"Pecorino" cheese	kg	1	Primary data
		Waste water	kg	51.25	Primary data; ELCD

[a] Feed industrially produced.
[b] Packaging materials.

distance covered during transportation is about 40 km per week;

3) Cheese production – in this phase the transformation processes of milk into “Pecorino” cheese at the dairy factory (1700 m^2) are included. Cheese production is characterised by eight different sub-processes: 1) pasteurisation, in which milk is sterilised at the temperature of 73–74 °C for eight minutes; 2) cooking, in which the pasteurized milk is firstly blended with the rennet and the starter culture and then cooked in 4 stainless steel tanks in order to produce the curd; 3) moulding, in which the curd is placed in polypropylene moulds in order to obtain the shapes and to drain the whey; 4) fermentation, which is carried out at

the constant temperature of 28 °C, for 9 h; 5) salting, which is carried out with an average temperature of 14–15 °C; 6) drying, for which the cheese shapes are arranged in stainless steel carts for five days at the temperature of 8 °C; 7) aging, in which different types of cheese are produced (e.g. fresh cheese, semi-hard cheese, hard cheese, etc.) by exposing the shapes to different temperature (from 5 to 15 °C), moisture (from 75 to 95%), and time (from 1 month to 1 year); 8) packaging, in which paper labels are applied on the surface of the cheese shapes, which are then packed in cardboard boxes and stored in a refrigerating room (4 °C), ready to be sold.

The inventory analysis related to the FU of *1 kg of "Pecorino" cheese, packaged at dairy farm gate and ready to be distributed* includes foreground data which consist of primary data collected by means of direct interviews and specific questionnaires submitted to firms, and background data, in which secondary data were obtained from international scientific literature and specific databases. In particular, primary data are related to: the feed directly produced on farms (including seeds, diesel, pesticides and fertilizers), water, electricity and natural gas consumption, transport, infrastructures, machinery, equipment, and materials used. Instead, secondary data were collected to calculate the direct emissions related to phase 1 (Table 1) due to: pesticide use (EMEP/EEA, 2009; Audsley et al., 2003), fertilizer use (Brentrup et al., 2000), diesel consumption (Nemecek and Kägi, 2007), and enteric fermentation and manure management/use (IPCC, 2006). Furthermore, international databases (Ecoinvent, 2007; LCA Food DK, 2003; ELCD, 2010) were used to include inventory data related to industrially produced feed, raw materials and energy sources. Data sources are summarized in Table 1.

Due to the co-production of sheep milk, meat live weight (LW), and greasy wool during the breeding (phase 1), the economic allocation method was selected to face the problem of multi-output process in the studied system (Table 2), considering only the inputs and outputs associated with sheep milk production used in "Pecorino" cheese manufacturing (phase 3), which is the main product obtained on farms. The economic allocation was selected since it is the most common allocation method used when multi-functional systems have to be assessed (Wiedemann et al., 2015). Data related to the economic values of co-products were calculated by cross-checking the data obtained from direct interviews with the farmers and the data obtained from the Italian Institute of Services for the Agricultural and Food Market ISMEA database (ISMEA, 2015).

2.3. Impact assessment

SimaPro 8.0.2 software (PRè Consultant, 2010) was used to assess the environmental impacts related to the production of Tuscan "Pecorino" cheese. The impact assessment was carried out by means of the ReCiPe Midpoint (H) method, version 1.09 (Goedkoop et al., 2009), in which eighteen different impact categories were assessed (Climate change, Ozone depletion, Terrestrial acidification, Freshwater eutrophication, Marine eutrophication, Human toxicity, Photochemical oxidant formation, Particulate matter formation, Terrestrial ecotoxicity, Freshwater ecotoxicity, Marine ecotoxicity, Ionising radiation, Agricultural land occupation, Urban land occupation, Natural land transformation, Water depletion, Metal depletion, Fossil depletion). This method was adopted in order to achieve a higher level of detail by using different impact categories largely adopted in the LCA studies. Moreover, characterisation and normalisation (normalisation factors related to Europe reference) were applied in order to better understand which system processes (hot-spots) and impact categories show the highest environmental impacts. After hot-spot analysis, a comparison between the baseline system and potential improvement scenarios that may allow the reduction of environmental impacts was carried out.

Table 2
Allocation factors obtained through the economic allocation procedure.

	Unit	Milk	Meat (LW)[a]	Greasy wool
Amount produced	kg head^{-1} yr^{-1}	175.1	40	2
Economic value	€ kg^{-1}	0.9	0.8	0.5
Allocation factors	%	82.7	16.8	0.5

[a] The allocation procedures related to meat live weight (LW) have been carried out connecting the inputs to six years (average life of one head) of production.

3. Results and discussion

In this section, characterisation and normalisation results related to the baseline system are presented and discussed in order to highlight which phases and processes (environmental hot-spots of the system) have greatest impact and to analyse which categories present the highest environmental impacts. After the hot-spot analysis, the potential improvement scenarios are described and compared to the baseline system. Lastly, the results obtained from the sensitivity analysis are presented.

3.1. Characterisation results

Characterisation results related to the Tuscan "Pecorino" cheese production (baseline system) are shown in Fig. 2. The results highlight that, for all the assessed impact categories, the highest environmental impacts are due to breeding (phase 1), followed by cheese production (phase 3). On the other hand, the lowest impacts are related to the transport of milk from the farm to the dairy factory (phase 2) for which the contribution to all impact categories is less than 0.8%.

The analysis of Climate Change, which is one of the most important environmental indicators used in the agricultural and dairy sectors (IDF, 2015; Wiedemann et al., 2015), shows that the total impacts related to the FU are 22.13 kg CO_2 eq. Phase 1, phase 2 and phase 3 account for 86.2% (19.08 kg CO_2 eq per FU), 0.2% (0.05 kg CO_2 eq per FU) and 13.6% (3 kg CO_2 eq per FU), respectively. Analysing in depth phase 1 (breeding), results underscore that the main impacts are due to the production of feed at industrial level, which shows a value of 6.26 kg CO_2 eq per FU (accounting for 28.3% of total impacts). The highest percentage contribution to this process is connected to the production of soy, wheat and hay, which account for 31.1%, 30% and 22.4%, respectively, while lower impacts are related to the production of oats, barley and corn, which contribute less than 7% to Climate Change. It is important to highlight that industrially produced feed was analysed by using data from international databases. In addition, higher potential environmental impacts are related to the direct emissions from sheep enteric fermentation, for which the Climate Change impact category shows a value of 5.38 kg CO_2 eq per FU (accounting for 24.3% of total impacts), followed by the production of feed at farm level, which causes an increase of 3.29 kg CO_2 eq per FU (accounting for 14.8% of total impacts), in Climate Change results. Regarding the production of feed at farm, the highest impacts are mainly connected to the emissions from the diesel used for the agricultural machineries (2.02 kg CO_2 eq per FU). The other Climate Change impacts connected to phase 1 are due to electricity consumption and waste water treatment processes, which account for 5.05% and 4.97% of total impacts. Furthermore, infrastructure, machinery and equipment, for which Climate Change results are less than 0.47 kg

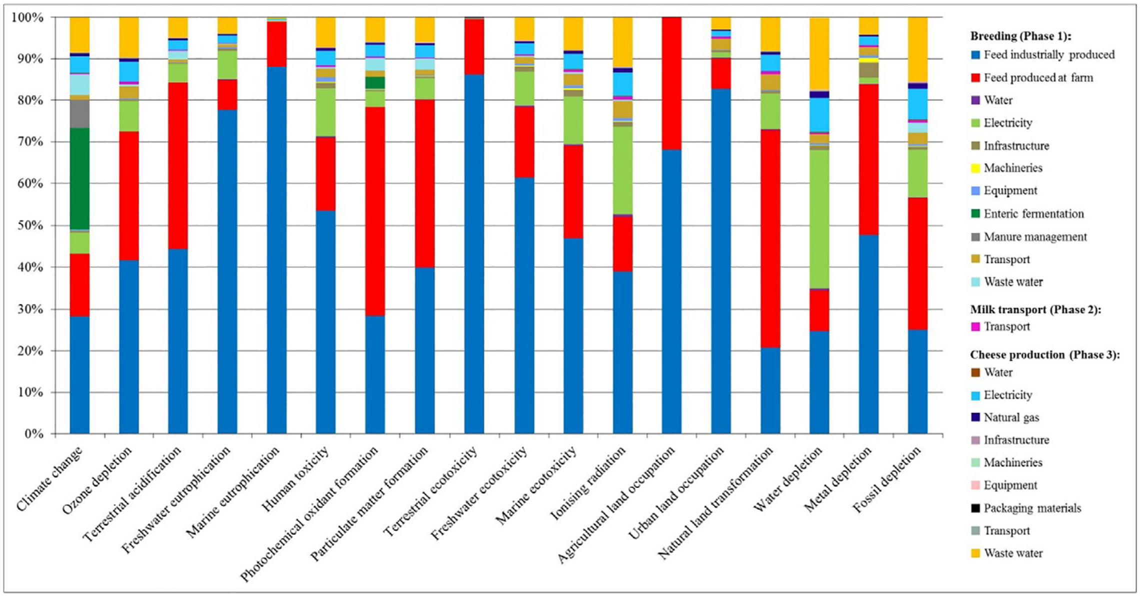

Fig. 2. Hot-spots analysis related to the functional unit of 1 kg of "Pecorino" cheese, packaged at dairy farm gate and ready to be distributed (ReCiPe Midpoint (H) method – characterisation results).

CO_2 eq per FU, cause the lowest impacts connected to phase 1.

The transport of milk from the farm to the dairy factory (phase 2) shows the lowest Climate Change impact related to the baseline system. The analysis of this phase underscores that higher impacts are related to diesel production and use during transportation, for which the results show a value of 0.04 kg CO_2 eq per FU. Furthermore, infrastructure and machinery cause 0.006 and 0.004 kg CO_2 eq per FU, respectively.

The Climate Change results related to cheese production (phase 3) underscore that the main impacts are connected to the waste water treatment process (1.87 kg CO_2 eq per FU), which accounts for 8.6% of total impacts. In addition, higher impacts are also associated with electricity consumption, which shows a percentage contribution of 4.1% (0.89 kg CO_2 eq per FU) to Climate Change. Instead, lower impacts are due to the other processes included in phase 3, for which the contribution to Climate Change ranges from 0.7% for natural gas consumption to less than 0.01% for packaging materials (paper and cardboard).

Results related to the other impact categories underscore that the percentage contributions of the system to the impacts range from about 99.9% for agricultural land occupation to 71.7% for water depletion in phase 1, from 0.8% for natural land transformation to 0.0003% for agricultural land occupation in phase 2, and from 27.8% for water depletion to 0.007% for agricultural land occupation in phase 3. The results highlight that the highest impacts for all the selected impact categories are associated with the breeding process (phase 1). In particular, phase 1 shows the highest potential environmental impacts in marine eutrophication by accounting for 99.4% (0.12 kg N eq per FU), in terrestrial ecotoxicity by accounting for 99.8% (0.03 kg 1,4-DB eq per FU), and in land use, including both agricultural land occupation (99.8 m^2a per FU) and urban land occupation (0.2 m^2a per FU). The production of wheat, soy and hay (feed industrially produced in phase 1) shows higher impacts in all the impact categories. For example, the main contribution to agricultural land occupation is due to hay production, which causes an increase of 55.3%. In addition, the electricity adopted in phase 1 causes higher impacts in ionising radiation, by accounting for 20.9% (0.2 kBq U235 eq), as well as in water depletion by accounting for 33.1% (7.4 m^3). Regarding cheese production (phase 3) the highest potential environmental impacts related to the waste water treatment and electricity processes are highlighted in the water depletion and fossil depletion impact categories. In particular, these processes account for 17.3% and 8.3%, respectively, to water depletion, and for 15.5% and 7.4%, respectively, to fossil depletion. As for Climate Change results, milk transport (phase 2) shows the lowest potential environmental impacts in all the other impact categories. The contribution to the impacts of phase 3 ranges from 0.0003% in agricultural land occupation to 0.8%.

The characterisation results allowed a detailed analysis related to the specific production of Tuscan "Pecorino" cheese. In this context, the main environmental hot-spots are related to agricultural practices and sheep breeding (phase 1), followed by the cheese production process (phase 3). However, the hot-spot analysis is directly connected to the type of impact category analysed. For example, when the Climate Change impact category is assessed, the system environmental hot-spots are mainly related to feed production, at industrial and farm level, as well as to emissions from enteric fermentation, in phase 1, and to the waste water treatment and electricity consumption, in phase 3. On the contrary, the environmental hot-spots are only related to the production of feed at industrial and farm level (phase 1), when, for instance, marine eutrophication, terrestrial ecotoxicity and agricultural land occupation are evaluated.

The allocation method adopted to face the problem of multi-output processes, by considering the economic values of the co-products, in phase 1, can play an important role in the results obtained from the analysis. In this context, a sensitivity analysis is carried out (in section 3.4) by comparing different allocation methods applied to the breeding system. Lastly, the characterisation results and the hot-spot analysis can be affected by some limitations regarding, in particular, the data and information related to the production of feed at industrial level, which were obtained from international databases.

3.2. Normalisation results

Normalisation results (Fig. 3) show that the main potential environmental impacts of Tuscan "Pecorino" cheese production are

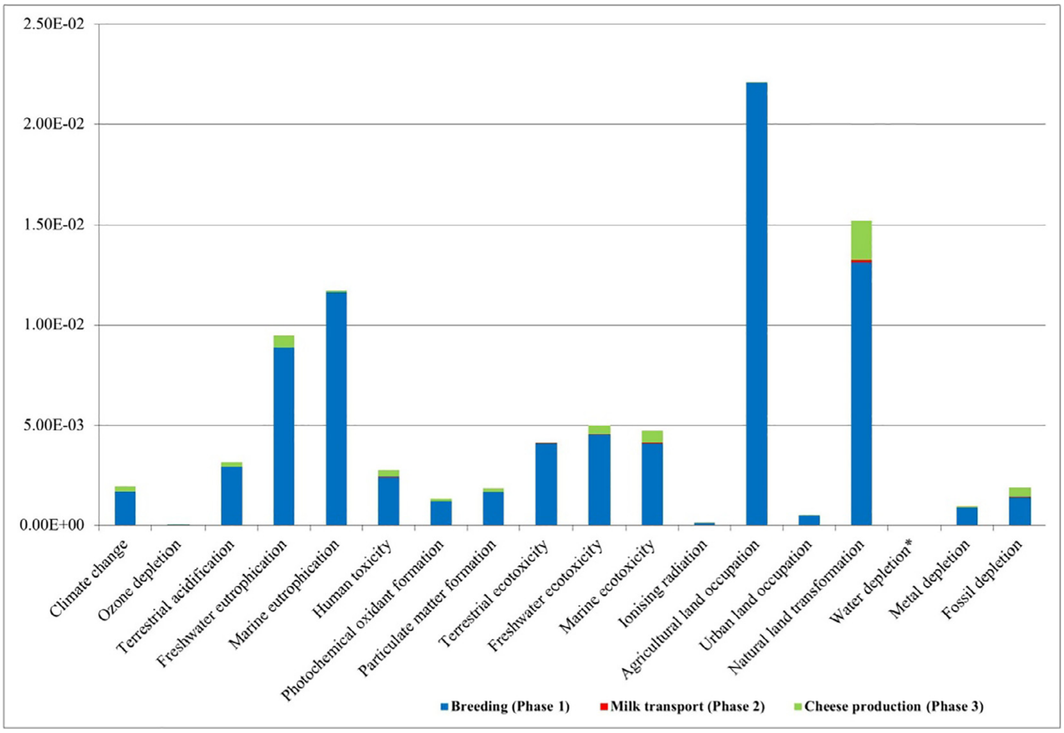

Fig. 3. Normalisation results (ReCiPe Midpont (H) method – Europe reference) related to the functional unit of 1 kg of "Pecorino" cheese, packaged at dairy farm gate and ready to be distributed (*normalisation factor for water depletion is not provided by ReCiPe Midpoint (H) method).

related to agricultural land occupation (2.21E-02 Pt per FU) followed by natural land transformation (1.52E-02 Pt per FU), marine eutrophication (1.17E-02 Pt per FU), and freshwater eutrophication (9.48E-03 Pt per FU).

Results related to the agricultural land occupation impact category highlight that the breeding process (phase 1) causes the main contribution (2.21E-02 Pt per FU). In particular, the production of hay (industrially produced feed), for which the land use background data included in the Ecoinvent database were related to "Occupation, pasture and meadow, extensive", shows a value of 1.22E-02 Pt per FU. Furthermore, the production of feed on farms accounts for 6.82E-03 Pt per FU to agricultural land occupation.

Regarding natural land transformation, the main contribution to the impacts is due to the production of diesel used in agricultural machinery during the production of feed on farms, by accounting for 47.5%. Indeed, the process that causes the main impacts is related to land transformation from forest to mineral extraction site. In addition, the electricity production process in phase 3 accounts for 6.9%.

Hay production and soy production show their main impacts when the freshwater eutrophication and marine eutrophication impact categories are assessed. In particular, phosphate (PO_4^{3-}) and phosphorus (P) emissions occurring during hay production account for 26.5% and 27.3%, respectively, to freshwater eutrophication. Furthermore, nitrate (NO_3^-) emissions in the groundwater, occurring during the production of soy, account for 33.6% to marine eutrophication.

Although the normalisation results allow us to understand which impact categories in the analysed system make the greatest contribution, it is important to highlight two main points: a) the normalisation results are strongly related to the reference selected to carry out the analysis, which is associated with Europe in this study; b) the normalisation results related to the impact categories may give a biased outcome directly connected to the method selected and, therefore, may present potential uncertainty, in particular when an external normalisation reference is adopted.

3.3. Improvement strategies

The analysis highlighted that the main environmental hot-spots of the baseline system were connected to feed production in phase 1 (breeding), as well as to waste water treatment and to electricity consumption in phase 3 (cheese production), particularly when the Climate Change impact category is evaluated. Due to the importance of reducing the environmental impacts (especially for GHG emissions) related to the agricultural sector, potential improvement solutions should be evaluated. In this context, two hypothetical improvement scenarios were analysed and compared with the baseline system.

Scenario 1 focuses on proposing an improvement practice in phase 1 by changing intensive sheep breeding to an extensive breeding system (in which the livestock is mainly managed on grazing and only housed one month per year in the shed). Extensive sheep breeding was also selected in accordance with Porqueddu (2007), who suggested that a breeding system based on an extensive method, with the integration of grasslands and other forage, may be a good solution to improve the quality of farming products and to reduce environmental impacts.

Scenario 2 was compared to the baseline system by changing the conventional electricity source adopted in cheese production (phase 3) to a photovoltaic system.

The potential improvement practices are highlighted in red in Fig. 4.

The main differences between intensive sheep breeding (baseline system) and the extensive breeding system (scenario 1) are related to a different amount of inputs and outputs between the two systems, and, particularly, to the type of feed used for feeding the livestock. Indeed, the feed adopted in the baseline system

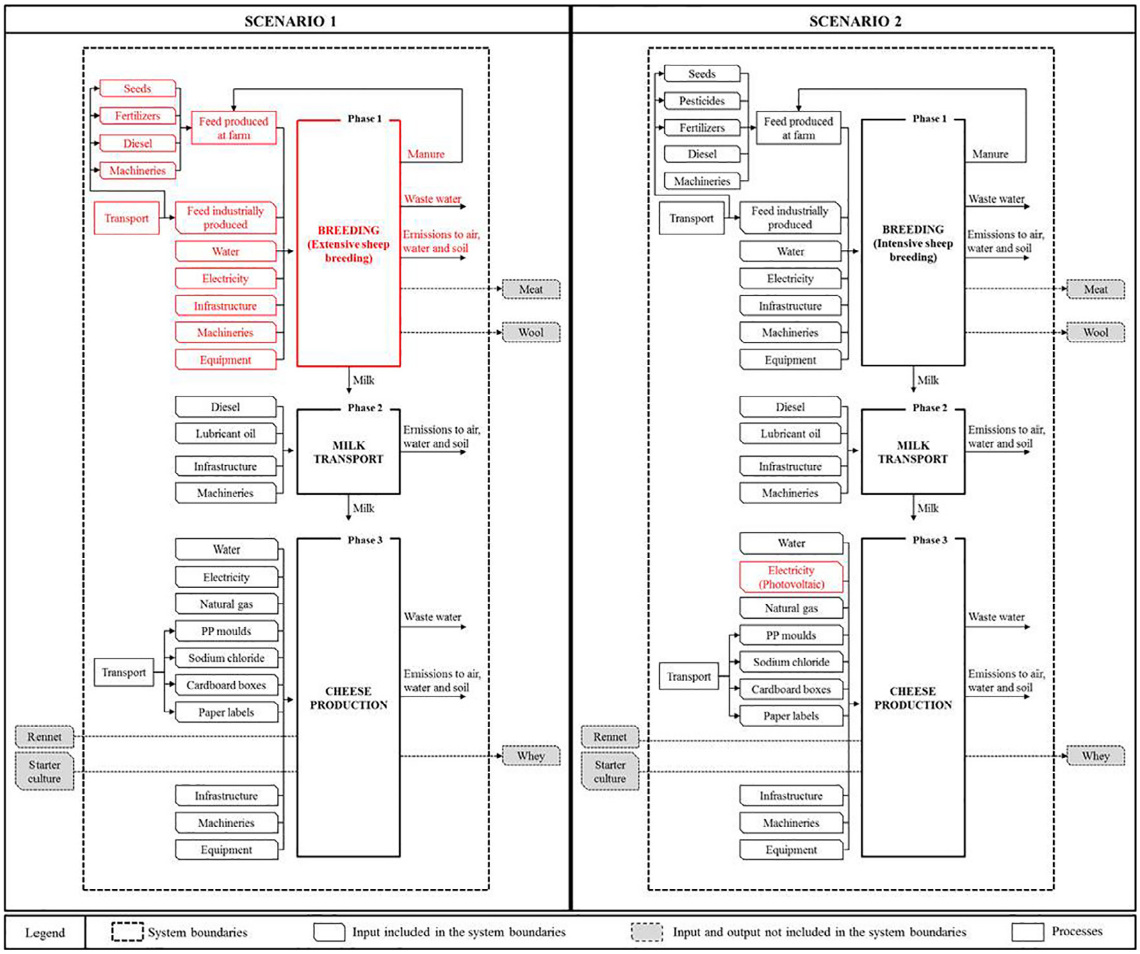

Fig. 4. System boundaries related to the two improvement scenarios: "Pecorino" cheese production through an extensive sheep breeding (scenario 1) and "Pecorino" cheese production with the adoption of electricity produced from a photovoltaic system during the cheese manufacturing process (scenario 2). The changes respect to the baseline system (Fig. 1) are highlighted in red.

(produced on farms and at industrial level), is largely replaced by grass grazing in extensive sheep breeding (scenario 1). In this context, the extensive system allows a reduction of about 85% in the utilisation of industrially produced feed. Moreover, the feed obtained on farms in intensive sheep breeding (baseline system) is produced yearly, while seeds, fertilizers, diesel, and agricultural machinery (without pesticides) are used only once every four years for the farm produced feed (only grass production) in the extensive breeding system. The adoption of an extensive breeding system also allows a higher performance in terms of milk production (from 170 L head^{-1} yr^{-1} for the intensive system to 290 L head^{-1} yr^{-1} for the extensive system) using a lower amount of commercial feed, as well as the possibility of increasing the number of livestock units raised (personal information obtained from direct interviews carried out with breeders).

The differences between the baseline system and the scenario 2 are connected to the type of electricity source used in phase 3 (cheese production). In this context, the Ecoinvent database process related to conventional electricity production in the baseline system (Electricity, medium voltage, at grid/IT U) is replaced with the photovoltaic electricity production process in scenario 2 (Electricity, production mix photovoltaic, at plant/IT U). This choice was adopted in order to evaluate the potential improvement connected to the utilisation of an alternative energy source.

The comparison results (Fig. 5) underscore that the adoption of extensive sheep breeding in the breeding phase (scenario 1) may represent the best improvement solution for all the investigated impact categories, except for ionising radiation, water depletion and fossil depletion, for which the adoption of a photovoltaic electricity production system in the cheese production phase (scenario 2) causes lower potential environmental impacts.

The main environmental benefits connected to scenario 1 are highlighted in the terrestrial ecotoxicity impact category, which shows a reduction of impacts from 0.034 kg 1,4-DB eq per FU (baseline system) to 0.008 kg 1,4-DB eq per FU (scenario 1). The results highlight that extensive sheep breeding allows a reduction of −12.5% in terrestrial ecotoxicity impacts, when the two breeding systems (in the baseline system and in scenario 1) are compared. The impact reduction is mainly connected to the replacement of industrially produced soy (baseline system) with farm produced grass (scenario 1). On the contrary, the adoption of a photovoltaic electricity production system in scenario 2 may cause higher impacts than the baseline system (conventional electricity production) in terrestrial ecotoxicity. An improvement of environmental performances related to the scenario 1 is also highlighted in marine eutrophication (0.04 kg N eq per FU) and freshwater eutrophication (0.002 kg P eq per FU), for which the main environmental benefits are connected to the use of grass for feeding livestock in scenario 1, as substitute for industrially produced feed in the baseline system (particularly soy and hay).

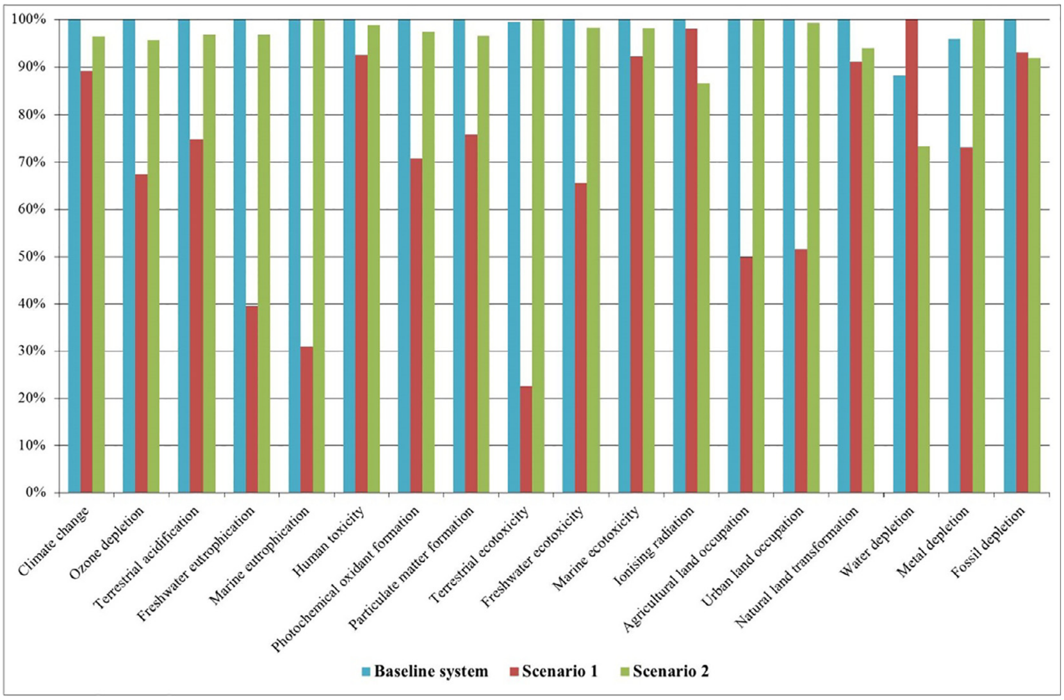

Fig. 5. Contribution analysis related to the comparison between the baseline system, scenario 1, and scenario 2 (ReCiPe Midpoint (H) method – characterisation results).

Regarding the improvement scenario related to the utilisation of electricity produced by means of a photovoltaic system (scenario 2) in the cheese production phase (phase 3), the results underscore that this change may bring about higher environmental benefits in ionising radiation (0.006 kBq U235 eq per FU), in water depletion (2.4 m^3 per FU), and in fossil depletion (0.5 kg oil eq per FU). In particular, the contribution of phase 3 to total impacts ranges from 19.1% in the baseline system to 6.5% in scenario 2 for ionising radiation, from 27.8% in the baseline system to 13.1% in scenario 2 for water depletion, and from 24.8% in the baseline system to 18.2% in scenario 2.

The results related to the Climate Change impact category show a smaller variation of the impacts among the three analysed systems. Scenario 1 (use of the extensive sheep breeding system in phase 1) causes the lowest potential environmental impacts (19.74 kg CO_2 eq per FU), followed by scenario 2 (use of the photovoltaic system in phase 3), and the baseline system (21.34 kg CO_2 eq per FU and 22.13 kg CO_2 eq per FU). Comparing scenario 1 to the baseline system, the results underscore a percentage variation of −10.8% in impacts, mainly connected to the lower amount of feed produced at industrial level adopted in extensive sheep breeding, which allows a reduction of Climate Change impacts of about 74%. Despite this, the production of feed at farm level in extensive sheep breeding (scenario 1) causes higher Climate Change impacts than the farm produced feed in the intensive breeding system, increasing impacts by about 85% (variation from 3.29 kg CO_2 eq per FU in the baseline system to 6.11 kg CO_2 eq per FU in the scenario 1).

Regarding land use impacts, the results show that the adoption of extensive sheep breeding (scenario 1) may be a good option to reduce environmental impacts in comparison with the intensive system (baseline system). This is mainly highlighted in agricultural land occupation and in urban land occupation, where the impacts range from 99.9 m^2a per FU (baseline system) to 49.9 m^2a per FU (scenario 1) and from 0.2 m^2a per FU (baseline system) to 0.1 m^2a per FU (scenario 1), respectively. The lower impacts related to scenario 1 are mainly connected to the reduction of industrially produced feed.

This comparative analysis allowed useful information to be added to the existing literature by proposing improvement practices directly related to sheep cheese production and, particularly, by assessing scenarios in which the production of sheep milk through different breeding systems and related manufacturing processes (including a comparison between different electricity sources) adopted to produce "Pecorino" cheese. This may allow the best practice to be found, considering all the different phases involved in the production of sheep cheese.

3.4. Sensitivity analysis

As reported in the previous discussion (section 3.1) the type of allocation method (and the related allocation factors) used to face the problem of multi-output processes may influence the final results (Guinée and Heijungs, 2007), in particular when a sheep breeding system is investigated (Mondello et al., 2016). In this context, a sensitivity analysis is carried out in order to compare three different allocation methods applied to avoid the co-production problem in phase 1 (baseline system). Therefore, economic allocation (base case), mass allocation, and energy allocation are assessed. The mass and energy allocations were performed by considering the amount (expressed in kg) and the calorific value (expressed in MJ), respectively, of the three co-products obtained in phase 1 (breeding).

A first assessment underscores that the main differences in terms of allocation factors (Table 3) are connected to the energy allocation method. These differences are also highlighted in the

Table 3
Allocation factors for the three selected allocation method: economic (base case), mass, and energetic.

	Milk	Meat (LW)	Greasy wool
Economic allocation	82.7%	16.8%	0.5%
Mass allocation	80.7%	18.4%	0.9%
Energetic allocation	70%	25%	5%

results obtained from the sensitivity analysis (Fig. 6).

The application of the energy allocation method causes a remarkable decrease in all the impact categories. For instance, the results of the three allocation methods related to Climate Change impacts are a value of 22.1 kg CO_2 eq per FU (economic allocation), 21.7 kg CO_2 eq per FU (mass allocation), and 19.4 kg CO_2 eq per FU (energy allocation). Furthermore, the main variation of the impacts is highlighted in marine eutrophication, in terrestrial ecotoxicity, and in agricultural land occupation, which are the impact categories most affected by the breeding phase (see section 3.1). These results underscore the importance in selecting the allocation method and its potential to affect inventory data and environmental impacts.

4. Conclusions

The “cradle to gate” LCA analysis applied to the production of Tuscan “Pecorino” cheese allowed us to identify and assess the environmental impacts and hot-spots connected to the system. Furthermore, the analysis allowed assessment of potential improvement strategies in order to propose alternative practices that can lead to environmentally sustainable production.

The hot-spot analysis highlighted that the highest contribution to environmental impacts, for all the considered impact categories, is connected to agricultural activities occurring in intensive sheep breeding (phase 1), followed by cheese production (phase 3), while the lowest impacts are connected to the milk transport phase (phase 2). The analysis of Climate Change showed that the highest impacts related to phase 1 are due to the production of feed at industrial level, followed by direct emissions from sheep enteric fermentation. This is in accordance with various LCA studies related to the dairy sector, which underscored that the main environmental impacts are connected to agricultural practices, especially when Climate Change is considered (see e.g. Favilli et al., 2008). Regarding phase 2 and phase 3, higher Climate Change impacts are related to diesel production and use during transport in phase 2, and to waste water treatment and electricity consumption in phase 3. The results also highlighted that infrastructure, machinery and equipment cause lower environmental impacts for all of the three phases assessed. Furthermore, the production of feed (phase 1) represented the main system hot-spot in the other assessed impact categories, and particularly, in marine eutrophication, in terrestrial ecotoxicity, and in agricultural land occupation.

Concerning the normalisation results, the analysed system caused the main contribution in agricultural land occupation, followed by natural land transformation, marine eutrophication and freshwater eutrophication. The production of feed (at industrial and farm level) were the processes that mainly contributed to the impacts in these categories. Despite this, it is important to highlight that the use of an external normalisation reference (in the analysis presented the normalisation factors were referred to Europe) may give a biased outcome and therefore the results may be affected by uncertainties (Prado et al., 2017).

The analysis also allowed the proposal of improvement scenarios in order to assess alternative practices for processes related to the environmental hot-spots. In this context, the replacement of the intensive sheep breeding system with an extensive breeding system in phase 1 (scenario 1), as well as the adoption of a different electricity production source in phase 3 (from conventional to photovoltaic system in scenario 2) may represent two good options for reduction of the impacts connected to the baseline system. Indeed, the extensive sheep breeding system may bring about higher environmental benefits in all the assessed impact categories, except for ionising radiation, water depletion and fossil depletion, in which the adoption of a photovoltaic electricity production system showed lower impacts. This is in accordance with Karekezi and Kithyoma (2002), who considered the photovoltaic system as “one the most attractive renewable energy options” to be adopted in the agricultural sector. Furthermore, extensive sheep breeding would allow higher performance in terms of the amount of milk

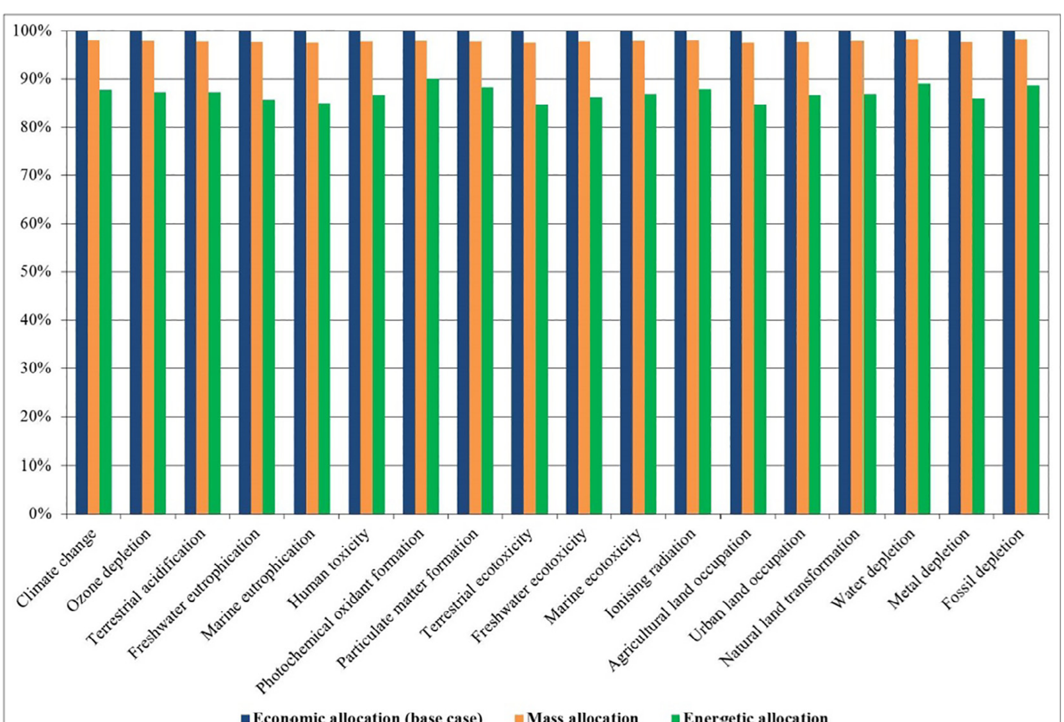

Fig. 6. Results of the sensitivity analysis (ReCiPe Midpoint (H) method – characterisation results).

produced yearly (from about 120 tonnes per year in the intensive system to about 310 tonnes per year in the extensive system).

Lastly, the sensitivity analysis allowed us to highlight the uncertainties in the inventory data caused by the type of allocation method applied. Indeed, the comparison between three different allocation methods (economic, mass and energy) showed remarkable differences in the allocation factors and in the results when the energy allocation method is adopted. This underscores the importance of the decision over the use of the appropriate method when the multi-output problem occurs.

This study allowed useful information to be gathered relating to LCA studies applied to the agri-food sector, since, to the authors' knowledge, very few studies have been carried out proposing a detailed assessment of environmental impacts related to Tuscan “Pecorino”, and none of these has proposed improvements in practices, also considering all the phases related to its production. Furthermore, this study can provide supporting information for Tuscan “Pecorino” cheese producing firms that are involved in the reduction of environmental impacts related to the final products. This could be achieved by selecting appropriate suppliers (by purchasing milk from farmers that adopt extensive sheep breeding) or by improving the environmental performance of the plant (by adopting a photovoltaic system for electricity production). However, since the adoption of intensive sheep breeding is connected to territorial traditions, changing suppliers, and therefore the breeding system, may cause negative social impacts related to the local communities.

Author contribution

Giovanni Mondello, Roberta Salomone and Elena Neri defined the research design and carried out the LCA analysis. Nicoletta Patrizi, Simone Bastianoni and Franceso Lanuzza carried out a detailed revision. All authors wrote the body of the paper and read and approved the final manuscript.

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