PAPER

# THE ECO-EFFICIENCY OF THE DAIRY CHEESE CHAIN: AN ITALIAN CASE STUDY

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## ABSTRACT

The eco-efficiency of mozzarella cheese production was investigated in two dairy chains that differ in liquid whey recycling, with whey recycling (B) and without whey recycling (A), in cow diets. The total eco-efficiency (total GVA/total GWP) for 1 kg of mozzarella cheese ranged from € 0.19 (B) to € 0.16 per kg $CO_2$-eq (A). The cheese-making phase of each diet accounted for about 3% of GWP total emissions. The mozzarella cheese making phase had the highest eco-efficiency ratio, while the milk production phase showed the lowest economic value and the highest impact. Findings suggest improvements in reducing the environmental burden of the primary phase while increasing its economic value.

*Keywords*: carbon footprint, cheese whey recycling, eco-efficiency ratio; economic value added, mozzarella cheese production

## 1. INTRODUCTION

Food supply chains are increasingly associated with environmental impacts, and this has brought global attention to the sustainability of the agri-food systems (FANTOZZI *et al.*, 2015).

Dairy products have a great impact, especially in terms of resource depletion and greenhouse gas emissions (GONZÁLEZ-GARCÍA *et al.*, 2013). Furthermore, the dairy industry is considered responsible for a significant impact due to the characteristics of its wastewaters and effluents (MIRABELLA *et al.*, 2014). Solid waste treatment and wastewater treatment along the dairy chain affect several environmental indicators. Cheese whey is the main pollutant generated from cheese production that can cause several environmental impacts (PRAZERES *et al.*, 2012). Thus, cheese whey cannot be discharged directly into the environment without appropriate treatment. According to some authors (SUCCI *et al.*, 1986), apart from potential environmental benefits, liquid whey is also an interesting animal diet ingredient from an economic point of view, especially when distances from the cheese industry are short and costs of handling and transportation are high.

In the framework of a circular economy approach, the reuse of whey in dairy cows' diet may minimize resources use and waste production from cheese making. In this regard, the European Commission has recently adopted an action plan on the circular economy - where the value of products, materials, and resources is maintained in the economy as long as possible, and the generation of waste is minimized- to develop a sustainable and competitive economy with low carbon content and efficient resource use.

Assessing the environmental performance of dairy chains can reduce their impacts and improve the efficiency of resource use (MU *et al.*, 2017).

Life cycle assessment (LCA) is a methodology widely used to investigate the environmental impact of food production. SALA *et al.* (2017) underlined the importance of the environmental and socio-economic impacts associated with the food supply chains and indicated life cycle thinking and assessment as key elements in identifying more sustainable solutions for global food challenges. Furthermore, NOTARNICOLA *et al.* (2015) deepened the issue of LCA in the agri-food sector with case studies, methodological issues and best practices.

Existing literature reports several studies that addressed different topics related to the LCA of cheese production. KIM *et al.* (2013) conducted a US-based LCA to determine the environmental impacts of cheddar, mozzarella cheese and dry whey from cradle-to-grave. GONZÁLEZ-GARCÍA *et al.* (2013) studied the life cycle of mature cheese production in Portugal from a cradle-to-gate perspective and identified the environmental hotspots. PALMIERI *et al.* (2017) applied an LCA approach to assess the impacts of mozzarella cheese production and evaluate the contribution of different strategies in a traditional dairy chain.

Global warming potential is one of the most studied impacts of dairy products. ROTZ (2018) reviewed the models for evaluating GHG emission from dairy farms —along a continuum from relatively simple models for single GHG emission sources to very detailed simulations over the whole farm production system— and concluded that LCA is a comprehensive method for quantifying and evaluating the different sources of emissions over the full cycle. COLOMBINI *et al.* (2015) applied an LCA cradle-to-farm-gate to assess the global warming potential of milk production in three forage systems scenarios and lactating cow diets. HAWKINS *et al.* (2015) estimated how the formulation of the ration and the associated land allocation decisions, contribute to reductions in GHG emissions of the intensive dairy production systems in Ontario. VAN MIDDELAAR *et al.* (2013) studied the environmental effect of replacing grass silage with maize silage in a feeding strategy and applied a life cycle assessment to predict GHG emissions at chain level. Finally, FINNEGAN *et al*. (2015) measured the global warming potential associated with the processing of raw milk into 11 dairy products in the Republic of Ireland following a cradle-to-processing factory gate boundary.

A general result from literature suggested that raw milk production is the most impactful phase along the chain due to feed production and animal emissions.

Few studies dealt specifically with the environmental impact of mozzarella cheese production. Two studies investigated the impact of American and Canadian mozzarella cheese production (KIM *et al*., 2013; VERGÉ *et al*., 2013) by considering several impact categories. Concerning the Italian mozzarella product, a study (DALLA RIVA *et al*., 2017) investigated a cradle-to-processing-gate LCA of two types of mozzarella (the traditional one produced from raw milk, and the mozzarella obtained from curd) focusing mainly on transformation and consumption of mozzarella cheese, also dealing with different environmental impacts. A study by PALMIERI *et al*. (2017) focused on several impact categories of both farm and factory phases based on some study cases of the mozzarella production in Italy. HELMES *et al*. (2016) assessed the carbon footprint of an Italian mozzarella facility dealing with the sensitivity of LCA results according to different allocation choices. Finally, FALCONE *et al*. (2017) applied the LCA approach to assess the environmental effect of a shelf life extension technique in the lacto fermented Italian mozzarella cheese production.

Under a wider sustainable perspective, the assessment of a dairy product should be extended beyond environmental impacts by considering its profitability and economic performance. Recent studies started focused on the economic and environmental assessment of dairy products by using different approaches and focusing on minimising costs and/or on maximising profits.

SOTERIADES *et al*. (2016) proposed to combine the LCA approach with the Data Envelopment Analysis (DEA) method in order to holistically assess dairy farm eco-efficiency by maximising output per unit of environmental impacts.

KIRILOVA and VAKLIEVA-BANCHEVA (2017) designed an optimal "green" portfolio for curd production in Bulgaria to demonstrate the role of the environmental impacts - measured in terms of wastewater and $CO_2$ emissions- within a profit maximization function that includes the costs of the above impacts. MURPHY *et al*. (2017) compared male dairy calf-to-beef production systems based on different animal performance and applied economic profitability and GHG emissions models to highlight the best performing system per each perspective. HAWKINS *et al*. (2015) used an optimization model of ration formulation to determine how specific GHG targets can be reached while maximising net returns to an intensive dairy farming system.

WETTEMANN and LATACZ-LOHMANN (2017) estimated the potential costs and GHG emissions savings for a sample of 216 dairy farms in northern Germany using an input-oriented Data Envelopment Analysis and showed that cost and GHG emission reductions are complementary across a wide range. An economic approach focused on costs is also followed by HUYSVELD *et al*. (2017) that analysed a sample of 103 specialized dairy farms in Flanders (Belgium) and showed potential simultaneous savings in costs and overall natural resource demand (up to 48%). FALCONE *et al*. (2017) applied a Life Cycle Assessment and Life Cycle Costing methods in order to assess the environmental and economic impacts of innovations in the Lacto-fermented mozzarella cheese production in Calabria region. Finally, HESSLE *et al*. (2017) studied different production scenarios of the dairy chain in Sweden by performing a Life Cycle method to assess the best environmental performance and by quantifying the costs in the primary production of dairy and beef to find out the most cost-efficient production models.

Another approach that integrates economic and environmental assessment is based on the eco-efficiency ratio (SALING, 2016). Eco-efficiency is defined as economic efficiency combined with environmental benefits and deals with three main goals: the reduction of resource consumption, the reduction of environmental impacts, and the increase of product value. The concept of eco-efficiency has been applied to several agricultural products to estimate the value added per kg of GHG emitted into the atmosphere for each system studied. In the dairy sector, BASSET-MENS *et al*. (2009) applied an eco-efficiency analysis of milk production in Flanders. MEUL *et al*. (2007) studied the eco-efficiency of milk production in some Flemish dairy farms, but the authors intended *eco*-efficiency in terms of *ecologic* and not economic terms and measured an indicator based on nitrogen and energy use efficiency.

To the best of our knowledge, few studies considered the eco-efficiency of the dairy chain. A study measured the economic performance of the cheese production chain by calculating the gross value added (GVA) of stages along the chain (VAN MIDDELAAR *et al*., 2011). Another study (SANJUAN *et al*.. 2011) measured the economic added value and the net income of Mahon-Menorca cheese production under different scenarios regarding technical and cleaner production criteria. However, that study included the assessment of the cheese production phase and excluded the milk production phase. A different approach to eco-efficiency was applied in a study that related the environmental performances with the economic efficiency in the use of dairy farms inputs (IRIBARREN *et al*., 2011).

This study aims to contribute to the literature on the environmental and economic performances of the mozzarella cheese production by measuring its eco-efficiency ratio based on an Italian case study. The study answers the question, "how much value is added per kg of GHG emitted to the atmosphere?". Firstly, the environmental and economic assessments were implemented; subsequently, the two perspectives were combined within an eco-efficiency analysis. In an earlier study (PALMIERI *et al*., 2017) an environmental analysis was performed according to a global approach. The present study goes further by focusing on the carbon footprint assessment and adding the analysis of the economic performance of mozzarella cheese production.

## 2. MATERIALS AND METHODS

### 2.1. The environmental assessment

2.1.1 Goal and scope definition

The main purpose of the study was to calculate the eco-efficiency ratio of mozzarella cheese production based on raw milk produced following different feeding strategies. The environmental impact of the dairy cheese chain was based on GHG emissions, and the economic performances considered the GVA of the dairy cheese chain. The value added per GHG emission of one kg of mozzarella cheese produced was finally measured.

The carbon footprint (CF), an important index of the climate change impacts of food production within the whole supply chain (ROMA *et al*., 2015), was measured by an Attributional Life Cycle Assessment methodology (BAITZ, 2017; ISO 14040, 2006; ISO 14044, 2006). The CF of 1 kg of mozzarella cheese is defined as the sum of all GHGs emitted along the production cycle (RÖÖS *et al*., 2014). GWP is expressed in $CO_2$ equivalent ($CO_2$-eq) using weights of 1,28 and 265 for carbon dioxide ($CO_2$), methane ($CH_4$) and nitrous oxide ($N_2O$), respectively (assuming 100 years lifespan; IPCC, 2015).

Furthermore, an economic analysis considered the added economic value of the dairy cheese chain as the difference between total revenues and total costs for intermediate consumption (VAN MIDDELAAR *et al*., 2011). Intermediate consumption costs measure the value of goods and services consumed, including raw materials, services, and other operating expenses, other than fixed assets. The GVA does not include labor costs, depreciation, nor interest loan payment; when considering the depreciation of fixed capital, a net value added is obtained. The GVA indicator was chosen because it is frequently used to measure the economic sustainability of agricultural systems (VAN MIDDELAAR *et al*., 2011). The final goal of jointly assessing the environmental and economic performances in the case study was pursued by measuring the eco-efficiency ratio (GVA/GWP) of mozzarella cheese production based on milk produced following different feeding strategies.

2.1.2 Functional unit and system boundary

The functional unit (FU) of the environmental and economic analysis was expressed per 1 kg of mozzarella cheese produced from 8.11 L of cow milk. The LCA system boundary (Fig. 1) refers to the first two phases of a dairy chain, namely the dairy farming and the cheese-making phases.
The boundary considers: the dairy farm - including the agricultural processes of feedstuffs and the whole life cycle of cows -; and the cheese factory -including all the activities that take place for the mozzarella cheese making, from the milk reception to the mozzarella production and the whole liquid whey disposal (the wastewater treatment plant or recycled into the cow diets).
Two dairy diets that differ in the usage/non-usage of liquid whey were assessed. In relation to the different disposal of the liquid whey, along with the two diets (A and B diets), two different chains are considered. In A chain, the whole amount of liquid cheese whey is mixed with the wastewater effluent from the mill and delivered to a municipal wastewater treatment plant (Fig. 1). In the B chain, the whole amount of liquid whey produced at cheese-making level is delivered to the farm where it is used, after microbial stabilization, in animal feeding as partial substitute of drinking water.
The physical allocation method was used in the baseline scenario to share the environmental burden between milk and meat at the farm level, while the environmental burden of the mozzarella production was totally allocated to curd (GONZÁLEZ-GARCÍA *et al*., 2013). The percentages of physical allocation at case farm level were 88% to milk and 12% to meat (as live weight cow and calf) (IDF, 2015). The manure/slurry allocation was not necessary because farmyard manure was recycled as fertilizer in the feed cultivation.

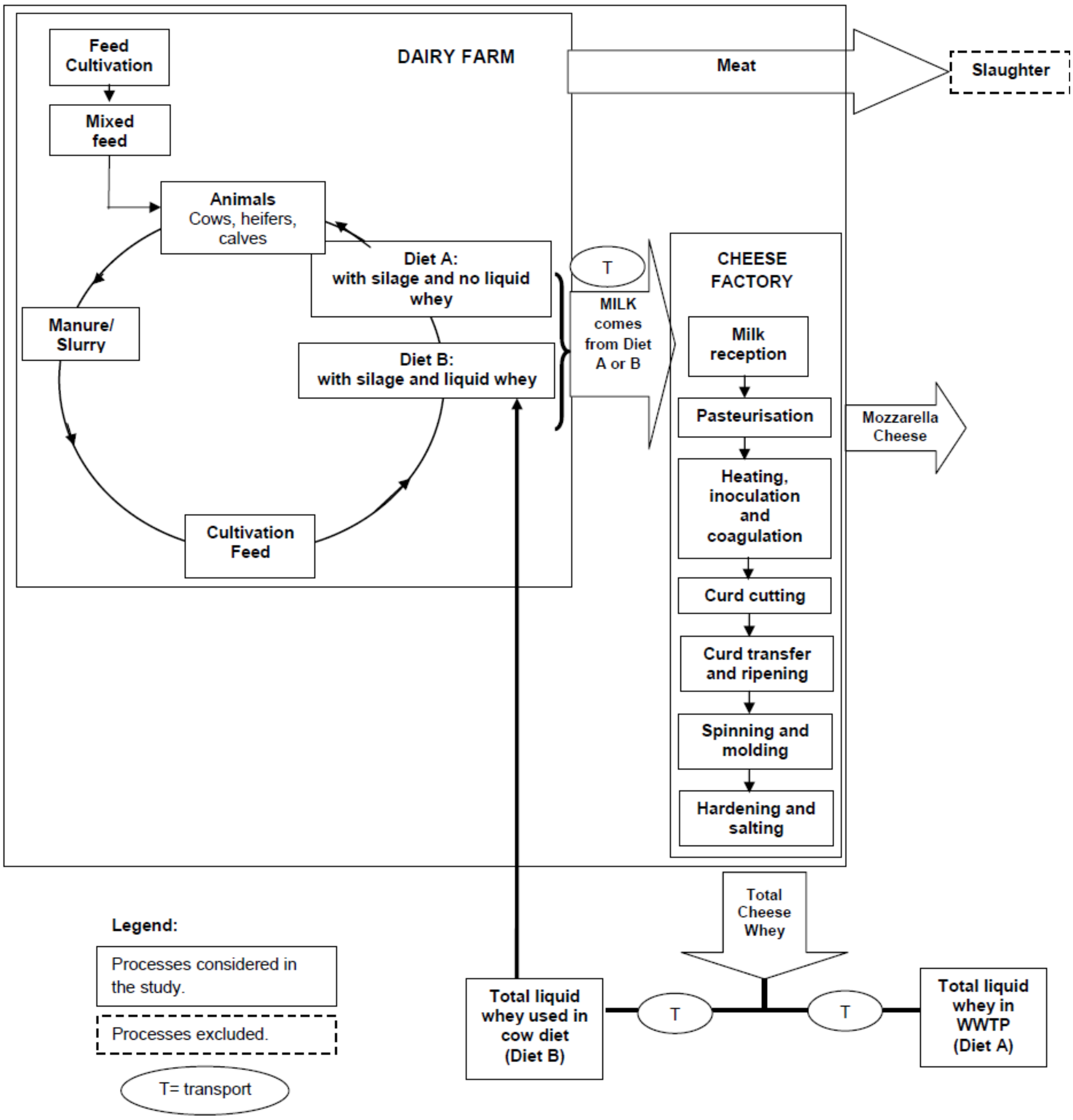


**Figure 1**. System boundaries: dairy farm and cheese factory. Abbreviations: See Table 1.

**Table 1.** List of Abbreviations and Acronyms.

| | |
|---|---|
| ALCA | Attributional Life Cycle Assessment |
| CF | Carbon Footprint |
| $CO_2$ | Carbon dioxide |
| CU | Cereal Unit allocation method |
| $CH_4$ | Methane |
| FPCM | Fat and Protein Corrected Milk |
| FU | Functional Unit |
| GVA | Gross Value Added |
| GHG | Greenhouse Gas Emissions |
| GWP | Global Warming Potential |
| IPCC | Intergovernmental Panel on Climate |
| LCA | Life Cycle Assessment |
| $N_2O$ | Nitrous Oxide |
| WWTP | Wastewater treatment plant |

### 2.1.3 Life cycle inventory

Data for the life cycle inventory analysis partly comes from the INLATTE Project (Tables 2-4) and were collected through a questionnaire drawn according to the guidelines for the application of LCA to food and agricultural products (NERI, 2009). Secondary data (Table 5) were taken from both the ECOINVENT database v. 3.0 (WEIDEMA *et al*., 2013) and literature (FRANCHINI and NERI, 2004; NERI and BORSARI, 2005; KIM *et al*., 2013).
Primary data were collected from two firms (a dairy farm and a cheese factory) located in Molise region (IT). Data from the case farm reported the milk quantity and quality, the Italian Friesian cow rations and water consumption, and the manure/slurry produced. The case farm experimented two different dietary strategies: a diet including ensiled forages and no liquid whey usage (A diet) and a diet including both silages and liquid whey (B diet). Data reported in Table 2 summarise the management of animals in the case farm. For the present study, 36 lactating cows were divided into two groups of 18 cows each which were homogeneous and comparable in terms of milk yield and days of lactation and parity. The average fat and protein corrected milk (FPCM) yield has been calculated on a 305 days basis for each experimental group and used in the LCA study. The FPCM yield was calculated according to FINNEGAN *et al*. (2015). Table 3 shows the composition of the diets. In this regard, it is worth noting that feedstuffs were offered as total mixed rations, except for the microbiologically stabilized liquid cheese whey offered to B diet cows as partial substitute of drinking water. Water consumption in B diet was, therefore, lower than that in the A diet.
Primary data from the cheese factory have been recorded throughout the experiment and summarised in Table 4. Mozzarella cheese for fresh consumption traditionally obtained directly and solely from liquid milk is the dairy product considered in the study.

**Table 2**. Case farm characteristics.

| **Case farm data** | | |
|---|---|---|
| Cow breed | | Holstein Friesian |
| Number of lactating cows | | 36 |
| Number of dry cows | | 9 |
| Dairy replacement calves and heifers, n. | | 32 |
| Number of calves (male) | | 18 |
| Days of production/year (lactating cows) | | 305 |
| Males raised as beef cattle, age (days) | | Calves: 20 |
| **Milk production** | **Diets** | |
| Milk yield – FPCM (kg/per yr) | A | 8,332 |
| | B | 8,039 |
| % Fat | A | 4.03 |
| | B | 3.99 |
| % True Protein | A | 3.68 |
| | B | 3.60 |

**Table 3**. Water consumption and characteristics of diets on a dry matter (DM) basis.

| | **Diets** | |
|---|---|---|
| Calves diet | A | B |
| Water consumption (L/day) | 10 | 10 |
| Liquid whey (kg/day) | - | - |
| Total DM intake (kg/ day) | 1.96 | 1.96 |
| Heifers diet | A | B |
| Water consumption (L/day) | 35 | 25 |
| Liquid whey (kg/day) | - | 0.57 |
| Total DM intake (kg/ day) | 4.53 | 5.10 |
| Lactating cow diet | A | B |
| Water consumption (L/day) | 80 | 50 |
| Liquid whey (kg/day) | - | 1.48 |
| Total DM intake (kg/ day) | 20.06 | 21.54 |
| Dry cow diet | A | B |
| Water consumption (L/day) | 40 | 40 |
| Liquid whey (kg/day) | - | - |
| Total DM intake (kg/ day) | 13.08 | 13.08 |

When real data were not available, inventory data were collected from literature and ECOINVENT database (v. 3.0) (WEIDEMA *et al*., 2013), as reported in Table 5. Emissions considered in the study were drawn from literature (Table 6). Data for the raw milk and whey transportation and for the wastewater treatment plant for whey disposal came from ECOINVENT database.

**Table 4.** Cheese factory data.

| **Products data** | |
|---|---|
| kg of mozzarella produced by 8.11 L of milk | 1 |
| kg of whey produced by 1 kg of mozzarella | 0,89 |
| Fat in mozzarella (g/kg of product) | 185 |
| Protein in mozzarella (g/kg of product) | 154 |
| Fat in whey (g/kg of product) | 2 |
| Protein in whey (g/kg of product) | 7 |
| **Resources consumption** | |
| Electricity consumption (kWh/ kg of mozzarella) | 0,20 |
| Heat consumption (MJ/kg of mozzarella) | 0,11 |
| Water consumption (L/kg of mozzarella) | 18,08 |

Data source: INLATTE Project.

**Table 5.** Secondary data considered in the study.

| | Source |
|---|---|
| **Feed cultivation and processing** | |
| Barley | |
| Maize | ECOINVENT DATABASE (v. 3.0) |
| Meadow hay | |
| Milk powdered | FRANCHINI and NERI (2004); ECOINVENT DATABASE (v. 3.0) |
| Mixed feed | |
| Mineral feed | |
| Sugar beet pulp | ECOINVENT DATABASE (v. 3.0) |
| Soybean meal 44% | |
| Triticale silage | |
| **Mozzarella production** | |
| Milk reception | ECOINVENT DATABASE (v. 3.0); |
| Pasteurisation | FRANCHINI and NERI (2004); ECOINVENT DATABASE (v. 3.0) |
| Heating, inoculation and coagulation | |
| Curd cutting | |
| Curd transfer and ripening | ECOINVENT DATABASE (v. 3.0) |
| Spinning and molding | |
| Hardening and salting | |
| **Raw milk transportation** | ECOINVENT DATABASE (v. 3.0) for diesel track of 16 t capacity. Real distance from the dairy farm to the factory 10 km |
| **Wastewater treatment** | ECOINVENT DATABASE (v. 3.0); moderately large municipal wastewater treatment plant with a three-stage process (mechanical, biological and chemical) |

**Table 6.** Emissions considered in the study.

| Emissions | Source |
|---|---|
| **Enteric and animal housing emissions** | |
| $CH_4$ emissions and the ammonia emissions | BATTINI *et al.* (2016); EMEP/EEA (2009) |
| Nitrous oxide ($N_2O$) emissions from animal housing | Not considered according to BATTINI *et al.* (2016) |
| **Storage emissions** | |
| Emissions of methane ($CH_4$) and nitrous oxide ($N_2O$) | DALLA RIVA *et al.* (2014); IPCC (2006) (Tier 2); using ISPRA (2008) methods |
| Ammonia ($NH_3$) emissions due to manure/slurry storage | FALCONI *et al.* (2011) using ISPRA (2008) method |
| Nitrogen oxides (NOx) emissions | BATTINI *et al.* (2016) using the factor by IPCC (2006) |
| **Emissions related to manure/slurry spreading** | |
| $N_2O$, $NH_3$, NOx and nitrate leaching | BATTINI *et al.* (2016) using IPCC (2006) |
| The P leaching run-off emissions | BATTINI *et al.* (2016) |
| Emission factor of Potassium, Copper and Zinc | NERI and BORSARI (2005) |

## 2.2. Economic assessment and eco-efficiency ratio of the dairy chain

The eco-efficiency indicator is based on data from both environmental and economic accounting systems. The higher the indicator value, the higher the economic performance per unit of environmental burden. Since ecological and economic data need to be derived

from the same data set (MULLER *et al.*, 2015), we collected information based on the annual budget of the considered dairy farm and the cheese factory.
The economic data for both stages, milk production and mozzarella cheese making, are shown in Table 7. The B dairy chain had lower total costs than A chain due to both the elimination of treatment costs of whey in the WWTP and saved transportation costs of whey from the cheese factory to the dairy farm. The factory and the farm agreed to equally share the costs of both whey transportation (from the cheese factory to the dairy farm) and whey management at firm's level. Finally, the lower costs of B chain were due to the reduction of water consumption in the diet.
The eco-efficiency analysis was applied to the two stages of mozzarella cheese production (i.e., milk production and mozzarella cheese-making phases). The eco-efficiency of each stage was computed by dividing its economic value added by its ecological impact (VAN MIDDELAAR *et al.*, 2011).

**Table 7.** Cheese factory and dairy farm economic data.

| Economic data | Units | Cheese factory (€/kg of mozzarella) | | Dairy Farm (€/8,11 L of milk) | |
|---|---|---|---|---|---|
| | | A chain | B chain | A chain | B chain |
| Gross revenue | €/kg | 6.10 | 6.10 | 4.00 | 4.00 |
| Variable and fixed costs | €/kg | 5.10 | 4.90 | 3.44 | 3.37 |
| Economic value added | €/kg | 1.00 | 1.20 | 0.56 | 0.63 |

Source: Data came from the dairy farm and cheese factory case studies.

### 2.3. Sensitivity analysis: allocation method and variability of GVA

The choice of the allocation procedure for agricultural co-products may affect the results of LCA study as discussed in FLYSJO *et al*. (2012) and HELMES *et al*. (2016). Both studies compared the dry matter and the economic allocation methods for assessing the impact of dairy industry and underlined the need for testing results against different approaches.
For this reason, a sensitivity analysis for environmental impacts was performed by changing the allocation method of milk according to a cereal unit (CU) method (BRANKATSCHK and FINKBEINER, 2014). This sensitivity analysis involved only the case farm level, as in many reported studies (FANTIN *et al*., 2012; GONZÁLEZ-GARCÍA *et al*., 2013; KIM *et al*., 2013; VAN MIDDELAAR *et al*., 2011), because milk production is more impactful than cheese-making. The CU allocation method is based on the metabolizable energy content of product and co-product for feed purpose so that it allows considering agricultural products and co-products used in different sectors. The environmental burden was allocated 86.6% to milk, 6.8% to live-weight dairy cow and 6.6% to live-weight fattening male calf (BRANKATSCHK and FINKBEINER, 2014).
Furthermore, if the economic dataset was based on the annual reports of the dairy farm and the cheese factory -and therefore are real and accurate-, a further sensitivity analysis was performed to estimate the effect a ±10% change of GVA of the two stages for each dairy chain.

## 3. RESULTS AND DISCUSSION

### 3.1. The carbon footprint of 1 kg of mozzarella: baseline allocation

Results of the environmental impact of 1 kg of mozzarella cheese showed that raw milk production was the most impactful phase along the considered supply chain, irrespective of the diet followed at the farm level (Fig. 2).

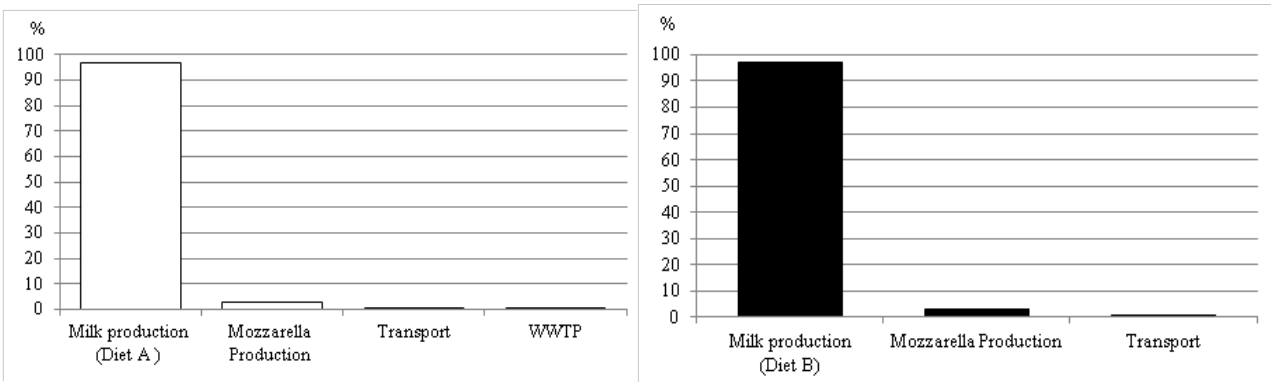


**Figure 2**. Carbon footprint of 1 kg of mozzarella cheese in A supply chain (on the left side) and B chain (on the right side): milk and mozzarella production (physical allocation).
Note: Transport refers both to the milk delivered to the dairy factory (supply chain A and B) and to the liquid whey delivered to the dairy factory (B supply chain) or the wastewater treatment plant (WWTP; A supply chain).

Milk production was the most critical phase along the dairy chain, with contributions of 96% (A diet) and 97% (B diet) of the global warming potential (GWP). The high contribution of milk production phase to the environmental impact of the mozzarella dairy chain observed is consistent with the study of DALLA RIVA *et al*. (2017), even considering the farm gate-to grave perspective followed by the authors. A similar conclusion was in the study of FINNEGAN *et al*. (2015) that, although was based on different cheese product and fluid milk, showed that milk production contributes to GWP within 81% - 97% range (depending on the amount of raw milk per kg of the six cheese products considered in the study). The remainder contribution being mainly due to the processing phase.

The environmental impacts of milk production phase were due to emissions of both methane from the enteric fermentation process and dinitrogen monoxide and carbon dioxide from manure management and spreading, confirming the study of GONZÁLEZ-GARCÍA *et al*. (2013) which referred to the cheese chain in Portugal. Methane from enteric fermentation and manure management was also the main GHG emission source in other studies dealing with cheese (KIM *et al*., 2013) and milk production (VIDA and TEDESCO, 2017). In the studies of VAN MIDDELAAR *et al*. (2011) and SANTOS *et al*. (2016), the enteric fermentation was the main emission source affecting GWP. According to VAN MIDDELAAR *et al*. (2011), the stage that contributed most to total global warming potential along the production chain of Dutch semi-hard cheese was on-farm milk production (65%), mainly due to enteric fermentation. In a study by SANTOS *et al*. (2016) about the cheese production in a small-sized dairy industry in Brazil, the contributions of the raw milk production ranged from 70 to 98% depending on the different midpoint impact categories.

The cheese-making phase of each diet accounted for about 3% of GWP total emissions. Mozzarella production phase showed impacts due to carbon dioxide from heat consumption during the cheese making process. This result confirms VAN MIDDELAAR *et al*. (2011) findings that measured the contribution of semi-hard cheese-making and packaging phases in about 3% - 4% of GWP emissions, each. Even in the study of HELMES *et al*. (2016), the contribution from the processing step of mozzarella production was quite limited compared to raw milk and transport impacts.

Furthermore, in our study, impacts of transportation of both milk —from dairy farm to cheese factory— and whey, either from factory to the wastewater plant or from factory to the dairy farm- were negligible due to the close distance between the locations of the two firms involved, the farm and the factory. A similar result was reported in the study of FINNEGAN *et al*. (2015) where liquid milk transportation contributed for less than 0.5%, whichever dairy products considered in the assessment. The relative burden of the wastewater treatment (in A diet) along the whole dairy chain was also considered insignificant.

Comparing impacts between the chains, results based on a cradle-to-processing-gate boundary showed that the B dairy chain had a CF 1% higher than the A chain per unit of product. The carbon footprint of mozzarella cheese in A chain was 9.65 kg $CO_2$-eq/kg mozzarella cheese, while it was 9.81 kg $CO_2$-eq /kg mozzarella cheese in B chain. The B dairy chain, although with the liquid whey usage, appeared to be a slightly worse solution due to a lower milk yield (8,039 kg FPCM) compared with A chain (8,332 kg), confirming that the environmental impact increases at decreasing milk yields (NEMECEK *et al*., 2011). Study findings were similar to those reported in KIM *et al*. (2013) where the carbon footprint of US mozzarella cheese was 9.30 kg $CO_2$-eq/kg. Furthermore, the results of our study are consistent with the study of HELMES *et al*. (2016), even if these authors considered different scenarios (mozzarella with ricotta or mozzarella with whey powder) from that of the present study. According to SANTOS *et al*. (2016), GWP emissions of cheese production were 14.44 kg $CO_2$-eq/kg of product, while in VERGÉ *et al*. (2013) the carbon footprint of Canadian dairy products was significantly lower than the one assessed in this analysis. However, both studies cannot be directly compared to the present findings due to several differences related to the final cheese products, to the production process and different methodological choices.

In our study, GWP emissions of mozzarella cheese-making phase were 0.32 kg $CO_2$-eq with A diet and 0.29 with B diet. These findings are quite in line with the study of FINNEGAN *et al*. (2015) that calculated the GWP emission of six groups of dairy products (not mozzarella cheese) and showed that GWP emissions from the dairy processing phase ranged 0.11-2.5 kg $CO_2$-eq/kg according to the different groups of studied products.

In conclusion, despite different environmental assessment methods used in literature, the milk production is the process that mostly contributed to the environmental impact. Improvement alternatives at the dairy-farm level are therefore required, and they involve many aspects, among which is the use of fertilizers for feedstuffs cultivation. In this regard, KOESLING *et al*. (2017) assessed the variations in nitrogen utilisation of conventional and organic dairy farms in Norway. These researchers concluded that, for both a dairy farm and system area, N-surpluses increased with increasing use of fertilizer N per hectare, biological N-fixation, and imported concentrates and roughages, while they decreased with higher production per area. PAGANI *et al*. (2016) investigated direct and indirect energy inputs in a sample of dairy farms -either grain-based, forage-based or organic- and demonstrated that potential reduction in the overall energy input could be achieved by shifting to organic farming, switching to forage-based farming, and by promoting reduced use of fertilizers. Both studies highlighted the importance of good agronomy that utilizes available nitrogen and reduces energy inputs properly.

Other studies focused on improvements in the composition of dairy ration to mitigate the environmental impact. HAWKINS *et al*. (2015) suggested that feeding decisions have important implications for GHG emissions from intensive dairy production due to the wide variation in emissions from alternative crops that can be used in the ration. PATRA *et al*. (2011) reviewed several potential methane mitigation options such as animal interventions (i.e., number and productivity of animals or genetic selection), dietary interventions, suppression of rumen methanogens, and new potential technologies, by underlying areas worthy of investigation for CH4 mitigation and improvements most likely to be adopted by farmers. Finally, WHITE (2016) proposed a farm-scale diet optimization model to reduce land use, water use, and GHG emissions within dairy production systems and assessed how improved energy and protein use efficiency reduces the environmental impacts of dairy production systems.
Finally, improvements in the environmental profile of cheese production should also be directed at the dairy factory level, mainly due to a high-energy consumption of machinery used during the production process. However, according to VAN MIDDELAAR *et al*. (2013), mitigation strategies may be case-specific and must consider the level of the analysis –at animal, farm and chain level-.
To achieve a sustainable mozzarella cheese production chain, not only its environmental impact must be considered and minimized, but also the economic value that is added along the chain.

### 3.2. The eco-efficiency of the dairy chain

The total eco-efficiency (total GVA/total GWP) of 1 kg of mozzarella cheese accounted for € 0.19 per kg $CO_2$-eq in the B supply chain and € 0.16 per kg $CO_2$-eq in the A supply chain (Table 8). Findings showed that dairy chain in case of B diet had a better eco-efficiency ratio per unit of GHG emitted to the atmosphere.

**Table 8**. Carbon footprint and gross value added (GVA) per functional unit (FU=1 kg mozzarella cheese), and eco-efficiency of the two stages in the dairy chain (Physical allocation).

| Stage | GWP (kg $CO_2$-eq/FU) | | Economic Performance GVA/FU (€) | | Eco-efficiency Total GVA/ total GWP | |
|---|---|---|---|---|---|---|
| | A chain | B chain | A chain | B chain | A chain | B chain |
| Milk production | 9.33 | 9.52 | 0.56 | 0.63 | 0.06 | 0.07 |
| Mozzarella cheese- making | 0.32 | 0.29 | 1.00 | 1.20 | 3.12 | 4.13 |
| Total | 9.65 | 9.81 | 1.56 | 1.83 | 0.16 | 0.19 |

Under the economic viewpoint, the B dairy chain had lower total costs than the A chain due to: 1) the elimination of treatment costs of whey in the WWTP at cheese factory level; 2) the reduction of water consumption due to whey usage in B diet; 3) finally, to lower transportation costs.
The total value added for 1 kg of mozzarella cheese was € 1.56 for the A dairy chain and € 1.83 for the B chain. When considering the distribution of total GVA along the chain, milk production accounted for a lower economic weigh (36 % in A chain and 34 % in B chain) compared to the value contribution of the cheese making process. For the above reasons, mozzarella cheese making had the highest eco-efficiency ratio for each dairy chain (€ 3.12

in A chain and € 4.13 in B chain) and added the highest economic value per unit of environmental impact.
The average GVA per 1 kg of fat and protein correct milk (FPCM) for the milk production phase was € 0.56 (per 8.11 kg FPCM to produce 1 kg of mozzarella) for the A dairy chain and € 0.63 per (8.11 kg FPCM to produce 1 kg of mozzarella) for the B chain.
Our results were consistent with the VAN MIDDELAAR *et al*. (2011) study that calculated the economic performances of a cheese chain as defined in this study (*i.e.* gross value added per environmental impact of stages along a production chain) and showed that the milk production contributed 34% to the total GVA of mozzarella cheese production. Furthermore, the economic performance of mozzarella production phase accounted for € 1.00 for the A chain and for € 1.20 in the B supply chain, confirming the VAN MIDDELAAR *et al*. (2011) results that showed a GVA of € 1.04 for the cheese-making phase. The above differences, while negligible, were likely due to both different local markets, products, and manufacturing costs and prices.
For this reason, two sensitivity analyses were carried out to test eco-efficiency results against changes in the economic indicator and to test environmental results against an allocation method different from the one applied in the baseline analysis.

### 3.3. Sensitivity analysis results

Results of the sensitivity analysis confirm previous results about the eco-efficiency of mozzarella cheese production.
The first sensitivity analysis (Table 9) showed that results from the CU allocation were lower than results achieved through a physical allocation for each dairy chain, but the differences in the value of the carbon footprint were negligible (around 1% for each chain). Furthermore, comparing findings based on CU allocation for the two dairy chains, results were consistent with those presented in Fig. 2 based on the physical allocation method (data are available on request). The B dairy chain confirmed its lower environmental performance.

**Table 9**. Sensitivity results of the Carbon footprint to the allocation method (Physical and CU allocation).

| Stage | **GWP** (kg $CO_2$-eq/FU) | | | |
|---|---|---|---|---|
| | **Physical allocation** | | **CU allocation** | |
| | **A chain** | **B chain** | **A chain** | **B chain** |
| Milk production | 9.33 | 9.52 | 9.18 | 9.37 |
| Mozzarella cheese- making | 0.32 | 0.29 | 0.32 | 0.29 |
| Total | 9.65 | 9.81 | 9.50 | 9.66 |

FU=1 kg mozzarella cheese

The second sensitivity analysis (Table 10) was performed to estimate the effect of ±10% change of GVA for each stage, for each dairy chain and each allocation method on the eco-efficiency ratio. Compared with the baseline scenario, the ±10% change of GVA modified the eco-efficiency scores in the range ±0.04 €/kg $CO_2$-eq, (e.g., from a score of 0.14 to 0.18 and from a score of 0.16 to 0.20 €/kg $CO_2$-eq, respectively in the A and B chains under the physical allocation method). Finally, findings showed higher eco-efficiency values with a CU allocation than a physical allocation method. Even in this case, results reported small changes in the absolute values of the eco-efficiency per 1 kg of mozzarella cheese and showed that the best-performing dairy chains did not change. Therefore, the dairy chain in case of B diet had the best eco-efficiency ratio per unit of GHG emitted to the atmosphere. From the two sensitivity analysis, it is possible to affirm that study results are not very much influenced by the choice between the two considered allocation methods, nor by the change in the economic value added.

**Table 10**. Sensitivity results of the Economic performance (±10% change of GVA) and of the Eco-efficiency scores in the two dairy chains (Physical *versus* CU allocation and ±10% change of GVA).

| Change | Stage | Economic* performance GVA/FU (€) | | Eco-efficiency* scores GWA/GWP (€/kg $CO_2$-eq) | | | |
|---|---|---|---|---|---|---|---|
| | | | | Physical allocation | | CU allocation | |
| | | A chain | B chain | A chain | B chain | A chain | B chain |
| +10% of GVA | Milk production | 0.62 | 0.69 | 0.06 | 0.07 | 0.07 | 0.08 |
| | Mozzarella cheese-making | 1.10 | 1.32 | 3.44 | 4.55 | 3.44 | 4.55 |
| | Total | 1.72 | 2.01 | 0.18 | 0.20 | 0.19 | 0.21 |
| *Baseline scenario* | Milk production | 0.56 | 0.63 | 0.06 | 0.07 | 0.06 | 0.07 |
| | Mozzarella cheese-making | 1.00 | 1.20 | 3.12 | 4.13 | 3.13 | 4.14 |
| | Total | 1.56 | 1.83 | 0.16 | 0.19 | 0.17 | 0.20 |
| - 10% of GVA | Milk production | 0.50 | 0.57 | 0.05 | 0.06 | 0.05 | 0.06 |
| | Mozzarella cheese-making | 0.90 | 1.08 | 2.81 | 3.72 | 2.81 | 3.72 |
| | Total | 1.40 | 1.65 | 0.14 | 0.16 | 0.15 | 0.17 |

*The different allocation method (Physical or CU allocation) does not imply any variation in the economic performance (GVA), while it influences the environmental assessment (GWP, as reported in Table 9) and the eco-efficiency results (because the eco-efficiency is the ratio between Total GVA/total GWP).

## 4. CONCLUSIONS

In this paper, the eco-efficiency ratio of mozzarella cheese production is assessed in an Italian case study according to the handmade cheese making system considering two different diets at the farm level, including or not including liquid cheese whey in cows' diet.

From an environmental point of view, one of the main findings of the study was that the primary phase had the highest impact within the mozzarella cheese supply chain.

For the phases along the dairy chain, the mozzarella cheese making had the highest eco-efficiency ratio for each dairy chain and produced the highest economic value per unit of environmental impact. The milk production phase added the lowest value of total GVA in both dairy chains while showing the highest environmental impact in GHG terms.

To reduce the environmental impact of the dairy chain and the wastage of a mozzarella cheese co-product, we assessed the carbon footprint of two dairy chains changing the diet composition at case farm level and using the liquid whey in cows' diet. The study hypothesis was that the use of the by-product of mozzarella cheese production within the local dairy chain would provide benefits under both environmental and economic perspectives. From the environmental point of view, the B supply chain with the whey showed an environmental performance per unit of mozzarella cheese lower than that of the A chain, although in a negligible measure, due to the effect of the milk yield in the primary phase. However, when considering the economic assessment of the two diets, the comparison of the eco-efficiency indicator evidenced a better performance of the B chain whose value per unit of impact was higher thanks to the liquid whey recycling.

Study findings lead to certain conclusions on the need of improving both sides of sustainability. On the economic side, improvements are needed in the market mechanisms to set costs and revenues that increase the value added along the dairy chain, mainly at the farm level. Under an environmental perspective, based on the carbon footprint assessment, improvements in the milk production should provide practices and alternatives that can further reduce the primary phase emissions up to the limit allowed by the ruminant physiology. Finally, the circularity in nature and economic cycles should be further analysed to improve the performances of both sides of sustainability. By recycling the liquid whey and strengthening the relation between dairy farms and cheese factories at a local level, some economic benefits (the cost of whey transportation and the disposal costs of liquid whey) emerged, while the environmental burden of whey treatment is avoided.

The best scenario satisfying both environmental and economic goals would realise a reduction in costs related to efficiency improvements in the usage of natural resources and dairy chain by-products, and a lower environmental burden associated with production processes. Concerning the revenues, the best scenario would be related to the attainment of a price premium for the environmental performances of the dairy products. For example by leveraging on marketing tools, such as environmental standards, labels, and environmental product declarations.

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