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LIFE CYCLE ASSESSMENT OF ITALIAN DAIRY CHEESE CHAIN

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ANALISI DEL CICLO DI VITA APPLICATA ALLA FILIERA LATTIERO CASEARIA ITALIANA

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THESIS FOR DEGREE OF DOCTOR OF PHILOSOPHY

Life Cycle Assessment of Italian dairy cheese chain

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Declaration

I declare that this thesis has not previously been submitted as an exercise for a degree at the University of Padova, or any other university, and I further declare that the work embodied in it is my own.

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Alessandro Dalla Riva

Table of Contents

Table of Tables

Table of Figures

Abstract

Dairy sector is growing fast, contributing to important share of global and national economic sector and bringing nutrient components into human diets. However, dairy sector is one of the main contributors to environmental impacts arising from food sector. Cheese sector is strategic to Italian dairy sector and economy, exporting high quality and Protected Designation of Origin (PDO) cheese to international countries. There is urgent need to increase the sustainability of dairy sector, considering the whole dairy chain perspective. The aim of this Ph.D. Project was to assess the environmental impacts associated to the Italian dairy cheese chain. The Project has been conducted in Veneto Region (northeast Italy). Life Cycle Assessment (LCA) methodology have been applied to assess the impacts producing raw milk at farm gate (Manuscript I), Asiago PDO cheese from cradle to dairy plant gate (Manuscript II) and Mozzarella from cradle to grave (Manuscript III).

In the Project, the primary data have been collected through direct interview to dairy farmers and visits to each dairy farm, direct interviews and visits to Asiago and Mozzarella cheese plants. Primary data collection regarded 34 dairy farms and an Asiago and Mozzarella cheese dairy plants. Ecoinvent® v3 and Agrifoodprint® v1 databases have been use for secondary data, while data from literature and national inventories have been use to model the post plant phases (distribution, retail, consumption and disposal) in the Manuscript III. Simapro© 8 was the modelling software. The impacts estimated affect human health, ecosystem and resources use.

Manuscript I and Manuscript II represent the LCA of Asiago PDO cheese production. Indeed, the 34 dairy farms analyzed are located in the adjacent area of the Asiago plant, creating a unique narrow chain for producing Asiago PDO cheese which is manufactured by the PDO guidelines. In the Manuscript I, the functional unit was one kg of milk, and it was the first LCA on milk production in Veneto Region. The production of purchased feed and on-farm feed (which require land, water, chemical fertilizers and manure, machinery use) and animal emissions (enteric methane, and nitrogen emissions from manure management) were main hotspots for overall impact categories, such as climate change, acidification, eutrophication, water and land use, and energy usage. Minor contribution to final impacts originated from electricity, fuels and detergents use, and waste produced during farm activities (such milking, cleaning). Different allocation approaches were tested beside the biological default allocation,

and all approaches modified the final results per kg of milk. The results were similar to those reported in literature.

In Manuscript II, the LCA model represents the production chain to produce one kg of Asiago PDO cheese, ready to sell, at dairy plant gate. The raw milk production represented the main contributor to all impact categories, except for ozone depletion where the cheese-making process was the first driver. Excluding farm phase from the assessment the manufacturing operations resulted the hotspots for overall impacts, except for eutrophication and water depletion mainly caused by wastewater treatment, and land occupation which was occurred due to primary and secondary paper packaging. The main contributor inside the cheese plant were electricity and natural gas usage, and process water, moreover transport of raw milk from farm to cheese plant impacted toxicity and photochemical oxidant formation. Economic allocation was applied and compared to milk solids content allocation, which reduced the final emissions per kg of Asiago than economic allocation. In fact, the milk solids allocation assigned more impact to the co-products (whey and other cheese) than economic allocation. Uncertainty analysis and sensitivity analysis of aging period were included into the study.

In Manuscript III the LCA methodology has been applied to an high industrialized mozzarella plant, the Italian third largest mozzarella plant. The LCA was performed in a cradle to grave perspective, including the post manufacturing phases, as distribution, retail, consumption and end of life phases. The plant used Italian and foreign milk, and distribute the mozzarella to Italy and international countries. The functional unit was one kg of mozzarella consumed. Result confirmed that raw milk production was the main contributor to overall impacts categories, except for ozone depletion where refrigerant used for cooling along the post farm chain were the main hotspot. Manufacturing and packaging were the second most important contributors to final impacts, followed by disposal of wastewater, while minor impacts were associated to distribution, retail and consumption; although relevant contribution was transport of milk and mozzarella, considering the international origin and delivery of the products. Electricity and natural gas usage, together with cardboard packaging for delivery drove the impacts during mozzarella-making process. While the impact arising from post plant phase were mainly determine by energy usage. The normalized results showed ecotoxicity, acidification, eutrophication and climate change as the main impact category contributing to the European impact and these categories are the first scope to apply strategies for reduction. A sensitivity analysis was performed to test different allocation approaches and to analyzed how the final results are influenced by allocation method; finally, a sensitivity analysis was performed determining the difference of impacts among the tradition high moisture mozzarella and the low moisture mozzarella. This analysis highlighted, excluding the difference derived from farm phase, transport is the main cause of larger impact for low moisture mozzarella, because foreign raw milk is generally used for this type of production, and the cooking in oven in the consumption phase, because low moisture mozzarella is largely used as pizza topping, in fact a cooking in an electric oven was assumed.

Abstract (Italian language)

Il settore lattiero-caseario è in crescita, contribuendo in maniera importante al settore economico mondiale, inoltre è un settore che apporta fondamentali nutrienti nella dieta umana. Tuttavia, il medesimo settore è uno dei principali comparti che determinano l'impatto ambientale associato al settore alimentare. Il settore della produzione di formaggi è un ambito strategico del comparto lattiero caseario italiano e per l'economia italiana, che vanta esportazione di formaggi di alta qualità e formaggi DOP verso numerosi paesi internazionali. C'è un urgente bisogno di aumentare la sostenibilità del settore lattiero caseario, considerando questa necessità in una prospettiva "dalla culla alla tomba", ossia dalla produzione delle materie prime per la produzione di prodotti lattiero caseari, al loro consumo, ed infine allo smaltimento dei rifiuti associati al loro ciclo di vita. Lo scopo generale del progetto di dottorato di ricerca è stato quello di valutare gli impatti ambientali derivanti dal settore lattiero caseario italiano con particolare riferimento alla Regione Veneto. L'analisi del ciclo di vita (Life Cycle Assessment, LCA) è stata la metodologia utilizzata per valutare gli impatti ambientali associati alla produzione di latte "dalla culla al cancello della azienda" (Manoscritto I), del formaggio Asiago DOP in una prospettiva "dalla culla alla cancello del caseificio" (Manoscritto II) e della mozzarella in una prospettiva "dalla culla alla tomba" (Manoscritto III).

I dati primari del progetto sono stati raccolti tramite interviste agli allevatori delle 34 aziende agricole coinvolte nel progetto, e ai responsabili del caseificio produttore di Asiago e dello stabilimento di produzione della mozzarella. Ecoinvent® v3 and Agrifoodprint® v1 database sono stati usati come fonte di dati secondari usati nel progetto. Dati da letteratura scientifica e report nazionali sono stati utilizzati per modellare le fasi post-stabilimento (distribuzione, consumo e smaltimento) nel Manoscritto III. Simapro© 8 è stato il software utilizzato per stimare gli impatti ambientali nei tre Manoscritti. Gli impatti stimati hanno riguardato la sfera della salute umana, l'ecosistema e utilizzo di risorse.

Manoscritto I e Manoscritto II presentano lo studio LCA per il formaggio Asiago DOP. Infatti le 34 stalle da latte analizzate sono localizzare nel territorio regionale, creando una unica filiera produttiva, come richiesto dal disciplinare di produzione del formaggio Asiago DOP. Nel Manoscritto I, l'unità funzionale è stata un kg di latte prodotto. In particolare, il Manoscritto I rappresenta il primo studio LCA relativo alla produzione di latte bovino nella Regione del Veneto. La produzione di mangimi extra-aziendali e la produzione dei mangimi aziendali (i quali richiedono terra, acqua, fertilizzanti e reflui zootecnici, e macchinari) e le

emissioni riconducibili ai bovini (metano enterico, e emissioni di ossido di diazoto dai reflui) sono stati i principali driver per la totalità degli impatti stimati, tra cui cambiamento climatici, acidificazione, eutrofizzazione, utilizzo di acqua, suolo ed energia. Un minore contributo agli impatti stimati è associato all'utilizzo di elettricità, carburanti e detergenti, e ai rifiuti prodotti durante le attività svolte in stalla (es. mungitura e pulizie). Sono stati testati differenti metodi allocativi alternativi al metodo base, il quale era l'allocazione biologica tra latte e peso vivo prodotto in stalla. Diversi metodi allocativi hanno portato a diverse emissioni per unità funzionale come riscontrato in letteratura.

Il Manoscritto II ha presentato LCA della filiera produttiva del formaggio Asiago DOP, e come unità funzionale aveva un kg di Asiago al cancello del caseificio, dopo la fase di stagionatura. La produzione di latte bovino in stalla è il driver principale per gli impatti stimati ad eccezione del depauperamento dello strato di ozono del quale il processo di caseificazione era il principale driver. Escludendo la fase di produzione del latte bovino, l'analisi LCA ha dimostrato come le fasi di caseificazione siano quelle maggiormente impattanti, ad esclusione di eutrofizzazione e utilizzo di acqua per le quali il maggiore responsabile è rappresentato dai processi di trattamento delle acque reflue ottenute durante i processi di caseificazione, ed infine l'occupazione di suolo, il quale è stato primariamente determinato dalla produzione del packaging cartaceo primario e secondario. I principali driver durante le fasi di caseificazione del formaggio sono risultati l'utilizzo di elettricità e gas naturale, e l'acqua utilizzata durante la caseificazione (principalmente in fasi di pulizia), inoltre il trasporto del latte dalla stalla al caseificio ha contributo agli impatti di tossicità e formazione di ossidi fotochimici. E' stata comparata l' allocazione economica e l'allocazione basata sul contenuto di solidi del latte presenti nel formaggio Asiago e nei coprodotti (altri formaggi prodotti in caseificio e siero liquido), ed è stato evidenziato che l'allocazione basata sul contenuto di solidi del latte ha determinato delle minori emissioni per kg di formaggio Asiago rispetto alla allocazione economica. Infatti, l'allocazione basata sul contenuto di solidi del latte assegna una maggior percentuale di impatti ai due coprodotti presenti. Infine è stata svolta l'analisi di incertezza dei risultati ottenuti, e analisi di sensitività basata sulla durata del processo di stagionatura.

Il Manoscritto III a differenza del Manoscritto II ha applicato la metodologia LCA in un stabilimento altamente industrializzato per la produzione di mozzarella (terzo produttore di mozzarella a livello italiano). LCA è stato realizzato in una prospettiva "dalla culla alla tomba", considerando le fasi post-stabilimento, quali distribuzione presso la GDO e i piccoli rivenditori, fase di consumo e il fine vita. Lo stabilimento produttivo usava sia latte bovino italiano che estero, e la mozzarella prodotta veniva distribuita sia sul mercato nazionale che internazionale. L'unità funzionale dello studio era un kg di mozzarella consumata. Il risultato dello studio ha confermato come la produzione di latte in stalla rappresenti il principale driver per la maggioranza degli impatti stimati, con eccezione del depauperamento dello strato di ozono, per il quale i gas refrigeranti utilizzati per la refrigerazione e lo stoccaggio dei prodotti nelle fasi di produzione e in quelle post-stabilimento produttivo erano i principali drivers. Le fasi di produzione in stabilimento e il packaging sono risultate essere secondi principali drivers per gli impatti finali, seguiti da trattamento e smaltimento delle acque reflue, mentre i minori impatti sono stati identificati per le fasi di distribuzione e consumo della mozzarella. I risultati ottenuti sono stati normalizzati e hanno mostrato nella eco-tossicità, acidificazione, eutrofizzazione e cambiamenti climatici le principali categorie di impatto; per queste categorie di impatto dovrebbero essere focalizzate primariamente le strategie per la riduzione delle emissioni. L'analisi di sensitività condotta nello studio ha evidenziato come il metodo allocativo influenzi i risultati finali. Inoltre un'analisi di sensitività è stata eseguita per differenziare le due principali tipologie di mozzarella nel mercato italiano ed anche internazionale: bocconcino di mozzarella (alto contenuto di umidità) e mozzarella da pizza (basso contenuto di umidità). La comparazione ha evidenziato che, una volta non considerata la differenza derivante dalla fase di stalla la quale contiene anche la maggior variabilità, il trasporto del latte in stabilimento rappresenta la causa principale del maggiore impatto per la mozzarella da pizza, infatti a livello italiano, come nello stabilimento analizzato, la mozzarella da pizza è prodotta utilizzando primariamente latte di origine estera, richiedendo una maggiore distanza di trasporto, con conseguente aumento della emissioni. Infine, un'altra rilevante parte degli impatti è stata associata alla cagliata acquistata da stabilimenti italiani e esteri ed utilizzata per la produzione di mozzarella da pizza. Infatti, tale semilavorato prima di essere trasformato in mozzarella, è stato a sua volta prodotta in stabilimenti appositivi, richiedendo vari input quali energia, materiali e packaging, ed infine trasportata nello stabilimento di produzione della mozzarella.

List of the Manuscripts

This Ph.D. Project is composed by the following three Manuscripts (the manuscripts are named "Manuscript" followed by roman number in the text).

Manuscript I — Dalla Riva, A., Burek, J., Kim, D., Thoma, G., Cassandro, M., and De Marchi, M. (2015). **The environmental impact of cow milk in the Northeast of Italy.** *PoljoPrivreda, 21(1 Supplement), 105-108.*

Manuscript II — Dalla Riva, A., Burek, J., Kim, D., Thoma, G., Cassandro, M., and De Marchi, M. (2017). **The Environmental Analysis of Asiago PDO Cheese: a case study from farm gate-to-plant gate.** *Italian Journal of Animal Science, 1-13.*

Manuscript III — Dalla Riva, A., Burek, J., Kim, D., Thoma, G., Cassandro, M., and De Marchi, M. (2017). **Environmental Life Cycle Assessment of Italian Mozzarella Cheese: hotspots and improvement opportunities.** *Journal of Dairy Science.*

List of the other Contributions

The other Contributions (chronologically listed in the follow table) represent the writing production (Full paper/Abstract/Poster) related to attendance as author to international conferences and disseminating scientific contributions.

Contribution I	**Carbon footprint from dairy farming system: comparison between Holstein and Jersey cattle in Italian circumstances -** Full paper and oral presentation. Dalla Riva A., T. Kristensen, M. De Marchi, M. Kargo, J. Jensen, M. Cassandro. 22nd International Symposium Animal Science Days on "Current challenges in reproduction related to food security and safety". In: Acta Agraria Kaposváriensis. Hotel Helikon – Keszthely, September 16-19th, 2014, Kaposvári Egyetem, Agrárés K: Dr. Hancz Csaba, vol. 18, p. 75-80.
Contribution II	**Environmental impact of Italian dairy industry: case of Asiago PDO cheese** – Abstract and oral presentation. Dalla Riva A., J. Burek, D. Kim, G. Thoma, M. Cassandro, M. De Marchi. 66th Annual Meeting of the European Federation of Animal Science (EAAP) on "Innovation on livestock production: from idea to practice", Campus of the Warsaw University of Life Sciences SGGW, Poland, 31st of August to 4th of September 2015.
Contribution III	**The environmental impact of cow milk in the northeast of Italy** – Full paper and oral presentation. Dalla Riva A., J. Burek, D. Kim, G. Thoma, M. Cassandro, M. De Marchi. 23rd International Symposium Animal Science Days on "Utilization of local animal breeds and production systems in sustainable production of high quality animal products". In: Journal POLJOPRIVREDA / AGRICULTURE. National Park Brijuni, Hotel Istra Neptun, Croatia, September 21-24th, 2015
Contribution IV	**Performance ambientali ed economiche della filiera lattiero-casearia italiana: il caso studio dell'asiago dop –** Full paper and oral presentation. Dalla Riva A., J. Burek, D. Kim, G. Thoma, M. Cassandro, M. De Marchi. Il mondo del latte, n 4 aprile 2016. Conference "Universo Latte: Giovani Ricercatori e imprese a confronto", March 17-18th 2016. Piacenza, Cattolica University. Available at http://www.assolatte.it/zpublish/4/uploads/4/comunicati/14646819814002463745_Speciale%20ricerca.pdf

Contribution V	**Il concetto di sostenibilità ambientale nel settore lattiero-caseario: il caso dell'Asiago DOP –** Full paper and oral presentation. Dalla Riva A., J. Burek, D. Kim, G. Thoma, M. Cassandro, M. De Marchi. L'Informatore Agrario n. 29 Supplemento Stalle da latte, pag. 27 del 21/07/2016. Available at http://www.informatoreagrario.it/BDO/BDO_popupAbstract.asp?D=126447
Contribution VI	**Life cycle analysis of mozzarella manufacturing –** Abstract and poster. Dalla Riva A., J. Burek, D. Kim, G. Thoma, M. Cassandro, M. De Marchi. Conference SUSMILK "Solutions for sustainable milk processing" Santiago de Compostela, FEUGA - Avenida Lope Gómez de Marzoa, Campus Vida, Spain 22-23th September, 2016.
Contribution VII	**Carbon footprint of mozzarella manufacturing –** Abstract and poster. Dalla Riva A., J. Burek, D. Kim, G. Thoma, M. Cassandro, M. De Marchi. 1st Dafnae Postgraduate Scientists Meeting (PGSM). Padova, University of Padova, Agripolis, 22-23 September, 2016.
Contribution VIII	**Cradle-to-grave lifecycle impacts of Italian mozzarella cheese –** Full paper and oral presentation. Dalla Riva A., J. Burek, D. Kim, G. Thoma, M. Cassandro, M. De Marchi. 10th International Conference on Life Cycle Assessment of Food 2016, Dublin, University College Dublin (UCD), October 19th – 21st 2016.
Contribution IX	**Life cycle assessment of Italian mozzarella cheese manufacturing –** Abstract. Dalla Riva A., J. Burek, D. Kim, G. Thoma, M. Cassandro, M. De Marchi. 22nd Congress of Animal Science and Production Association 2017, Perugia, Hotel Giò Wine and Jazz Area, June 13th-16th 2017.

1 General Introduction

World is changing. In the 21st century, the human being is called to face changes on social, economic and environmental sphere. People are doing mainly three actions in the Earth: they live, eat and produce, and these activities are indissolubly related to the environment, which is the source of all the resources used by humans to continue their life and development on the Earth. Developing methodologies to manage Earth's limited resources in a sustainable way is the crucial challenge, and people have to face it. Sustainability is defined in The Brundtland report (WCED, 1987) as: “Development that meets the needs of the present without compromising the ability of future generations to meet their own needs”

Global resource use is increasing, driven by population growth and improving standards of living. According to COM (2011), in the 2050 the demand for food, feed and fiber will be 70% of current level, and the demand for energy and water is expected to rise more than 40%. The world population is growing, by 200,000 people a day (Grida, 2016). Nine billion of people are expected for 2050, +22% of 2016 (UN, 2015). Population growth determines an increasing of people who live in urban areas. The urbanization, migration and industrialization, along with the increase in production and consumption, have generated an increasing demand of freshwater and resources (WWAP, 2015) and larger losses in the supply chain (Herrero et al., 2015). In 2050, the world’s population living in urban areas is projected to be 70%, aggravating challenges such as air pollution, transport congestion, and waste management (Marchal, 2012). Water depletion and population growth determine a reduction of water availability per capita, passing from 16,000m^3 in 1950 to 4,500m^3 per capita in 2050 Siwi (2016). The arable land on the earth is about 3% or 1.5 billion ha and the percentage is decreasing; in 1950, the arable land was a 0.52 ha per capita, nowadays 0.25 ha, and 0.16 ha are expected for 2050 (Jarvis et al., 2011). A growth of food demand is expected to 2050: the rising population and the expected dietary changes associated with income growth determine 70% more food production globally, and 100% more in developing countries (FAO, 2016). In 2050, the global economy is expected to be four times larger than today, increasing the energy use by 80% (Ehrlich, 2012).

The challenge is to study and to modify the food sector, where available, and its indissoluble relationship with the environment in order to reduce resources depletion, to limit environmental impacts and to increase sustainability along the production and consumption chain. The stewardship of a sustainable management of the environment can belong to each actors along the food chain.

Food is part of our entire life. As remembered by Berlin (2005), a tasty meal is first of all a perfect company for a glad, joyful and convivial moment with a lowed family and dear friends. Moreover, while we are eating delicious animal and vegetable food, we are also providing us fundamental nutrients for our growth and health.

Food requires several and complex processes to be transformed into delicious meal. Considering the long chain of food, "from farm to fork", a huge amount of resources is used. Starting from extraction of raw materials and encompassing the agricultural phase, manufacturing, distribution, consumption and ending with the final disposal. All these phases have several repercussions on the environment by depletion of resources and emissions to air, soil and water. Food production and consumption is responsible for a major quote of the environmental burdens in the developed countries (Tukker et al., 2006), after energy and transport sector (ISPRA, 2016). Tukker et al. (2006) estimated the food consumption contributes to 20-30% of environmental impacts of total consumption in Europe.

Studies on environmental impacts associated to single product or consumption-oriented approach are increasing and these studies are fundamental for providing information in making decisions to shift to more sustainable production and consumption. Recent studies on the environmental impacts associate to food consumption in Europe (Notarnicola et al., 2016; Monforti-Ferrario and Pascua, 2015) have been reported that the agricultural phase is the first contributor to many environmental impacts, and its influence depends on the kind of product, production technologies, transport, and processing (Nemecek at al., 2016). Agricultural impacts are mainly characterized by emissions of greenhouse gases (CO_2, CH_4, N_2O), particulate matter (PM), NH_3, N_2O, SO_2, heavy metals, energy and fuels usage, water and land use (Thoma et al., 2013). Processing and logistic phases, transport activities, and production and use of packaging are mainly characterized by energy and fuels usage (Kim et al., 2013). Meanwhile minor impacts are associate to other phases (housing, consumption and disposal) (Notarnicola et al., 2016). Although the post farm phases have generally a lower impact than farm phases, the inclusion of all the phases in environmental studies are fundamental to give a total weight of each phase in the lifecycle of a product. Indeed, the post processing and logistic phase can be relevant for human excretion and wastewater treatment, determining sometimes higher emissions than processing and transport. Moreover the food losses (agricultural/processing/logistic/housing) should be included into the analysis because they can contribute up to 60% of total initial food stuffs (Notarnicola et al., 2016). These results found a strong similarity with other studies where the 70-80% of impact of a product derived by food and drink, transport and housing (Huppes et al., 2008; Nijdam et al., 2005; Weidema et al., 2005).

The food sector has a crucial role in international and Italian economy. The Italian food industry ranks second following the metal-mechanical engineering sector. In 2014, the sector included about 58,000 companies, about 385,000 people and 850,000 farmers, reaching a total sales turnover of the Italian food industry amounted to 132 billion € (+1.5% in 2015), where 27 billion € are export. Moreover, the sector is marking a clear increase in consumption (+0.6%), production (+1.2%) and export (+6%) (Federalimentare, 2015). SCP (2013) stated into a policy act that the food sector is a strategic sector for the Italian economy and high environmental impacts are related to this sector. This statement helped to build an attention for sustainability in the Italian food sector, both production and consumption side.

Nowadays the sustainability aspects of production are gaining more attention, also from the consumer side. According to a recent survey (Conad, 2016) the average Italian citizen chooses the food first of all considering the taste of the food (51%), secondly the traceability, nutritional values, organized products and at the end the 12% of the interviewees asserted to consider the sustainability of food. Although sustainability is just at the end of the list this is a promising data, considering that around 15-20 years ago the sustainability aspects was difficultly known by the customers. Instead

Therefore, food is one of the main aspect in the past, present and future society: nutritional, economic and environment performances are deeply and indissolubly related to each other's. But environmental performance is fundamental, without the conservation of environmental sources the other aspects cannot survive.

Animal production represents a large part of the food sector. Sustainability has great relevance on the products of animal origin. Animal products have been always part of human history; they represent a key factor in the nutrition people. Animal food products contribute to bring suitable nutrients and compounds for human diet. However, their production and consumption have repercussions on social, economic and environmental sphere. Among food, meat (beef, pork and poultry) and dairy products (cheese, milk and butter) are the main contributors to food impacts along the whole chain (Notarnicola et al., 2016). The global consumption of meat, dairy and eggs is increasing (Steinfeld et al., 2006), therefore the environmental impacts related to livestock production will increase, if any changes will be produced (Westhoek et al., 2014). In the last 30 years, the animal production and animal products and their environmental impacts have become one of most worldwide debated and studied topic.

Particularly, dairy sector is increasing in terms of production and consumption. Dairy has a vital role for food security and poverty reduction, dairy sector has the key function to manage and to preserve the ecosystem and environment, and finally there is the need to increase and to integrate sustainability in the dairy system at all levels along the dairy chain (The Dairy Declaration of Rotterdam, 2016). Milk and dairy products are a local-global commodity and a key to nutrition and health. Dairy sector is growing fast and it is strongly related to the environment (use of natural resources such as land, water, nutrients and energy, and emissions, such greenhouse gas) (Pica-Ciamarra, 2016).

1.1 Current dairy Italian cheese sector

"*While the dairy industry has continued to see many changes over the years, one thing has remained constant: a high consumer demand for milk products*" Nita (2016).

Dairy is a global production: dairy animals are milked from people in the whole world; dairy farms are a vital support for more than one billion of people; it is a key sector of the global food system and it is a crucial tool to sustain the rural area development (IDF, 2013).

The International Farm Comparison Network (IFCN, 2016) estimates a growth of global milk demand of 25% over 10 years (2.3% per year), more than 20 million tonnes per year by 2025. The IFNC (2016) assesses 127 kg of milk equivalent consumed per capita in 2025, representing a growing global milk supply and a positive preference for milk by consumers.

The global cow's milk production was estimated at 638 millions of tons, equaling 198 billions of USD (FaoStat, 2013). The milk production value counts from 8.5 to 10.5% of total agriculture value, and the dairy sector provides jobs, especially for rural communities, from upstream (inputs and farm) to downstream (marketing, distribution) of the whole milk chain, representing 3% of the total agricultural employment (IDF, 2013).

One quarter of the total raw milk production in the world is manufactured into a wide range of cheese by the global cheese-manufacturing industry (Xu et al., 2009). Cheese is one of the most known and manufactured dairy product, its production is predicted to reach 110.5 million of kilograms in 2021 (ZRA, 2016), and it is a fundamental part of European and Italian dairy sector.

European cheese consumption is dominated by hard and semi-hard cheese. Europe is the first consumer of cheese in the world and the average European consumption is 18 kg per capita per year, while 58 and 4.5 kg of fluid milk and butter are consumed per European capita per year, respectively (Clal, 2015c). Italy is the highest cheese consumer with 23 kg per capita per year (Clal, 2015c). ISMEA (2016) reported that the Italian citizens food basket is composed by vegetable and fruit (19.2%), meat and cured meat (16.9%), dairy products (14.7%), cereals (14%) and others. Meanwhile considering the chilled and fresh food (IRI, 2015), the cheese represents the 25% of the food purchased by the Italian citizens in 2015, followed by meat products (15%) and vegetable (14%), meanwhile cheese are 23% in Germany, 20% in France, 17% and 12% in Spain and Netherlands, respectively (IRI, 2015).

Dairy products represent 8.9% of Italian food export (Federalimentare, 2015). The Italian dairy sector is composed by 2,000 companies, 25,000 employees and 15 Euro billions of turnover process and package milk and dairy products (Koeleman, 2015; Clal, 2015b). Cheese production is an important sector in Italian economy: it presents an upward curve for both production and export level. Italy produces 11.1 million of tonnes of cow’s milk. The 60% of Italian cow’s milk is destined to cheese production (1.1 million tonnes), which places Italy as the third cheese producer in Europe (Clal, 2015d). The 48% of Italian cow’s milk cheese is qualified for the Protected Designation of Origin (PDO) (ISMEA, 2015).

The Veneto Region (Northeast of Italy) accounts for 3,630 dairy farms, with a total annual milk production of 1.1 million tonnes, providing 10% of the Italian cow’s milk (ISMEA, 2015), 0.74% of the European (Clal, 2015a) and 0.18% of global production (FaoStat, 2013). The 2/3 of milk produced in Veneto is delivered to dairy cooperative (ISMEA, 2013). The Veneto dairy sector, as the Italian one, is based on cheese production (Sumner, 2013) indeed 3/4 of milk are destined to cheese manufacturing (ISMEA, 2013). In Veneto

Region, more than 50% of cheese production are PDO cheese (ISMEA, 2013), and 8 of the 42 Italian cow's milk PDO cheese are produced (Mipaaf, 2016).

1.3 Sustainability and Life Cycle Thinking approach

Life Cycle Thinking (LCT) approach is a methodology to identify possible strategies to reduce environmental impacts and reduce use of resources across the lifecycle of goods and production activities (EPLCA, 2016). The method tries to avoid burden shifting: minimizing the burdens at one stage and to avoid increase elsewhere. LCT provides a wide perspective: it considers the full lifecycle of goods and services (supply/use/end-of-life). This holistic approach can help businesses and government actions, which often consider just a stage of the supply chain, or have a regional-local scale, focusing in a specific region without considering the impacts or the benefits occurred in other regions. LCT could be applied to all sustainability pillars (environmental, social and economic).

The choice to reduce the impacts are essentially of three types (Cappellaro, 2009):

1- "end of pipe": which aims to reduce the impacts using filters, chemical treatments or combustion at the end of the supply chain, however this type cannot be define a sustainable choice.

2- Clean technologies: it transforms the production activities in clean production activities, where the pollution substances are determined, measured, and reduced. However this choice is only focus to production phase, with any attention to other phases along the supply chain.

3- Products oriented life cycle approach: the environmental impacts are not only related to initial or production phase, but it is necessary to act along the whole supply chain.

The third choice introduces the Life Cycle Assessment (LCA), which is a part of LCT, but totally focalized on environmental sustainability, while LCT included the social and economic sustainability.

Environmental considerations have to be integrated into different decisions made by business, individuals, and public administrations and policymakers. LCT and LCA are used by governments to develop, to implement and to monitoring environmental acts, and by the private sector for environmental improvement, strategic decision support and environmental product communication (JRC, 2010).

1.4 Life Cycle Assessment

Life Cycle Assessment (LCA) has been widely recognized and accepted as a suitable tool to assess the environmental impacts occurring during food production (Notarnicola et al., 2016). The malleability of the LCA methodology permits to focalize the impact estimation on specific phase of the dairy chain, including or excluding specific phases and specific impacts (Briam et al., 2015; FAO, 2010).

LCA is defined as: “Life cycle assessment is an objective process to evaluate the environmental burdens associated with a product, process, or activity by identifying energy and materials used and wastes and emissions released to the environment, and to evaluate opportunities to achieve environmental improvements” (SETAC, 1991). And the main objectives of carrying out a LCA are:

• providing a picture as complete as possible of the interactions of an activity with the environment,

• contributing to the understanding of the overall and interdependent nature of the environmental consequences of human activities,

• providing decision−makers with information which defines the environmental effects of these activities and identifies opportunities for environmental improvements.

LCA is the focalization on products in a life-cycle perspective. LCA estimates the impacts from raw material acquisition, via production and use phases, to waste management (disposal as well as recycling). Natural environment, human health, and resources are included into the LCA comprehensive assessment (ISO, 2006a).

The international standard series, ISO 14040-14044 (ISO, 2006 a, b), present standardized methods for conducting LCAs.

LCA study includes four phases (Figure 1): I) Goal and Scope Definition, II) Life Cycle Inventory Analysis (LCI), III) Life Cycle Impact Assessment (LCIA), and IV) Interpretation.

1.4.1 Goal and Scope Definition

The Goal and Scope Definition describe the reasons for performing the study, the intended application, and the intended audience (ISO, 2006a). In this first step there is the definition of:

- *Functional Unit (FU)*: it is the reference unit to quantify the environmental performances of a product. Comparison between different studies can be make only using the same functional unit.
- *System boundaries*: definition of which unit processes are part of a product system.
- *Allocation*: assignation of inputs and/or outputs between the product system, and between the coproducts of the system.

1.4.2 Life Cycle Inventory (LCI)

The LCI is a compilation of the inputs-outputs from the product over its life-cycle in relation to the functional unit (ISO, 2006a).

1.4.3 Life Cycle Impact Assessment (LCIA)

The LCIA describes and evaluates the magnitude and relevance of the potential environmental impacts, which are the environmental issues to which inputs and outputs of LCI results are assigned (ISO, 2006a). It is composed by:

- *Characterization*: the magnitude of the contribution of input/output is calculated, the contribution is aggregated within each category. There is a linear multiplication of the inventory data with characterization factors for each substance and impact category.
- *Classification*: the inputs and outputs collected in the LCI are assigned to impact categories according to each substance's potential to contribute to each of the impact categories considered.

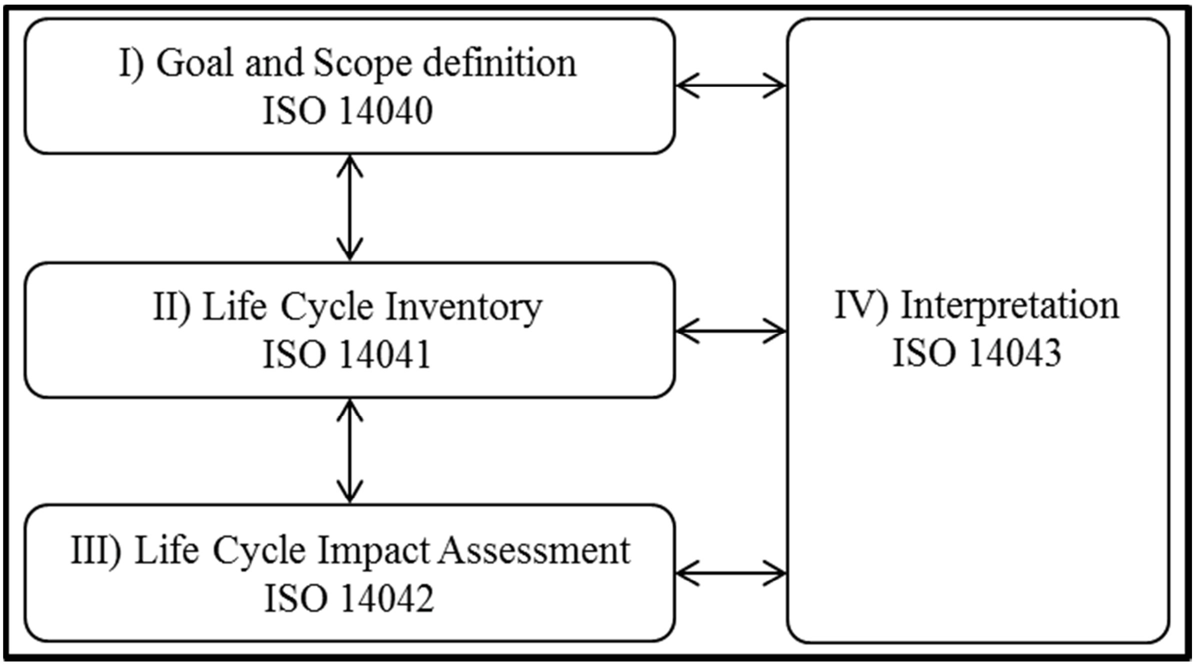
1.4.4 Interpretation

The Interpretation evaluates the results from the previous phases to the goal and scope in order to reach conclusions and recommendations (ISO, 2006a). It can contain:

- *Normalization*: it is an optional step. The impact assessment results are multiplied by normalization factors that represent the overall inventory of a reference unit (e.g. a whole country or an average citizen). The normalized results express the relative shares of the impacts of the system in terms of the total contributions to each impact category per reference unit. Normalization highlights which impact categories are affected most and least by the analyzed system. Normalized results are dimensionless, but not additive.

- *Weighting*: it is an optional step, which could be useful for interpretation and communication of the results. Impact assessment results are multiplied by a set of weighting factors, which reflect the perceived relative importance of the impact categories considered. Weighted impacts can be directly compared across impact categories, and also summed across impact categories to obtain a single-value overall impact indicator. Weighting requires making value judgements as to the respective importance of the impact categories considered.
- *Sensitivity analysis*: the effects of the choices about methodology and data in the study are estimated using systemic procedures.
- *Uncertainty analysis*: systematic procedure which determines the uncertainty of results due to the cumulative effects of model imprecision, input uncertainty and data variability.

Figure 1. The four phases of LCA.



2 LCA of dairy cheese chain

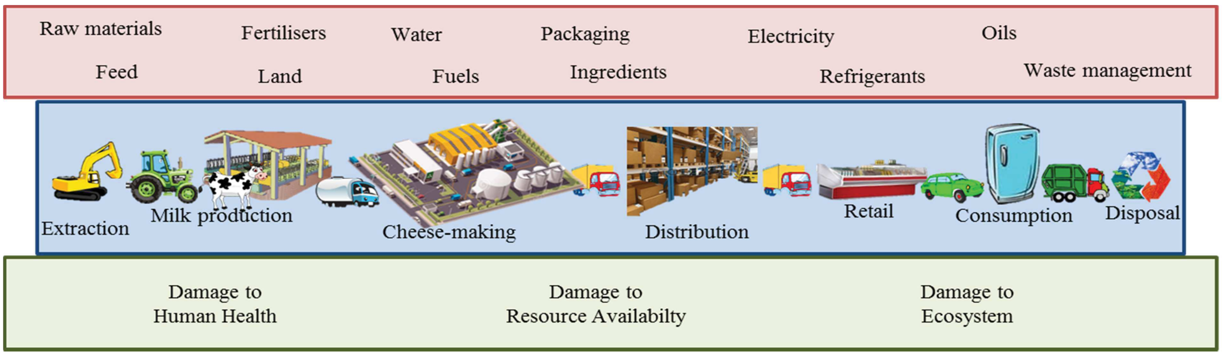
Dairy products as a food source are identified for their uniqueness, desirability, economic value, and nutrition (Milani et al., 2011). However, dairy products are linked to several environmental impacts. My people are considering to substitute the dairy products with other food with same nutrient values and which are recognized lower impacts (such as vegetable) (Westhoek et al., 2014). However, it is considered that to substitute the whole spectrum of macro and micro nutrients of milk and its effects on human growth and health is not feasible (Milani et al., 2011). Therefore, it is reasonable to preserve the dairy production and to search for more efficient and more environmental dairy production system, well knowing that the environmental sustainability can pursue along the whole chain production.

Tukker et al., (2006) estimated raw milk and dairy products account for 5% of climate change, 10% of eutrophication and 4% of photochemical ozone creation of the total European impacts. Moreover, Weidema et al. (2008) found the 30-40% of the impacts of food consumption is Europe arise from dairy products.

In Table 1 the main LCAs on cheese are listed highlighting the critical characteristics of each study, as modeled by Baldini et al. (2016). The selected studies reported the main differences on the type of impact categories estimated, system boundaries and allocation method at cheese plant. Some studies estimate just one impact, such as climate change (Flysjö et al., 2014; Vergè et al., 2013; Sheane et al., 2011), meanwhile other studies have a large number of impact categories, such as climate change, acidification, eutrophication, land use, water footprint, ozonde depletion, photochemical oxidant formation (Broekema and Kramer, 2014; Trevisan and Corrado, 2014; Kim et al., 2013; Berlin, 2002). The system boundaries of many studies do not take into account the whole cheese lifecycle, indeed the most common system boundaries encompass from cradle-to-dairy plant gate (Palmieri et al., 2016; Finnegan et al., 2015; Djekic et al., 2014; González-García et al., 2013a, b) or from cradle-to-distribution phase (Kristensen et al., 2015; Flysjö et al., 2014; van Middelaar et al., 2011) or the study is focalized on cheese-making process impact (Briam et al., 2015; Xu et al., 2009) and finally a complete analysis from cradle-to-grave (Barjolle et al., 2015; Kim et al., 2013; Broekema and Kramer, 2014; ICS Studio, 2014; Berlin, 2002). Allocation is a crucial step in each LCA study and it is more crucial in cheese production because cheese plant is commonly a multioutput system and beside cheese other valuable dairy products (i.e. whey, cream, other cheese) are produced. In the selected studies the allocation method at cheese plant was based on physical relationship, such as milk solids content (EPD, 2014; Flysjö et al., 2014; Fornasari 2013; Kim et al., 2013; Head et al

2011), mass (González-García et al., 2013b; Briam et al., 2015), dry mass (Sheane et al., 2011), and fat and protein content (Trevisan and Corrado, 2014); or an allocation based on economic value (Broekema and Kramer, 2014; van Middelaar et al., 2011; Berlin, 2002), or an allocation based on the model by Feitz et al. (2007), where a physico-chemical allocation matrix is applied to the plant (Finnegan et al., 2015; Djekic et al., 2014; Doublet et al., 2013;Vergè et al., 2013); or some authors avoid allocation, assigning all impacts to cheese (Palmieri et al., 2016; González-García et al., 2013a), or applying a system expansion (Kristensen et al., 2015; Nielsen and Hoier, 2009; Favilli et al., 2008). Moreover, the selected studies present differences arising from calculation methods, models and allocations at dairy farm, material and resource flows included into the LCI and data source, and completeness of the LCA performed (normalization, weighting, uncertainty and sensitivity analysis).

Figure 2. Cradle-to-grave cheese lifecycle.



The LCA studies on cheese lifecycle concord on the general results of the assessment. Considering the whole cheese lifecycle (Figure 2), the raw milk production at dairy farm, including feed production for animals, animal emissions (enteric methane and nitrous oxide from manure) and farm activities (such as milking, manure management, electricity, fuels, etc.), is the main hotspots for several impacts, such as climate change, acidification, eutrophication, resource (land and water) and energy use. The cheese-making process (energy usage, solid waste and wastewater) at dairy plant is another important contributor to several impacts, moreover packaging production and use contributes to impacts. Transport activities and further phases of the chain (distribution and retail, consumption and disposal) are mainly linked with use of energy (electricity and natural gas) and refrigerant for cooling, however these impact on the total cheese lifecycle are low when compared to farm phase and cheese-making process (Broekeman and Kramer, 2014; Kim et al., 2013; Thoma et al., 2013; IDF, 2009; Berlin, 2002). However, in some studies (Gonzales-Garcia et al., 2013c; Kim et al., 2013) the post farm gate phases were estimated as first contributor for energy use, eutrophication, ozone depletion. Therefore the consideration of the entire lifecycle of a product is considered the best way to give a complete picture of the environmental impacts associated to this products, simplifying strategies for reduction in each lifecycle phase (Notarnicola et al., 2016).

Table 1. LCA studies on cheese lifecycle.

Product/Functional Unit	Author	Year	Country[1]	Pub[2]	System boundaries[3]	Allocation at dairy plant (% to cheese)	Data source[4]	Impact category[5]
1 kg Cheese packaged (Hushallsost Angsgarden, 26% fat content)	Berlin	2002	SE	OA	CR-GR	Economic (67.8%)	RD, AD	EU, EC, GWP, AP, EP, POF, OD, ET, HT, LU
1000 kg Emmental blue-label cheese	Voutilainen et al.	2003	FI	RD	CR-GR	Milk solids content	RD, AD	GWP, AP, EP
1 kg Cheese	Foster et al.	2006	GB	R, RD	CR-GR	Various	AD, LD	Various
Amount of raw milk collected from cows to curd cheese production	Castanheira et al.	2007	PT	OA	CR-DPG	-	RD, AD	GWP, POF, AP, EP
1 kg Cheese	Osojnik and Marinsek	2007	SL	R, RD	CR-GR	Various	AD, LD	Various
3.053 kg Tuscan Pecorino PDO cheese _ewe's milk	Favilli et al.	2008	IT	OA	CR-DPG	System expansion	RD, LD	EU,WC, GWP, AP, POF, EU, SW
1 kg cheese	IDF	2009	World	R	CR-GR	Various	LD	GWP, EU, AP, EP, WC
1 tonne cheese	Lundie et al.	2009	NZ	RD	CR-RE	Physico-chemical allocation matrix	AD, LD	GWP
1,000 kg Mozzarella	Nielsen and Hoier	2009	DK	OA	CR-DPG	System expansion	RD, AD, LD	GWP, AC, EP, POF, ET, EU,
1 kg Cheese	Xu et al.	2009	USA	R	DPG-DPG	-	LD	EU
1 kg Cheddar	Aguirre-Villegas et al.	2011	US	RD	CR-DPG	Physical processes and Total solids content	AD, LD	GWP, EU
1 kg Cheese	Head et al.	2011	NL	RD	CR-RE	Milk solids content	AD	BD, HH, GWP, LU
1 kg Cheese	Sheane et al.	2011	SCO	RD	CR-GR	Dry mass	RD, AD	GWP
1 kg Semi-hard cheese	van Middelaar et al.	2011	NL	OA	CR-RE	Economic (76%)	RD, AD	GWP, EU, LU
1 kg Cheese	Aguirre-Villegas et al.	2012	US	OA	FG-DPG	Subdivision and total milk solids allocation (50%), Subdivision and nutritional content allocation (69%), Subdivision and economic allocation (88%)	RD, AD, LD	GWP, EU
1 kg Cheese	Møller et al.	2012	NO	RD	CR-GR	-	-	GWP
1 kg Cheese	Djekic et al.	2014	RS	OA	CR-DPG	Physico-chemical allocation matrix	AD, LD	GWP, AP, EP, OD, POF, HT
1 kg Cheese (Fresh, Cream, Soft, Semi-soft)	Doublet et al.	2013	RO	RD	CR-GR	Physico-chemical allocation matrix	RD, AD, LD	GWP, HT, AP, EP, FEP, TEP, MEP, FET, LU, WC, ARD
1 kg Parmesan cheese	Mancini	2013	IT	OA	CR-GR	-	LD	GWP, EU
1 kg Parmiggiano Reggiano (24 months aging)	Fornasari	2013	IT	OA	CR-GR	Milk solids content	RD, AD, LD	HH, EQ, EU
1 kg San Simon da Costa (PDO)	González-García et al.	2013a	PT	OA	CR-DPG	No allocation	RD, AD,	GWP, ARD, AP, EP,

cheese							LD	OD, POF, EU
1 kg Cheese	González-García et al.	2013b	PT	OA	CR-DPG	Economic	RD, AD, LD	GWP, ARD, AP, EP, OD, POF, LU, EU
1 Tonne cheese and mozzarella (dry basis)	Kim et al.	2013	US	OA	CR-GR	Milk solids content	RD, AD, LD	GWP, AP, FEP, MEP, EC, HT, ET, WU, EU
1 kg Cheese	Vergè et al.	2013	CA	OA	CR-DPG	Physico-chemical allocation matrix	AD, LD	GWP
1 kg Semi-cured Gouda cheese	Broekema and Kramer	2014	NL	RD	CR-GR	Economic	RD, AD, LD	GWP, AP, FEP, MEP, LU, EU
1 kg Parmesan cheese	Cas. Caramasche	2014	IT	RD	CR-DPG	Fat and protein content	RD, LD	GWP
1 kg Mozzarella	EPD	2014	IT	RD	CR-RE	Milk solids content	RD, LD	GWP, AP, EP, OD, POF, LU, WF
1 kg Cheese	Flysjö et al.	2014	FI	OA	CR-RE	Milk solids content	RD, AD, LD	GWP
1 kg Pecorino Toscano PDO_ewe's milk	ICS Studio	2014	IT	RD	CR-GR	Nutritive content	RD, LD	GWP
1 kg Minas cheese	Nigri et al.	2014	BR	OA	FG-RE	-	RD, AD, LD	GWP, OD, ET, AP, EP, LU, ARD, PM
1 kg Grana Padano (9 months aging)	Trevisan and Corrado	2014	IT	OA	CR-DPG	Fat and protein content	RD, LD	GWP, OD, AP, FEP, TEP, MEP, LU,
1 kg Le Gruyère (PDO), L'Etivaz (PDO) cheese	Barjolle et al.	2015	CH	RD	CR-GR	-	RD, AD, LD	GWP, BD, ARD
1 kg Cheese	Briam et al.	2015	US	OA	DPG-DPG	Mass	LD	EU
1 kg Cheese	Finnegan et al.	2015	IE	OA	CR-DPG	Physico-chemical allocation matrix	AD, LD	GWP, EU, WF
1 kg Cheese	Kristensen et al.	2015	DK	OA	CR-RE	System expansion		GWP
0.123 kg Mozzarella	Palmieri et al.	2016	IT	OA	CR-DPG	No allocation	RD, AD, LD	GWP, ARD, OD, HT, FET, MET, TET, POF, AP, EP.

[1] OA= original article; R= review; RD= research direction; SA= scenario analysis.
[2] FG-CR= farm gate to cradle, milk transport is included; CR-PL= cradle to dairy plant gate; DPG-DPG= dairy plant; CR-RE: cradle to retail.
[3] RD= real data; AD= average data; LD= literature data.
[4] EU= energy use; EC= energy consumption; ET= ecotoxicity; FET= freshwater ecotoxicity; MET= marine ecotoxicity; TET=terrestrial ecotoxicity; HT=human toxicity; LU= land use; WC=water consumption; SW= solid waste; BD= biodiversity; HH= human health; EQ= ecosystem quality; WF=water footprint; TEP= terrestrial eutrophication; FEP= freshwater eutrophication; MEP= marine eutrophication; ARD= abiotic resource depletion; PM= particulate matter; EC= ecosystem.
[5] BR= Brazil; CA= Canada; CH= Switzerland; DK= Denmark; FI= Finland; GB= United Kingdom; IE= Ireland; IT= Italy; NL= Netherlands; No= Norway; NZ= New Zealand; PT= Portugal; RO= Romania; RS= Serbia; SC= Scotland; SE= Sweden; SP= Spain; SL= Slovenia; US= United States of America.

3 Aim and Objectives

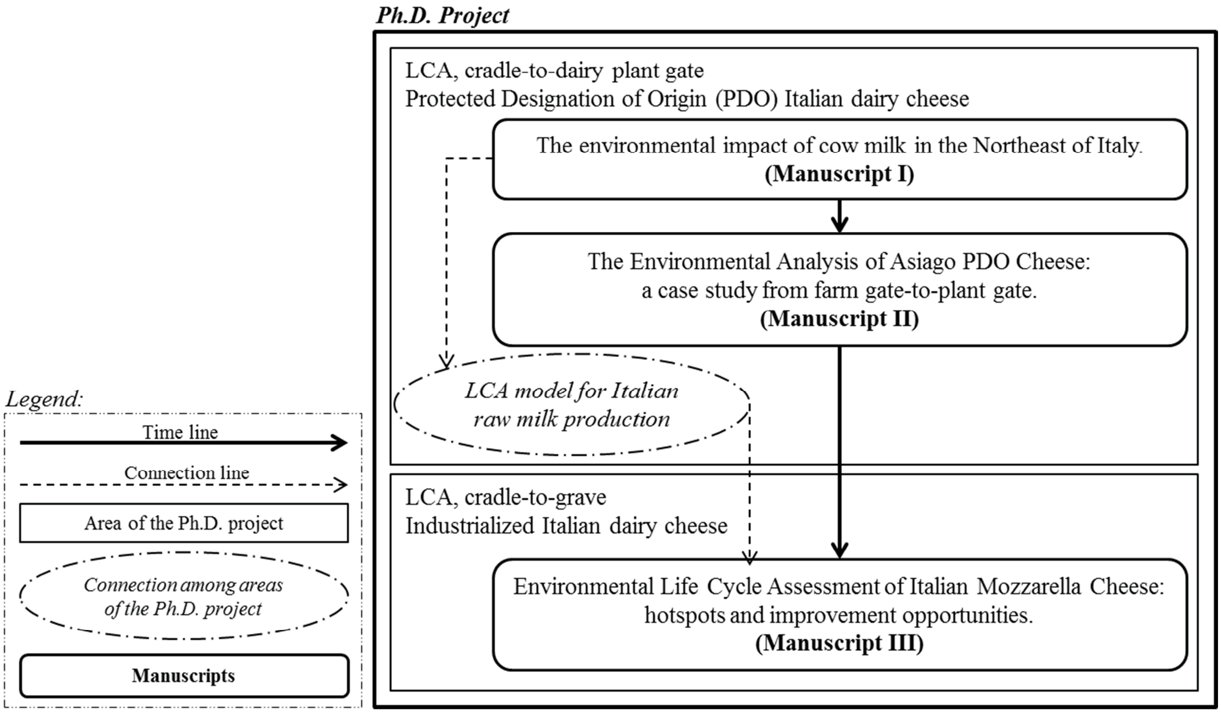
Cheese production is fundamental for the Italian dairy sector. National and international cheese sector is increasing in terms of production and consumption, and this situation is the trigger point for my Ph.D. Project: there is a need to preserve dairy cheese production, but at the same time the moral, ethical and legislative need to prevent the increment of environmental burdens occurring in the dairy sector.

The overall aim of this Project was to estimate environmental impacts of Italian dairy cheese sector and to highlight the environmental key issues of this sector. The Project aims to increase knowledge of environmental sustainability and to use the Life Cycle Assessment (LCA) methodology inside the Italian dairy sector. In particular, the Project pursues the possibility to use the larger number of real data to perform the studies. Therefore, the Project tries to collect the greatest available number of data through interviews and visits to dairy farms and dairy factories, in order to reduce to minimum the number of primary data derived by literature and report. At the same time, the Project aims to test if the dairy farmers and dairy companies are ready to apply sustainability studies to their products and their availability to further applications of strategies to improve sustainability. The LCA was applied both for the PDO cheese production (where the production technologies are often less industrialized and more traditional than other Italian dairy productions) and both for high industrialized cheese production. The impact results are compared with the results present in literature to verify the similarity of estimated results.

3.1 Structure of the Ph.D. Project

The structure of the Ph.D. Project is reported in Figure 3. Manuscript I, Manuscript II and Manuscript III are based on application of LCA methodology.

Figure 3. Structure of the Ph.D. Project.



Manuscript I is a case study which estimated the environmental impacts raised from raw milk production, in a "from cradle-to-dairy farm gate" perspective. The peculiarity of this paper is that the analyzed raw milk is produced in a specific area and it is produced following specific guidelines in order to be used to produced cheese with the title of Protected Designation of Origin (PDO), a group of Italian dairy products which have specific traits for quality, nutritional aspects, traditional production methods and produced in restricted geographical areas. During this study a series of interviews and farm visits have been organized, spanning a 9 months period (March-November 2014). Three fundamental meetings were done with the local dairy farmers and the representatives of Soligo dairy cooperative, in order to explain the Project and in order to motivate and to educate them about environmental aspects during the daily work. After the first cycle of farm visits, questionnaires were modified in order to make them available at the farm level, so to have the highest number of read data. This work aimed to build specific material flows and a whole life cycle inventory represent the raw milk production in that area, and to model a unit process in SimaPro© 8, the modeling software (PRé Consultants, The Netherlands, 2014), which have been used in the Manuscript II and III.

Manuscript II is a case study of a PDO cheese. Asiago PDO cheese the fourth most produced Italian PDO cheese (Clal, 2015d) and it is one of the eight PDO cheese produced in Veneto region (Clal, 2015d). The manuscript analyzed different environmental impacts associated to Asiago production, in a perspective from cradle-to-dairy plant gate. This manuscript is strongly related to Manuscript I, in fact the 34 dairy farm analyzed in the previous manuscript produce the raw milk which is delivered to the dairy plant analyzed. This represents an important point: raw milk and PDO cheese are part of the same dairy chain, reflecting the PDO cheese guidelines (Disciplinare di Produzione DOP "Asiago", 2006). Therefore the emission model built in the Manuscript I was used to represent the raw milk production for Asiago LCA model. The manuscript analyzed one dairy plant through a survey conducted from August to November 2014, considering the annual data production of year 2013. The data inventory of Asiago PDO cheese can be considered suitable to be used for environmental label certification, such as Environmental Product Declaration (EPD, 2016).

Manuscript III is a LCA study on Italian mozzarella consumption. This manuscript diverges from the previous ones:

- the case study is conducted for one dairy plant, specialized in mozzarella production (3rd Italian mozzarella producer), having a high technological level;
- the study is conducted from cradle-to-grave perspective, so all the phases after dairy plant have been included into the impact assessment;
- the study is mainly focalized on manufacturing plant, so farm phase has been represented considering the impact model of Manuscript I for Italian raw milk, and an impact model from Agri-footprint v2 database for European raw milk;
- each process into the plant has been inventoried and a model considering inputs and outputs of each manufacturing stage has been built;
- the manuscript analyzed the environmental differences among mozzarella produced directly from raw milk, and mozzarella produced using purchased curd.

The primary data were mainly composed by transport of raw milk and mozzarella, and plant data. Instead several data of post plant gate has been assumed and specific literature has been used. Data collection run from October 2015 to April 2016. The life cycle inventory has been performed to be used as Environmental Product Declaration (EPD, 2016) in the future development of the Project.

3.2 The relations between academic research and local territory

Manuscripts I and II were developed in collaboration with *Soligo dairy cooperative* (Soligo, Treviso, Italy), one of the first dairy cooperative in Veneto Region. While Manuscript III was performed thanks to collaboration with *Trevisanalat dairy factory* (Resana, Treviso, Italy), which is the third largest Italian mozzarella producer.

Soligo dairy cooperative (Farra di Soligo, Treviso):

Soligo Dairy Cooperative is one the largest dairy cooperative of the Veneto Region. It has been founded in 1883, it is one of the first dairy cooperative in Italy. Nowadays, it works 70,000 tonnes of cow's milk obtained by more than 2,000 dairy farms distributed in Veneto and Friuli Venezia Giulia Regions, reaching an income of 70 million Euro. It counts 4 dairy plants to manufactures several dairy products, which included fluid milk, cheese, yogurt, butter, mozzarella, etc. Soligo is the third Italian producer of Asiago DOP, beside other PDO cheese, like Montasio, Casatella Trevigiana, Grana Padano. This dairy cooperative has always dedicated time and resources to research and develop activities. (Soligo, 2016)

Trevisanalat dairy factory (Resana, Treviso):

Trevisanalat is an Italian single-product company specialized in the production of mozzarella cheese. The company was set up in 1980, and it has its own label, but the company manufactures mozzarella for other brands. It has a wide and solid national and international market. The company aims too innovation, advanced technology and safety in mozzarella production. Nowadays, it produces 7,000 tonnes of mozzarella, which is manufactured in 2 plants, using 8 production lines, in various product shapes and sizes. (Trevisanalat, 2016).

4 Manuscript I

The environmental impact of cow milk in the northeast of Italy

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THE ENVIRONMENTAL IMPACT OF COW MILK IN THE NORTHEAST OF ITALY

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Original scientific paper

SUMMARY

This study presents a "from cradle to farm gate" Life Cycle Assessment on cow milk produced in Northeast Italy. System boundaries consider milk and meat delivered at farm gate, including all upstream emissions. All farm activities were considered. Inputs and outputs required in one year are counted and information about 34 dairy farms are used to represent the production area. Different allocation approaches were used to share resources and emissions between milk and meat. Functional unit was one kg of raw milk. The Ecoinvent v3.1 and Agri-footprint v1.0 database were used for secondary data, and SimaPro© 8 was the main software in the analysis. The following impact categories were investigated: Climate Change (CC), Terrestrial Acidification (TA), Freshwater Eutrophication (FE), Land Occupation (LO), Water Depletion (WD) and Cumulative Fossil Energy Demand (CFED). Purchased feed production was the first emitter, followed by on-farm crop production, animals and manure management emissions. Considering the most debated impact categories, 1.80-2.19 kg CO_2eq and 8.84-10.78 MJ represent, respectively, CC and CFED per kg of raw milk. This research could be applied in regional studies on environmental impact of Italian dairy production.

Key-words: LCA, dairy farm, milk, environmental impact

INTRODUCTION

Life Cycle Assessment is becoming a solid tool to identify and estimate main emission drivers in dairy production chain. Italy has a developed dairy industry, mainly based on traditional cheeses and PDO products (Cassandro, 2003). Considering the several kinds of Italian dairy products and the difference dairy farming systems existing in the Italian territory, an estimation of environmental impacts occurring in raw milk production at farm is advantageous in order to better represents each production areas, furthermore considering that in terms of overall environmental impacts, the majority emission drivers in dairy products are located to raw milk production at farm (Kim et al., 2013). Several environmental impacts such as Climate Change, Acidification, Eutrophication, Land Use, non-renewable energy use, and other impacts belong to dairy farms as shown by Italian (Guerci et al., 2013a,b) and international (Thoma et al., 2013) researchers. The aim of this study was to estimate environmental impact of one kg of raw milk production in the Northeast Italy.

MATERIAL AND METHODS

Life Cycle Assessment (LCA), ISO 14040-14044 (ISO 2006), was used to perform the study, adopting a *"from cradle to farm gate"* perspective and an attributional approach (Thoma et al., 2013).

The functional unit used in this study was 1 kg of raw milk delivered at farm gate. Meanwhile 1 kg of Live Weight delivered at farm gate was the functional unit to express meat production. Six allocation methods were considered to allocate inputs and final emissions to milk and meat: *biological* (IDF, 2010), *economic* (using annual economic revenue derived from product sales), *mass*, *fat* and *protein content* of delivered products; moreover a *No-Allocation* approach is performed attributing all emissions to milk.

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System boundaries considered milk and meat delivered at farm gate, including all upstream emissions. All farm activities were considered. Main product was raw milk, but meat production was a relevant co-product in dairy farms. Meat derived from: culled cows, exceed heifers, male calves, male and female animals breed as beef, and reproduction bulls. Manure produced was spread in the on-farm land and it was not considered as co-products, and emissions from manure were part of the system.

Thirty-four dairy farms (75% of annual milk production) were selected among the 65 dairy farms that conferred milk to the dairy cooperative. Milk produced by members was collected and processed by a unique dairy plant in order to produce Italian PDO (Protected Designation of Origin) cheeses. Annual presence of animals in farm and feed rations were investigated in all 65 dairy farms. During 2014, data were collected throughout personal interviews with farm owners, covering all farm processes during 2013. The study pursues the idea to obtain the best realistic representation of dairy area emissions, then all data collected were considered valid data, and only limited adaptations and supplements were applied, where lack of data were presented.

All resources incoming in the whole dairy area during one year were counted and used to assess environmental impact, except emissions related to building, machinery, medicines and refrigerant gases due to lack of data or due to their low importance on the total impact (Thomassen et al., 2008). Data collected regard: land, water, electricity, fuels (diesel and LPG), plastic (PP, HDPE, LLDPE) and paper (cardboard, kraft paper and tissue paper) packaging and related waste, fertilizers, chemicals, pesticides, bedding materials, purchased feeds, crops produced on farm. Raw material compositions and active ingredients, and their related emissions, were considered for fertilizers, chemicals, pesticides, bedding materials, purchased feeds. Transport to farm and from farm was associated to all resources. Emissions on-farm and off-farm were estimated using different methods: Ellis et al. (2007) for enteric CH_4; IPCC (2006), with updated conversion factors (IPCC, 2013), is used for CH_4 and N_2O emissions from manure management, and NO_3 leaching and run-off at field level; Mikkelsen et al. (2006) for CH_4 from bedding materials; EEA (2013) for NH_3, NO_X, NMVOC, PM_{10}, $PM_{2.5}$, NO and pesticides emissions from on-farm crop production at field level; Nemecek et al. (2007) for PO_4^{3-} leaching and run-off at field level; UFE/UFAM (2014) for diesel and LPG burning emissions. The Ecoinvent v3.1 and Agri-Footprint v1.0 database were used for secondary data; where possible databases were implemented with local data to increase the precision on the results, such as local-real transport for all resources, except for fertilizers, chemicals and pesticides. Specific Italian recycling unit processes were adopted for paper waste (Arena et al., 2004) and plastic waste (Ferrari et al., 2005; Perugini et al., 2005).

SimaPro© 8 was used as the main software in the analysis (PRé Consultants, The Netherlands 2014).

Environmental impact estimation includes the following impact categories: Climate Change (CC), Terrestrial Acidification (TA), Freshwater Eutrophication (FE), Land Occupation (LO) and Water Depletion (WD) according ReCiPe Midpoint (H) v1.11 (Goedkoop M.Jet al., 2009), and Cumulative Fossil Energy Demand (CFED) according to Frischknecht et al. (2007) v1.09, excluding infrastructure processes and long-term emissions. Only classification and characterization LCA steps (ISO 14040-14044, 2006) are considered in the study.

RESULTS AND DISCUSSION

Results per kg of raw milk delivered at farm gate, throughout impact categories and allocations, are shown in Table 1. Considering impact drivers, purchased feed production was the main contributor on overall impact categories and allocations. Among allocation methods, the biological approach (IDF, 2010) is taken into account to explain the results: purchased feed production was the main emission driver in FE (83%), CFED (71%), LO (63%), AC (62%) and CC (53%), while on-farm crop production was the first contributor in WD (94%) and the second emitter in all impact categories, except in CC where animal emissions counted for 37% of the total CC. Contemplating CC category, CO_2, CH_4 and N_2O emissions represented, respectively, 55%, 38% and 7% of total CC impact: enteric CH_4 and manure management CH_4 are, respectively, 80% and 20% of CH_4 derived from animals. The highest CO_2 contribution of decreases when CO_2 from land transformation (51% of total CO_2) is not counted: CH_4 becomes the first contributor with 49% of total emissions (97% from animals), CO_2 marks 43% (mainly from fuel combustion), and N_2O grows to 9% (55% from on-farm crop production). In AC, NH_3 composed 84% of the total emissions; meanwhile organic and synthetic fertilizers used in purchased feed production counted 78% of emissions in FE.

Table 1. Emissions per kg of raw milk delivered at farm gate and allocation factor to milk using different allocation methods

Impact category	Biological	Economic	Mass	Fat	Protein	No-Allocation
Climate Change, kg CO_2 eq	1.80	2.06	2.13	1.80	1.84	2.19
Terrestrial Acidification, g SO_2 eq	13.20	15.13	15.61	13.20	13.52	16.10
Freshwater Eutrophication, g P eq	0.16	0.18	0.19	0.16	0.16	0.19
Land Occupation*, m^2a	1.64	1.89	1.95	1.64	1.68	2.01
Water Depletion, m^3	0.47	0.54	0.56	0.47	0.49	0.58
Cumulative Fossil Energy Demand, MJ	8.84	10.14	10.46	8.84	9.06	10.78
Allocation to milk, %	82	94	97	82	84	100

*: Agricultural + Urban + Natural transformation

Considering allocation approach to milk, our results were similar to those reported in the international methodology (IDF, 2010), while economic allocation values were similar to the results reported by Guerci et al. (2013a). Several *"from cradle to farm gate"* LCA have been performed for raw milk; these studies show results per kg of functional unit slightly lower than values estimated in the present study. Considering CC, an average value is 1.3 kg CO_2eq/kg milk (De Vrier and De Boer, 2010), although Guerci et al. (2013b) estimated values of 1.91 kg CO_2eq/kg ECM in Northern Italian dairy farms. Nevertheless, coherence is individualized in the main emission drivers. Italian authors (Fantin et al., 2011; Guerci et al., 2013a, 2013b) found on-farm emissions (mainly enteric, manure management and on-farm crop emissions) as the first emitter in CC, AC and FE, while purchased feed production as the second contributor in overall impacts and the first in CFED; moreover they underlined as enteric CH_4 was first contributor in CC, followed by CO_2 emissions. However, deep comparisons among studies are difficult due to different impacts under analysis, methods, functional units, system boundaries and emissions factors, such as the changing from IPCC (2006) to IPCC (2013). Reduction of impacts can achieve throughout rations for reducing enteric emissions, energy recovery technologies (such as manure anaerobic digestion), and the optimization in use as well as application of fertilizers.

CONCLUSION

In this assessment, purchased feed production deriving from the secondary data leads potential environmental impacts. This result derives by the choice to consider, and to break up, all concentrate feed used for each animal classes into singular raw materials. However, overlooking purchased feed impacts and CO_2 from land transformation, a general trend found in literature is recognized. An estimation of local emissions in raw milk production is better way to represent a specific dairy production. Comparison with other studies is made possible using international estimation methods for LCA and emissions. However, the specificity of region and data collected involves minor deep comparison with studies on national and international level.

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5 Manuscript II

The Environmental Analysis of Asiago PDO Cheese: a case study from farm gate-to-plant gate

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PAPER

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The environmental analysis of asiago PDO cheese: a case study from farm gate-to-plant gate

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ABSTRACT

A farm gate-to-plant gate life cycle assessment was performed to estimate the environmental impact of Asiago Protected Designation of Origin (PDO) cheese, the fourth most produced Italian PDO cheese. One manufacturing plant were surveyed for primary data. Emphasis was given to manufacturing processes, wherein environmental hotspots were identified. However the farm phase was discussed in order to obtain a clear prospect of Asiago cheese production. Inputs and outputs at the plant, such as cheese ingredients, fuels, electricity, water, cleaning agents, packaging, waste, and associated transport were included. Asiago cheese was the main product and co-products were other cheeses and liquid whey. Raw milk, other materials and energy flows were allocated using economic allocation strategy, while salt was attributed using plant specific information. Scenario analysis was about allocation strategies and time of cheese aging. SimaPro© 8.1.1 was the modelling software. Ecoinvent® v3.1 database was used for upstream processes. Climate change and energy consumption per kg of Asiago cheese was 10.1 kg CO_2-eq and 70.2 MJ, respectively. Uncertainty analysis gave 95% confidence interval of 6.2–17.5 kg CO_2-eq and 41.8–115 MJ per kg of Asiago cheese. The main impact driver was raw milk production. At the plant, electricity and fuels usage, refrigerants, packaging and wastewater treatment had the highest contribution to the overall impacts, except for fresh water eutrophication where wastewater treatment had the largest impact. Energy and fuel consumption were the crucial "hot spots" to focus on for efficiency and mitigation procedures at plant.

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Italian dairy industry; life cycle assessment; environmental impact; climate change; energy

Introduction

Increasingly, producers are giving attention to environmental sustainability in food production by seeking improved resource-use efficiency and aiming to sell eco-friendly products in order to enter new markets of consumers who are increasingly concerned about the environmental impacts of food. The Italian dairy industry has become more conscious of the environmental impacts of their activities, performing studies to determine the sources of impacts and to develop mitigation options.

Italy is the third largest European cheese producer (11%) (Clal 2015) and the fourth largest globally (6%) (FAOSTAT 2014). In 2014, Italy produced over 11 million metric tonnes (mt) of milk and 1 million mt of cheese (Clal 2015). Italian dairy industry is based on cheese production (Sumner 2013). Approximately 25% of Italian cheese production existing under the Protected Designation of Origin (PDO) (Assolatte 2015). PDO cheese is made with milk produced in defined production areas and follows a prescribed manufacturing process with rigorous specifications, and roughly 51% of all Italian milk (50% cows, 80% ewes and goats, 78% buffalos) is used to manufacture PDO cheese (Sumner 2013). PDO cheese made with cow's milk reached 433,000 mt in 2014, which made up 44% of the cow's milk cheese market in Italy (Clal 2015). Particularly, Asiago is a PDO cheese which is produced from cow's milk in two regions (Veneto and Trentino) in North-eastern Italy. Asiago cheese production was 21,458 mt (1,600 mt were exported) in 2014, ranking the fourth most produced Italian PDO cheese (Clal 2015). Asiago cheese must comply specific production guidelines (Disciplinare di Produzione DOP

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"Asiago" 2006), which define specific restrictions regarding classification; production area; cow feeding; product traceability; manufacturing processes; identification and branding; conservation and aging processes; chemical and organoleptic features; and packaging. Furthermore, there are three types of Asiago cheese: "pressato", "d'allevo", and "prodotto della montagna". For Asiago "pressato", the fat, protein, and moisture content must be 30% (± 4.0), 24% (±3.5), and 39.5% (±4.5), respectively. While for Asiago "d'allevo", the fat, protein, and moisture content must be 31% (± 4.0), 28% (±3.5), and 34.5% (± 4.5), respectively. Asiago cheese is often manufactured in small plants located in rural areas using traditional methods, and represents a pillar that supports a traditional Italian industry with significant cultural and social importance, therefore understanding its environmental sustainability is important. This is particularly true because of the expected Italian increase of PDO cheese production in the future (Clal 2015).

Life cycle assessment (LCA) is a technique for assessing the potential environmental impacts and relative hotspots associated with a product, process, or service throughout its lifetime (ISO 2006), and it is used to quantify mitigation and efficiency improvements. LCA can be used to measure the environmental impacts of PDO cheese (González-García, Hospido et al. 2013).

Various LCAs on dairy products are present in literature. These LCAs have differences in typology of analysed dairy product and country, system boundaries, functional unit, allocation and estimated impact categories, which lead to difficulties in making exact comparisons. Analyzed dairy products are fluid milk, such as fluid milk in the US (Thoma et al. 2013) and fluid milk in Italy (Fantin et al. 2012), or butter, such as Italian butter (Bianconi et al. 1998; Masoni et al. 1998) and butter in the UK, Germany, and France (Nilsson et al. 2010), or yogurt, like the Spain one (González-García et al. 2013a). Furthermore, there are LCAs on the cheese lifecycle, some of them consider the production of cheese, such as Dutch semi-hard cheese production (van Middelaar et al. 2011), Portuguese mature cheese production (González-García et al. 2013b), Serbian cheese production (Djekic et al. 2014) and Swedish cheese production (Flysjö et al. 2014), but others consider the whole lifecycle, including consumption, such as Swedish semi-hard cheese (Berlin 2002), world-wide cheese (Guinard et al. 2009), cheddar cheese and mozzarella cheese in the US (Kim et al. 2013). In some LCAs on cheese the functional unit is kg of cheese as sold (Berlin 2002; González-García et al. 2013b) or others use kg of dry matter consumed (Kim et al. 2013). Only few LCAs on PDO cheeses are reported in literature (Fornasari, 2013; González-García, Hospido et al. 2013; Barjolle et al. 2015), where González-García, Hospido et al. (2013) was the analysis of a Spain PDO cheese production, while Fornasari (2013) included the distribution and consumption phases for PDO cheese. Different authors determined different environmental impacts: Flysjö et al. (2014) quantified the carbon footprint of cheese production, while Djekic et al. (2014), González-García et al. (2013b) and Kim et al. (2013) estimated more than one environmental impact categories (such as energy demand, eutrophication, acidification, ozone layer depletion, photo chemical oxidant formation, human toxicity). Berlin (2002), Kim et al. (2013) and the abovementioned authors agree that cheese manufacturing is the second-largest contributor to post-farm gate environmental impacts, while post-manufacturing plant activities such as distribution, retail, consumption, and final disposal have lower relative contribution when they are compared to cheese plant overall impact (Fornasari 2013; Kim et al. 2013). As reported by Fornasari (2013), González-García, Hospido et al. (2013), Kim et al. (2013) and Guinard et al. (2009) energy usage is the main emission drivers at plant. Allocation is critical in LCAs on cheese, influencing final emissions per functional unit. The application of just one allocation strategy is not sufficient for decision making, considering the influence of allocation strategy on the LCA results, thus a comparison of different allocation strategies is crucial and suggested in order to consider LCA as a decision support tool (Luo et al. 2009). Economic allocation strategy (based on the revenue from each plant product) was used by Berlin (2002), Nilsson et al. (2010), van Middelaar et al. (2011) and Fornasari (2013). Kim et al. (2013) performed a LCA study where economic allocation and milk solids allocation strategies (base on milk solids content of each plant product) were applied, while the impacts have been totally assigned to cheese without using allocation strategy in González-García, Hospido et al. (2013). The time of cheese aging is one of the most sensitive inputs in the cheese-making process (Aguirre-Villegas et al. 2012), and its impact is derived mainly from electricity, heating, and refrigerants (Kim et al. 2013) that are used to maintain proper aging conditions. Ramirez et al. (2006) estimated that cheese storage uses 24% of energy consumption for cheese processing, while Xu et al. (2009) reported that cheese aging and storage contribute 32% (9–65%) of total energy used in the global cheese industry. Furthermore, Kim et al. (2013) showed that long aging (60 months) can increase CC by 6% and 22% per kg of cheese in cradle-to-plant gate and from the farm gate-to-plant gate assessment, respectively. Additionally, long aging has an impact on TO, which is primarily associated with increased electricity use for additional refrigeration.

Improving the sustainability of dairy cheese sector is a global issue in order to reduce environmental impacts from that sector. PDO cheese production represents an important part of the international and Italian dairy sector, however nowadays a limited number of studies on environmental impacts arising from PDO cheese production are present in literature. We consider a useful contribution to improve the sustainability of dairy sector to provide this first study on the potential environmental impacts arising from Asiago PDO cheese production, which has a strategical role in the Italian PDO cheese sector and which is facing an increase of production and export. This study has a great emphasis on the production plant, and the results may will help producers to underline inefficacies and to improve sustainability.

Materials and methods

Goal and scope definition

The goal of this study is to quantify potential environmental impacts and point out the principal impact drivers in Asiago PDO cheese production for the purpose of highlighting opportunities for improving environmental sustainability. The scope regards a farm gate-to-plant gate LCA and a great emphasis is given to the production cheese plant, although some data and discussion of the farm phase were integrated in the study. The LCA was based on the ISO 14040–14044 methodologies (ISO 2006) and ISO TS ISO 14067 methodology (ISO 2013).

Functional unit

The functional unit was one kg of Asiago cheese produced (37.7% moisture content) at the plant gate and ready-to-sell to wholesale/retail after an aging time (28 days). We consider that the chosen function unit (1 kg of Asiago cheese) is the most suitable one to represent the cheese production and the main addressees of the this study, that are stakeholders of cheese manufacturing chain. Liquid whey and other cheese, produced together with Asiago cheese in the plant, were also sources of revenue and therefore were considered as co-products of Asiago cheese. As abovementioned in Introduction section, there are three types of Asiago PDO cheese: “pressato”, “d’allevo”, and “prodotto della montagna”. This study did not consider “prodotto della montagna” Asiago PDO cheese because it is particular production manufactured during the summer in the highlands. Moreover, this study did not differentiate “pressato” and “d’allevo” Asiago PDO cheese, which are commonly produced in the same facility, but given the inability to collect data for a particular type of Asiago cheese and because data were collected at a plant level, we reported a combination of these two cheese. However, a scenario analysis, based on time of cheese aging, presents the differentiation of these two type of Asiago cheese.

System boundaries

The system boundaries encompassed raw milk production at farm and upstream emissions all the way up to the cheese plant gate, including the waste management of the plant (Figure 1). Notably, this study is not a detailed engineering analysis, and some data were available only at the whole plant scale, therefore there was not direct assignation to a specific cheese-making operation.

Cheese manufacturing was modelled as: raw milk collection at farm and transport to the cheese plant, raw milk refrigeration and pasteurisation, heating of pasteurised milk in vat, curdling, curd pressing and moulding, dry salting, and cheese aging. Cheese was generally sold as whole wheels and transported to retail centres. The inventory includes all inputs and outputs such as fuels, electricity, water, cleaning agents, packaging materials, waste. Furthermore, transport of inputs and waste were included in the model. All cheese ingredients were inventoried, but the environmental impacts were not identified for some (rennet, started cultures, lysozyme, and casein plates) due to the annual consumption ($<$ 0.01% of total input mass) and/or the lack of data to estimate their impacts (González-García et al. 2013a). The production of capital goods (machinery, buildings, infrastructures, and equipment) and employee-related activities were excluded from the study following Berlin (2002) and González-García, Hospido et al. (2013); although they were included in some Ecoinvent® processes (Fantin et al. 2012). The post-plant gate stages such as retailer distribution and customer consumption were excluded due to a lack of detailed data and in light of this study’s focussed aim of estimating the environmental impacts of the manufacturing stage.

Life cycle inventory

Information and data reported by Dalla Riva et al. (2015) were used to model impacts of raw milk production (Figure 1 and Table 1). One Asiago cheese

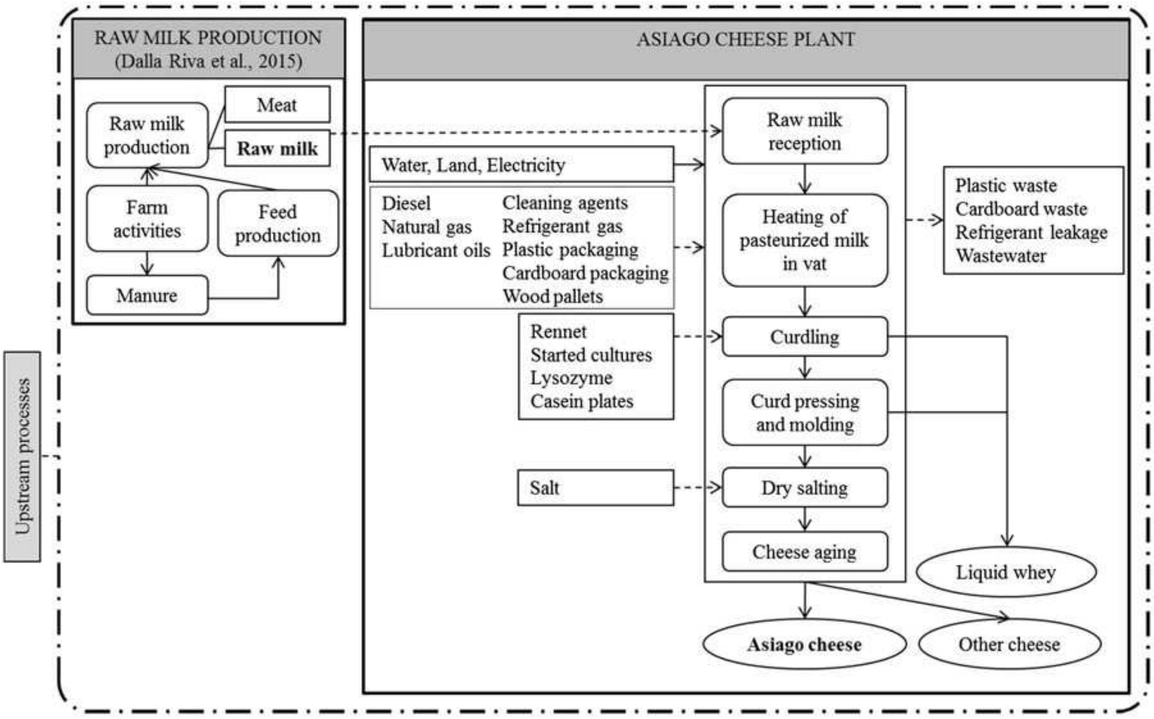

Figure 1. System boundaries of Asiago cheese production.

plant was surveyed for the analysis, and the plant worked milk deriving by 65 dairy farms. Dalla Riva et al. (2015) surveyed 34 dairy farms, which produced the 75% of milk collected from the 65 farms and processed by the plant. Table 1 shows the primary data for farm gate-to-plant gate perspective: in 2014, primary data for 2013 were collected through personal interviews with plant operators. The Ecoinvent® v3.1 default system model (Weidema et al. 2013) database was used for upstream processes, emissions, and waste treatments related to primary data. SimaPro© 8.1.1 was the modelling software used (PRé Consultants The Netherlands 2014).

The cleaning agents used in the plant were broken down into their active ingredients, and the environmental impacts for each of these were taken into account. When a specific active ingredient was not available in the background database, a substitute was utilised that was chemically similar. The transport processes were adopted from the Ecoinvent® v3.1 database (Weidema et al. 2013). The transport distance (km) of delivered materials was included in the study (Table 1). Where available, actual transport data were used (derived from plant-specific information). Where data of actual transport distance were not available and where background data of transport distance of Ecoinvent® v3.1 database (Weidema et al. 2013) were not appropriate, a transport distance was assumed. For example, 500 km transport was assumed for waste (cardboard, plastic, lubricant oil, and wood pallets) disposal, following a similar approach used by González-García et al. 2013a, 2013b). Moreover in cases where the origin of the materials was unknown and in cases where an input was composed by multiple ingredients with potentially different transport distances (such as cleaning agents and fuels) the Ecoinvent® v3.1 database (Weidema et al. 2013) was used.

The plant had not the equipment to treat the wastewater derived by plant processes, therefore wastewater was directly discharged into municipal wastewater collector and treated at a municipal wastewater treatment plant. The municipal wastewater treatment plant was modelled using Ecoinvent® v3.1 database (Weidema et al. 2013). The cardboard and plastic waste generated by the plant were treated using three treatments (recycling, municipal incineration, and landfill treatment according ARPA (2013) and ISPRA (2014)). ISPRA (2014) was used to assume the percentages of cardboard and plastic waste treated into recycling, municipal incineration, and landfill treatment. While wood pallet waste and lubricant oil waste were disposed by municipal incineration according plant-specific information. Municipal incineration and landfill treatments were modelled using Ecoinvent® v3.1 database (Weidema et al. 2013), while specific Italian recycling unit

Table 1. Inventory data, before allocation, at farm phase and at the plant. Transport and explanation of economic allocation model are shown for farm gate-to-plant gate perspective.

Cradle-to-farm gate[a]			
Resource	Resource kg^{-1} of milk	Resource	Resource kg^{-1} of milk
Land, m^2	1.96E + 03	Bedding materials[b], kg	2.44E-01
Water, m^3	7.35E-03	Purchased feed[b], kg	8.79E-01
Electricity, kWh	5.12E-02	On-farm feed[b], kg	8.03E-01
Diesel, MJ	1.09E + 00	Plastic waste, kg	9.51E-05
Propane gas, MJ	1.12E-02	Lubricant oil waste, kg	2.04E-04
Cleaning agents, kg	1.66E-03	Cardboard waste, kg	1.25E-04
Lubricant oil, kg	8.49E-04	Methane[c], kg	3.52E-02
Plastic packaging, kg	9.51E-05	Nitrous oxide[c], kg	3.16E-04
Cardboard packaging, kg	5.22E-04	Carbon dioxide, kg	2.26E-02

Farm gate-to-plant gate				
Primary resource	Resource kg^{-1} of Asiago	Transport[d]		EM[e]
Raw milk, kg	11.6	199	PSI	EA
Salt, kg	5.90E-02	780	PSI	PSI
Rennet, kg	2.28E-03	834	AS	PSI
Starter cultures, kg	1.20E-03	496	PSI	PSI
Lysozyme, kg	3.21E-05	65	PSI	PSI
Casein plate, kg	1.64E-04	14	PSI	PSI
Seed oil, kg	3.87E-05	1,000	AS	PSI
Pelure, kg	8.73E-05	193	PSI	PSI
Diesel, MJ	3.49E-02	1,000	AS	EA
Natural gas, MJ	8.9	1,000	AS	EA
Lubricant oil, kg	2.32E-04	1,000	AS	EA
Refrigerants, kg	1.49E-04	1,000	AS	EA
Cleaning agents, kg	4.24E-02	DB	ED	EA
Electricity, kWh	1.4	–	–	EA
Plastic packaging, kg	2.77E-03	280	PSI/AS	EA
Cardboard packaging, kg	5.16E-02	100	PSI	EA
Wood pallets, kg	3.87E-05	152	PSI	EA
Water, m^3	6.13E-02	–	–	EA
Land, m^2a	1.42E-02	–	–	EA
Plastic waste, kg	2.66E-03	500	AS	EA
Cardboard waste, kg	5.16E-02	500	AS	EA
Wood pallet waste, kg	7.75E-04	500	AS	EA
Lubricant oil waste, kg	2.32E-04	500	AS	EA
Refrigerants leakage, kg	1.49E-04	–	–	EA
Wastewater, m^3	3.48E-02	500	AS	EA

[a]Biological allocation at farm: allocation factor for milk (82%) and for live weight (18%).
[b]Ecoinvent® v3.1 database was used for bedding material and purchased feed, while specific unit process was modelled for on-farm feed using primary inventoried data.
[c]CH_4 and N_2O emissions from manure management were calculated using Tier 2 (IPCC 2006).
[d]Left column: distance (km) from place of origin to plant of unitary resource. Truck: EURO3; payload (raw milk_16-32t, salt_>32t, other resources_7.5-16t). Right column: source of data (PSI: Plant-Specific Information; AS: Assumption; ED: Ecoinvent® v3.1 database).
[e]Economic allocation model (EM): resources are attributed among Asiago cheese and co-products using Economic Allocation strategy (EA) or Plant-Specific Information (PSI).

processes were adopted for cardboard and plastic waste, based on Arena et al. (2004) and Perugini et al. (2005).

Allocation

The surveyed plant was a multi-output system, so allocation was necessary to assign resources and emissions to each product. The default allocation model is called Economic allocation Model (EM), which was based on simultaneous use of plant-specific information, called system separation of resource assignment (Kim et al. 2013), and use of economic allocation strategy (based on revenue derived from each product, which was based on the sales quantity and the mean price per kg of product obtained by averaging annual prices from 2009–2013, in order to attenuate price volatility and inflation effects) for remaining unassigned resources. In Table 1 the combination of plant-specific information and allocation strategy are shown for each resource at plant. System separation was used where plant-specific information was available to assign a specific resource and its amount to a specific product. For example, this situation is clear for salt and minor ingredients of cheese, and related transport. Salt and its transport were assigned exclusively to cheese and other cheese based on plant-specific information; specifically, a dry salting process was used during manufacturing, which allows separation of the liquid whey system from the cheese system for assignment of salt burdens. Other minor ingredients such as rennet, starter cultures, lysozyme, casein plates, and pelures, were also assigned, based on plant-specific information, to cheese and other cheese, as separate systems from liquid whey). In case specific information were not available, economic allocation strategy has been used for: incoming raw milk, inputs (electricity, fuels, lubricant oils, refrigerants, water, cleaning agents, land), packaging (corrugated cardboard boxes, plastics, wood pallets), solid wastes (lubricant oils, refrigerants, packaging waste), and wastewater.

Life cycle impact assessment

The environmental impact categories evaluated in the LCA were climate change (CC), ozone depletion (OD), terrestrial acidification (TA), freshwater eutrophication (FE), toxicity (TO: sum of human-terrestrial-freshwater-marine toxicity), photochemical oxidant formation (POF), land occupation (LO: sum of agricultural and urban), and water depletion (WD) using ReCiPe midpoint (H) V1.11 (Goedkoop et al. 2009). Cumulative energy demand (CED) was also accounted (Frischknecht, Jungbluth, Althaus, Doka et al. 2007). Normalization and uncertainty analysis were performed, and both analyses are explained and discussed in the last part of Results and discussion section.

Scenario analyses

Two scenario analyses (allocation strategy and time of cheese aging) were performed in order to test the robustness of the results.

The first scenario analysis evaluated how an alternate allocation strategy can influence the emissions per kg of cheese. The scenario analysis was carried out using an allocation strategy based on milk solids content (Milk Solids allocation Model, MSM). Each of the various milk solids of the incoming raw milk (fat, protein, lactose, ash) can be conceptually considered as a singular input, which is destined to different products (Kim et al. 2013). Therefore the milk solids content of each product became the allocation key, in conjunction with plant-specific information, following the EM. The milk solids allocation strategy in MSM was applied for all resources at manufacturing plant in order to provide a comparison with the economic allocation model (EM) and to assess the robustness of conclusions based on EM.

The time of cheese aging is one of the most sensitive inputs in the cheese-making process (Aguirre-Villegas et al. 2012). In our study the manufacturing data were available for the entire dairy plant; thus, a scenario analysis based on literature data was performed in order to differentiate Asiago PDO "pressato" (20 days of aging) and "d'allevo" (180 days of aging). Climate change and cumulative energy demand categories were investigated in the aging scenario. Actual primary data for cheese aging was not available at the plant, therefore we assumed this data from literature: 0.157 kWh per kg of cheese per day were assumed to age the cheese, according Karousou et al. (2010). In fact, Karousou et al. (2010) estimated environmental impacts of Parmigiano Reggiano PDO cheese, another Italian PDO cheese, which is produced in bordering regions and with similar aging room parameters of Asiago PDO cheese, thus we considered this data suitable to represent Asiago PDO cheese aging scenario. According to Xu et al. (2009) electricity and natural gas are used in aging cheese in the ratio of 33.5% electricity and 66.5% natural gas; we used this ratio in assigning whole plant energy data to the aging process. The total aging energy was calculated for the two types of Asiago cheese using number of aging days and energy requirement per day. This energy was removed from the plant total in order to highlight the impact of aging. All other material flows were allocated between the two types of Asiago PDO, other cheeses, and liquid whey, using EM and MSM.

Results and discussion

Life cycle impact assessment results

The analysis, results and discussion were done at the plant level, despite that milk production at farm was the main contributor, except for OD where cheese manufacturing was main contributor (Table 2). Farm impacts were mainly caused by feed production. Soybean and corn, used as main ingredients in concentrate feed for lactating cows, determined the main impacts related to purchased feed, while corn silage production drove the impacts of on-farm feed production. In feed production, main drivers were fertiliser

Table 2. Environmental impact per 1 kg of Asiago cheese from cradle-to-plant gate, for economic allocation model.

Environmental impacts	Unit	Total	Farm, %
CC	kg CO_2-eq	10.13	86.9
OD	kg CFC-11-eq	5.75E-06	7.1
TA	kg SO_2-eq	0.07	93.9
FE	kg P-eq	7.92E-04	98.1
TO	kg 1,4-DB-eq	0.54	86.3
POF	kg NMVOC	0.02	87.4
LO	m^2a	8.09	99.1
WD	m^3	2.37	98.1
CED	MJ	70.16	71.6

CC: Climate Change; OD: Ozone Depletion; TA: Terrestrial Acidification; FE: Freshwater Eutrophication; TO: Toxicity; POF: Photochemical Oxidant Formation; LO: Land Occupation; WD: Water Depletion; CED: Cumulative Energy Demand.

(nitrogen and phosphorus released in water during fertiliser application were main cause for FE and TA, respectively), water for irrigation and land use for cultivation. Enteric CH_4 and N_2O from manure management were main contributors to CC, while minor impacts derived by transport of off-farm inputs and field/cowshed operations.

The manufacturing stage was the main contributor in all impact categories (Figure 2), without considering the farm phase into the analysis. Figure 3 shows a detailed contribution at whole plant level of the drivers in the manufacturing stage for each impact category. Electricity was the largest contributor to CED, TA, CC and POF, and it was second largest contributor to LO. Fuels and lubricant oil were the second contributors to CED, CC, TA. TO was mainly derived from heavy metals released by usage of diesel, natural gas and electricity during cheese-making process and transport of resources to the plant. Waste treatment (mainly wastewater treatment) was the main contributor to FE. Refrigerant leakage was major responsible for OD. Raw milk transportation was the main driver for TO and secondary for POF. In LO, the largest influence came from packaging (mainly cardboard packaging), resulting from land occupation of tree plantations. Meanwhile packaging had minor contribution for FE, POF, TO and TA. Finally, plant process water was first driver for WD, where water was firstly present as steam, cold and hot water during cheese-making process, and secondarily mainly used for cleaning-in-place operations.

Production and utilisation of electricity and natural gas as first contributors at plant are in line with Kim et al. (2013) and Guinard et al. (2009). Primarily user of energy were cheese-making processes, such as pasteurisation of milk, and heat, steam and cool water production. Refrigeration and packaging had generally lower impact than energy usage for cheese-making due to the typology of cheese. In fact Asiago cheese requires low quantity of packaging because it is stored as wheels in the plant; furthermore the aging period does not requires extreme temperature therefore energy consumption is lower than energy used during manufacturing processes. Our results demonstrate that FE mainly occurred due to waste water treatment, which is in line with that reported by González-García, Hospido et al. 2013; González-García et al. 2013b) and Kim et al. (2013). Additionally, the packaging production and utilisation have large impacts on LO, in line with van Middelaar et al. (2011) and González-García et al. (2013b). Moreover, in our study the transport activities associated with the cheese plant had a relevant impact on TO and AC, as reported by Berlin (2002), Guinard et al. (2009), and González-García, Hospido et al. (2013). Finally, the Asiago cheese had similar values of CC and CED as those reported by

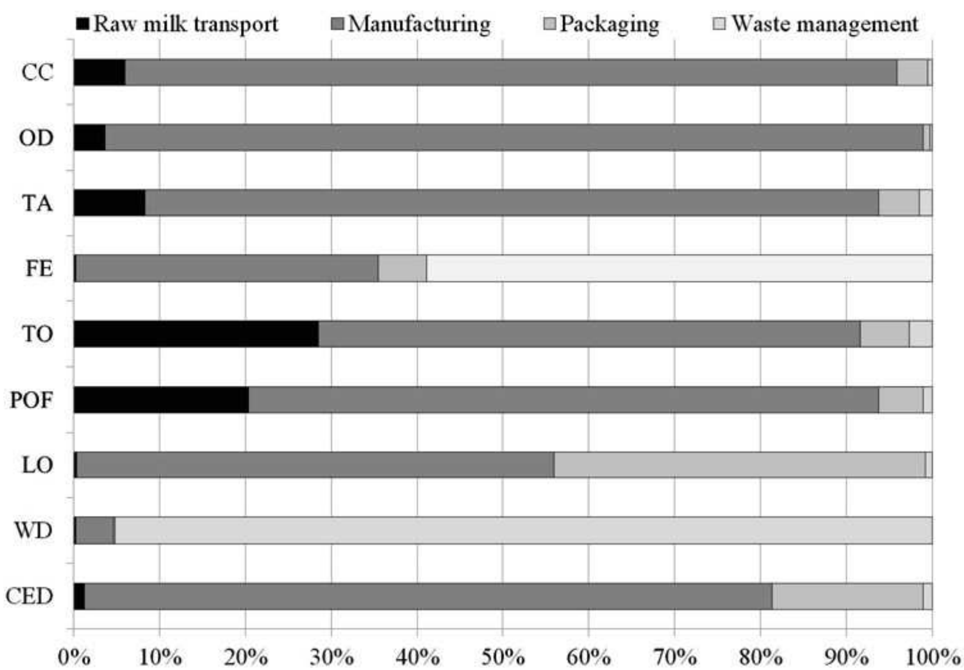

Figure 2. Environmental impact per 1 kg of Asiago cheese from farm gate-to-plant gate, and % contribution of emission drivers, using economic allocation model. (CC: Climate Change; OD: Ozone Depletion; TA: Terrestrial Acidification; FE: Freshwater Eutrophication; TO: Toxicity; POF: Photochemical Oxidant Formation; LO: Land Occupation; WD: Water Depletion; CED: Cumulative Energy Demand).

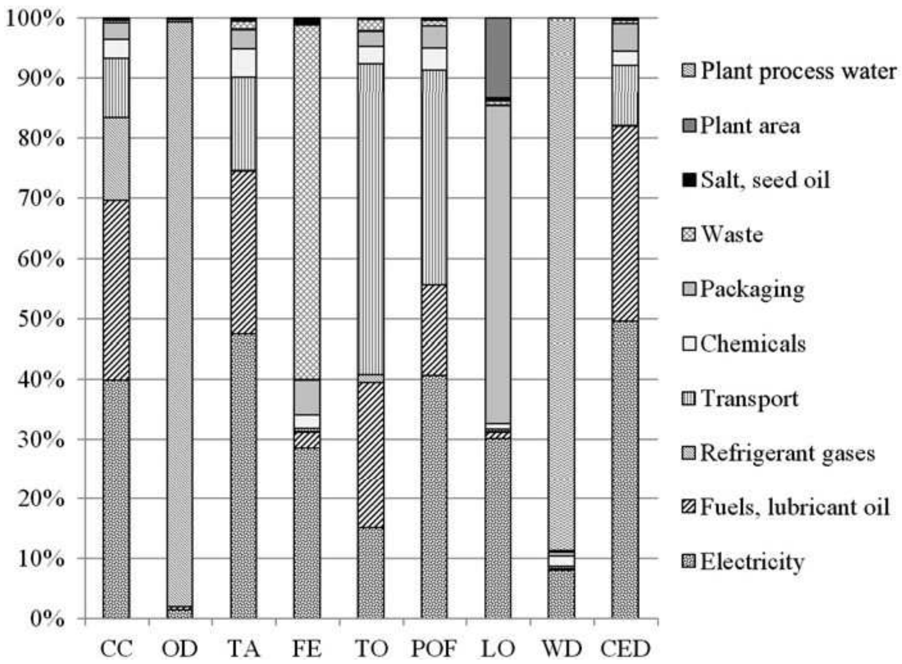

Figure 3. Environmental impact drivers in the manufacturing stage of Asiago cheese at the plant, using economic allocation model. (CC: Climate Change; OD: Ozone Depletion; TA: Terrestrial Acidification; FE: Freshwater Eutrophication; TO: Toxicity; POF: Photochemical Oxidant Formation; LO: Land Occupation; WD: Water Depletion; CED: Cumulative Energy Demand).

Table 3. Comparison between present study results and results of other cheese LCAs. Results are shown per 1 kg of cheese. The LCAs were selected considering only results with impacts having the same unit of measure, and no adjustment for system boundaries and adopted methods were applied. Cheese yield and allocation strategy are shown.

	Environmental impacts per 1 kg of cheese							
	CC	OD	TA	LO	WD	CED		
	kg CO_2-eq	kg CFC-11-eq	kg SO_2-eq	m^2a	m^3	MJ	Cheese yield[a], %	Milk allocation
Present study	10.1	5.75E-06	0.069	8.1	2.3	70.2	7.7	EM[d]
Berlin (2002)	8.8		0.136	14.0		39.1	6.8[b]	Economic
Guinard et al. (2009)	8.8		0.136		5	41.0	–[e]	–[e]
van Middelaar et al. (2011)	8.5			6.2		47.2	6.8[c]	Economic
González-García, Hospido et al. (2013)	10.4	4.69E-07	0.103			72.0	11.0	No-allocation[f]
González-García et al. (2013b)	7.5	5.53E-07	0.18	2.0		68.4	8.4	Economic
Kim et al. (2013)[g]	8.6				0.9	48.5	4.3[c]	Milk solids content
Djekic et al. (2014)	8.1		0.08				5.0-6.6	Physic-chemical and mass
Flysjö et al. (2014)	6.5						5.3	Fat and protein content

[a]Kg of cheese per kg of milk, after allocation of milk between cheese and co-products.
[b]Milk was considered as fat-protein-corrected-milk.
[c]Milk was considered as energy-corrected-milk.
[d]Economic allocation model.
[e]Data is not available.
[f]Plant processes are totally allocated to cheese.
[g]The results are expressed per kg cheddar (wet basis, 36.8% moisture content).
CC: Climate Change; OD: Ozone Depletion; TA: Terrestrial Acidification; LO: Land Occupation; WD: Water Depletion; CED: Cumulative Energy Demand.

González-García, Hospido et al. (2013), but greater emissions than those from other authors. TA was similar to that reported by Djekic et al. (2014), but lower than other studies. Furthermore, LO and WD were similar to results from other studies. Meanwhile our values of OD were greater than other reported values (Table 3).

Figure 4 shows the annual amount of products and emissions, as well as the comparison between allocation model (EM and MSM) results from farm gate-to-plant gate perspective. In our study economic allocation factors were 67%, 31%, and 2% for Asiago, other cheeses, and liquid whey, respectively; however, when using milk solids allocation strategy, the factors changed to 43%, 15%, and 42%, respectively. The larger economic allocation factor than milk solids allocation factors for cheese was in line to those reported by González-García et al. (2013b). According to EM, the

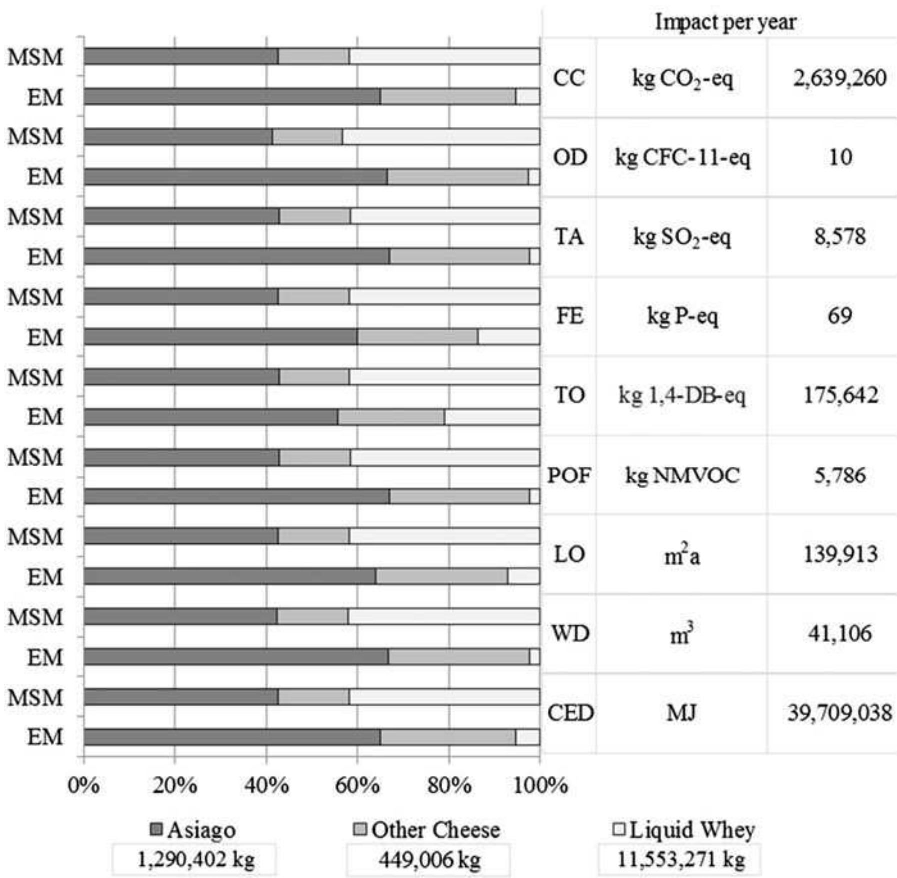

Figure 4. Impacts allocated between products at plant, using economic allocation model (EM) and milk solids allocation model (MSM). (CC: Climate Change; OD: Ozone Depletion; TA: Terrestrial Acidification; FE: Freshwater Eutrophication; TO: Toxicity, POF: Photochemical Oxidant Formation; LO: Land Occupation; WD: Water Depletion; CED: Cumulative Energy Demand).

largest portion of emissions (from 56% to 67%) was attributed to Asiago cheese, followed by other cheeses (from 24% to 31%); while liquid whey showed the lowest impact (from 2% to 21%). These values reflect the annual economic revenue derived from each product. In applying MSM, the main emissions for all impact categories were still assigned to Asiago cheese (from 41% to 43%) and secondarily to liquid whey (from 42% to 43%); while other cheeses (from 15% to 16%) had the lowest impacts, having been produced in smaller amounts than the other products.

Scenario analyses: Allocation strategy and time of cheese aging

The results appear to be deeply influenced by the allocation strategy. MSM (Table 5) resulted in the same trend for emission drivers as estimated using EM (Table 2). As expected, most of the impacts were allocated to Asiago cheese using EM, due to the low revenues obtained by selling whey; this is contrary to the results obtained by using MSM that allocated more impacts to whey. While the numerical results of individual co-products were affected by the choice of allocation strategy, the overall conclusions regarding sources of environmental impact remain unchanged, as do recommendations for improving the environmental footprint of the plant. Evaluating the effects of using different allocation strategies is considered an important point in the robustness of the study results. Accordingly, changing from EM to MSM reduced the fraction of total emissions assigned to the main product, Asiago cheese (Figure 4), which is similar to results reported by Flysjö et al. (2014) who showed a progressive decrease of emissions per kg of cheese moving from cheese revenue to milk solids allocation strategy. However, allocation does not make emissions disappear; it simply moves them from the Asiago cheese to the whey and to other cheese, as previously shown.

Asiago "d'allevo" with longer aging (162-180 days) had greater emissions than Asiago "pressato" (20 days of aging) in both allocation models (Table 6). In EM, Asiago "d'allevo" had 22% and 23% greater CC and CED, respectively, than Asiago "pressato", and the aging of Asiago "d'allevo" contributed about seven percent of the plant total of CC and CED. In this

Table 4. Results of 1,000 Monte Carlo runs uncertainty analysis of 1 kg of Asiago cheese from cradle-to-plant gate, using economic allocation model.

Environmental impacts	Unit	Mean	CV[a] (%)	95% CI[b]	
CC	kg CO_2-eq	10.13	96.6	6.2	17.5
OD	kg CFC-11-eq	5.75E-06	22.0	3.61E-06	8.43E-06
TA	kg SO_2-eq	7.00E-02	50.2	4.03E-02	1.15E-01
FE	kg P-eq	7.92E-04	79.9	5.64E-04	1.78E-03
TO	kg 1,4-DB-eq	0.54	7.29E + 03	0	464.4
POF	kg NMVOC	2.00E-02	36.2	1.11E-02	3.98E-02
LO	m^2a	8.09	84.8	4.6	13.7
WD	m^3	2.37	55.0	0	4.9
CED	MJ	70.16	27.8	41.8	115.1

[a]Coefficient of Variation.
[b]Confidence Interval.
CC: Climate Change; OD: Ozone Depletion; TA: Terrestrial Acidification; FE: Freshwater Eutrophication; TO: Toxicity; POF: Photochemical Oxidant Formation; LO: Land Occupation; WD: Water Depletion; CED: Cumulative Energy Demand.

Table 5. Milk solids allocation model and % variation compared with economic allocation model. Results per 1 kg of Asiago cheese.

		Cradle-to-plant gate		Farm-gate-to-plant gate	
Environmental impacts	Unit	Tot MSM	*% var. on EM*	Tot MSM	*% var. on EM*
CC	kg CO_2-eq	9.68	*−4.5*	0.87	*−34.5*
OD	kg CFC-11-eq	3.80E-06	*−34.0*	3.39E-06	*−36.6*
TA	kg SO_2-eq	6.75E-02	*−2.1*	2.83E-03	*−33.3*
FE	kg P-eq	8.00E-04	*−1.6*	2.28E-05	*−36.0*
TO	kg 1,4-DB-eq	0.53	*−3.2*	0.06	*−23.1*
POF	kg NMVOC	2.05E-02	*−3.7*	1.91E-03	*−28.9*
LO	m^2a	8.07	*−0.3*	0.05	*−36.1*
WD	m^3	2.34	*−0.3*	0.01	*−37.8*
CED	MJ	63.34	*−9.8*	13.11	*−34.4*

CC: Climate Change; OD: Ozone Depletion; TA: Terrestrial Acidification; FE: Freshwater Eutrophication; TO: Toxicity; POF: Photochemical Oxidant Formation; LO: Land Occupation; WD: Water Depletion; CED: Cumulative Energy Demand.

Table 6. Difference of climate change and cumulative energy demand impact between Asiago "pressato" (short aging) and Asiago "d'allevo" (long aging). Results per 1 kg of Asiago cheese at plant, using economic allocation model and milk solids allocation model.

	CC[a], kg CO_2-eq	Aging[c1], %	CED[b], MJ	Aging[c2], %
Economic allocation model				
Asiago "pressato[d]", kg	1.32	0.9	19.77	1.0
Asiago "d'allevo[e]", kg	1.61	6.5	24.42	7.6
Milk solids allocation model				
Asiago "pressato[d]", kg	0.87	1.4	13.07	1.6
Asiago "d'allevo[e]", kg	1.06	10.0	16.17	11.5

[a]CC: Climate Change.
[b]CED: Cumulative Energy Demand.
[c1,c2]Percentage contribution of aging on CC[a] and CED[b] per kg of Asiago cheese.
[d]Aging: 20 days.
[e]Aging: 180 days.

analysis, the contributions to CC and CED were 5.86E-04 kg CO_2-eq and 1.03E-02 MJ per kg of Asiago cheese per day of aging, respectively. We did not consider refrigerant leakage on the aging room due to lack of specific data. However, the longer the aging, the more refrigerant is required, which increases leaking losses, contributing to increased impact in OD, FE, POF, and TO, as shown by Kim et al. (2013).

Manufacturing plant and transport improvements

Concerning the manufacturing plant, we found that the energy and fuels were the main emission drivers; which was also reported by González-García et al. (2013b). Energy efficiency and more renewable sourcing of fuels have been suggested as ways to reduce plant impacts (van Middelaar et al. 2011; Aguirre-Villegas et al. 2012; González-García, Hospido et al. 2013; González-García et al. 2013a, 2013b). According to Karlsson et al. (2004), a reduction of emissions derived from energy use in plants is achievable by reducing total energy requirements, without the need for major investments or advanced technical equipment. Thus, we suggest a focussed energy audit analysis to identify plant-specific inefficiencies. Furthermore, reducing transport distances and

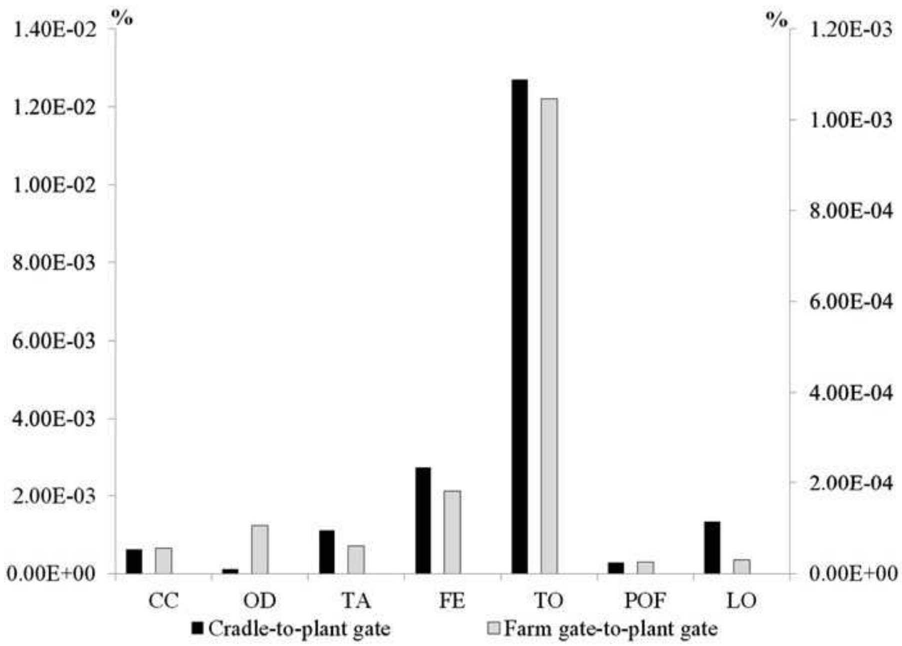

Figure 5. Normalization of Asiago cheese production (% contribution of Asiago cheese impacts to European impacts.: cradle-to-plant gate perspective on left axis; farm gate-to-plant gate perspective on right axis), using economic allocation model. (CC: Climate Change; OD: Ozone Depletion; TA: Terrestrial Acidification; FE: Freshwater Eutrophication; TO: Toxicity; POF: Photochemical Oxidant Formation; LO: Land Occupation; WD: Water Depletion; CED: Cumulative Energy Demand).

retrofitting existing trucks with emission controls could reduce the emissions attributed to transport. Although, we found the contribution of transport to impacts to be small compared to other sources (Berlin et al. 2008; González-García et al. 2013a); in our study, raw milk transport in Euro 3 diesel trucks had post-farm gate contributions to TO and POF, so a minor improvement is possible with a shift to more efficient trucks.

Normalization and uncertainty analysis

Emissions from the annual per capita Asiago cheese consumption were normalised using ReCiPe Midpoint (H) V1.11 European normalisation (Goedkoop et al. 2009). This shows the fractional contribution of Asiago cheese production to an average European citizen's cumulative environmental impact. As discussed by Kim et al. (2013), a direct quantitative comparison must be used with caution. Importantly, normalisation is a useful tool in representing cheese impacts on a national or international scale, and it can suggest to actors across the production chain where to focus strategies and policies to reduce the most relevant impacts on a regional scale. Results of normalisation before allocation, for both the cradle-to-plant gate and from farm gate-to-plant gate perspective are shown in Figure 5. Both perspectives suggest TO and FE as the main impact categories for targeting improvements such as transport improvement, electricity and fuels saving and chemical use.

The uncertainty of the results in cradle-to-plant gate perspective was analysed from 1,000 Monte Carlo simulation runs and presented in Table 4. The quality of individual data inputs was assigned using the Ecoinvent® 2.0 pedigree matrix (Frischknecht, Jungbluth, Althaus, Hischier et al. 2007). Specifically, the 95% confidence interval was 6.2 to 17.5 kg CO_2-eq and 41.8 to 115.1 MJ per kg of Asiago cheese for CC and CED, respectively.

Conclusions

This study assessed the environmental impacts of the manufacturing of the Asiago cheese, the fourth most produced Italian PDO cheese. Although raw milk production at farm was the main contributor to overall impact categories, the study emphasised the analysis from farm gate-to-plant gate perspective. Energy and fuels usage were the main contributors to ozone depletion, climate change, cumulative energy demand, terrestrial acidification, and photochemical oxidant formation; therefore, the use of renewable energy and fuels is suggested. Wastewater management was the largest contributor to freshwater eutrophication, while packaging (cardboard) was the largest contributor to land occupation. Allocation strategies influenced the emissions per kg of Asiago cheese, where economic allocation strategy attributed greater emissions to cheese than milk solids allocation strategy, which valorised the whey co-product. We also found that the time of cheese aging increased emissions per kg of Asiago cheese and represented 6–11% of the climate change and cumulative energy demand per kg of Asiago cheese at the plant.

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Disclosure statement

The authors declare that there is no conflict of interest associated with this paper. The authors alone are responsible for the content and writing of this article.

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6 Manuscript III

Environmental Life Cycle Assessment of Italian Mozzarella Cheese: Hotspots and Improvement Opportunities

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Environmental life cycle assessment of Italian mozzarella cheese: Hotspots and improvement opportunities

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ABSTRACT

The present study investigated a cradle-to-grave life cycle assessment to estimate the environmental impacts associated with Italian mozzarella cheese consumption. The differences between mozzarella produced from raw milk and mozzarella produced from curd were studied, and differences in manufacturing processes have been emphasized in order to provide guidance for targeted improvements at this phase. Specifically, the third-largest Italian mozzarella producer was surveyed to collect site-specific manufacturing data. The Ecoinvent v3.2 database was used for secondary data, whereas SimaPro 8.1 was the modeling software. The inventory included inputs from farm activities to end of life disposal of wasted mozzarella and packaging. Additionally, plant-specific information was used to assign major inputs, such as electricity, natural gas, packaging, and chemicals to specific products; however, where disaggregated information was not provided, milk solids allocation was applied. Notably, loss of milk solids was accounted during the manufacture, moreover mozzarella waste and transport were considered during distribution, retail, and consumption phases. Feed production and animal emissions were the main drivers of raw milk production. Electricity and natural gas usage, packaging (cardboard and plastic), transport, wastewater treatment, and refrigerant loss affected the emissions from a farm gate-to-dairy plant gate perspective. Post-dairy plant gate effects were mainly determined by electricity usage for storage of mozzarella, transport of mozzarella, and waste treatment. The average emissions were 6.66 kg of CO_2 equivalents and 45.1 MJ per kg of consumed mozzarella produced directly from raw milk, whereas mozzarella from purchased curd had larger emissions than mozzarella from raw milk due to added transport of curd from specialty manufacturing plants, as well as electricity usage from additional processes at the mozzarella plant that are required to process the curd into mozzarella. Normalization points to ecotoxicity as the impact category most significantly influenced by mozzarella consumption. From a farm gate-to-grave perspective, ecotoxicity and freshwater and marine eutrophication are the first and second largest contributors of mozzarella consumption to average European effects, respectively. To increase environmental sustainability, an improvement of efficiency for energy and packaging usage and transport activities is recommended in the post-farm gate mozzarella supply chain.
Key words: carbon footprint, climate change, energy use, dairy industry

INTRODUCTION

Cheese is a strategic way to conserve milk and represents a food with great nutritional value, as it contains proteins, EAA, minerals, vitamins, and milk fat; it has large economic value and its international production and trade are both increasing (CLAL, 2016). In recent years, the environmental consequences of dairy production are being considered at the policy level and in the development of new production technologies, in addition to economic, nutritional, and social values. Importantly, environmental sustainability is gaining more attention from producers and consumers, with aims of increased efficiency and new market areas on the one hand and environmental care by saving natural resources on the other hand. Modifications in dairy production facilities and studies (Berlin, 2002; Milani et al., 2011; Kim et al., 2013) have been made to increase environmental sustainability in dairy chain production, with each operator along the supply chain contributing to the reduction the environmental burden.

Mozzarella cheese is consumed worldwide and can be produced using bovine or water buffalo milk, with the former being the most produced and commercialized. Growth in bovine milk mozzarella production is

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projected for the future, whereas mozzarella continues to be a strategic product for the global dairy sector (Koeleman, 2015). Italy is one of the major cow milk mozzarella producers and consumers, evidenced by 253,000 t of mozzarella produced in Italy in 2015 and 4.6 kg per capita per year consumed (Assolatte, 2015). Furthermore, mozzarella production is a complex process, including several operations and numerous inputs and outputs, which in turn result in various environmental impacts. Notably, limited information exists on environmental impacts derived from mozzarella production and consumption in the Italian sector. Therefore, our study aims to increase the knowledge of environmental consequences of mozzarella production and consumption from a life cycle perspective. Mozzarella is produced in 2 different ways: the most traditional mozzarella (high-moisture mozzarella) is manufactured using raw milk directly, which is worked and transformed into mozzarella in the same mozzarella plant; otherwise, mozzarella can be produced using purchased curd, which is a semifinished product made in a different dairy plant and is purchased by the mozzarella plant to manufacture the mozzarella. The latter method produces low-moisture mozzarella, which is generally used as an ingredient in prepared dishes rather than consumed fresh.

Life cycle assessment (**LCA**), based on ISO 14040 and ISO 14044 LCA methodology (ISO 2006a,b), is a scientific method recognized worldwide to assess environmental burdens through the life cycle of a product; it has been used in several studies to assess environmental consequences of cheese production. Some authors (González-García et al., 2013a,b; Broekema and Kramer, 2014; Trevisan and Corrado, 2014; Finnegan et al., 2015) have investigated environmental impacts in the cheese life cycle, where general results show dairy farm activities and feed production as the main hot spots for impacts, followed by the manufacturing, distribution, and consumption phases. Fewer studies specifically assess the effect of the mozzarella life cycle. Palmieri et al. (2016) reported raw milk production as the main driver for several impacts along the Italian mozzarella production chain, whereas thermal energy to produce steam and hot water contributed to impacts arising during mozzarella manufacturing, particularly human toxicity, eutrophication, and ozone depletion. Nevertheless, the above study was focused on farm production, so little information was presented for manufacturing, and no information was provided on the distribution, consumption, and disposal phases. The only other LCA case study of Italian mozzarella was an assessment conducted to obtain an ecolabel for a private dairy company (EPD, 2013), where raw milk production, packaging, manufacturing, and home refrigeration were the main hotspots. Similarly, Kim et al. (2013) investigated the production of American mozzarella cheese, reporting that cattle feed production and farm milk production were the major contributors to most of the impact categories; whereas for the post-farm supply chain, cheese manufacturing drove several effects, followed by retail and consumption. Additionally, electricity and natural gas consumption were found to be drivers of climate change, cumulative energy demand, human toxicity, and ecotoxicity, whereas transportation influencing photochemical oxidant formation and on-site wastewater treatment were the main causes of eutrophication effects. Vergé et al. (2013) included mozzarella cheese in the LCA of Canadian dairy products, however, their study estimated only the greenhouse gases emissions, and the system boundaries excluded all the phases after dairy plant and the solid waste treatment; moreover, the study did not characterize the specific environmental impacts of mozzarella, but it was inserted into a generic cheese category without differentiation from cheddar, specialty cheeses, or processed cheese. Additionally, Nielsen and Høier (2009) studied the change of environmental impact using different enzymes during mozzarella manufacturing; thus, great attention was given to different manufacturing technologies, yet no information was given for environmental impacts of mozzarella consumption.

In light of this gap in the available literature, the objective of our study was to investigate the environmental impacts that occur during the life cycle of cow milk mozzarella (mozzarella from raw milk) production, from cradle-to-grave, with a strong emphasis on the manufacturing plant, which may in turn help producers highlight inefficiencies during manufacturing for the purpose of increasing environmental sustainability. In addition, our study investigates the environmental burdens of producing mozzarella from purchased curd, as no studies were found on this type of product, even though it has an important market share. Overall, the results from our study may help guide production decisions on mozzarella technologies and production.

MATERIALS AND METHODS

Goal and Scope Definition

The main goal of our study was to estimate the environmental impacts from mozzarella production and consumption. This estimation should assist the Italian dairy industry by providing environmental information of Italian dairy products that highlight opportunities for increasing the sustainability of the Italian dairy sector. To showcase these effects, an LCA based on ISO 14040 and ISO 14044 methodology (ISO 2006a,b) was performed, with the scope of the study being a cradle-to-grave assessment. Specific emphasis was given to the manufacturing process, which encompasses raw milk transport through delivery of mozzarella to the customer. Specifically, our study estimated the effects of the 2 types of commonly produced Italian mozzarella (Assolatte, 2015): high-moisture (**HM**) mozzarella (62.5% moisture content), which is produced directly from raw milk, and low-moisture (**LM**) mozzarella (52% moisture content), which is manufactured using purchased curd. Our study primarily focused on the impacts of HM mozzarella (68% of Italian mozzarella production); however, a scenario analysis has been performed to compare HM and LM mozzarella. Life cycle inventory for each type of mozzarella is shown in the Materials and Methods section, whereas the comparison between mozzarella types is presented in the Discussion section.

According to the Codex Standard 262–2006 (FAO, 2006), mozzarella is an unripened, near-white color, smooth elastic cheese, characterized by a long-stranded, parallel oriented, fibrous protein structure without evidence of curd granules and is also rindless. Mozzarella is made using cow or buffalo milk, or mixtures of the 2. Moreover, mozzarella is produced as 2 main types: high moisture content mozzarella, which is a soft cheese with overlapping layers that may form pockets containing a liquid of milky appearance, and can be packaged with or without brine (a preserving liquid); or low moisture content mozzarella with a firm or semihard homogeneous structure without holes, suitable for shredding. Mozzarella is manufactured by *pasta filata* processing, where the curd of a suitable pH is heated, kneaded, and stretched until it is smooth and free from lumps. After that, the warm curd is cut and molded, and then firmed by cooling.

Functional Unit

The functional unit was 1 kg of HM mozzarella produced in Italy and consumed in Italy and abroad (wet basis: 62.5% moisture content). A scenario was also prepared to compare HM mozzarella with LM mozzarella, and for this scenario we used DM content as the functional unit to avoid bias due to differences in moisture content.

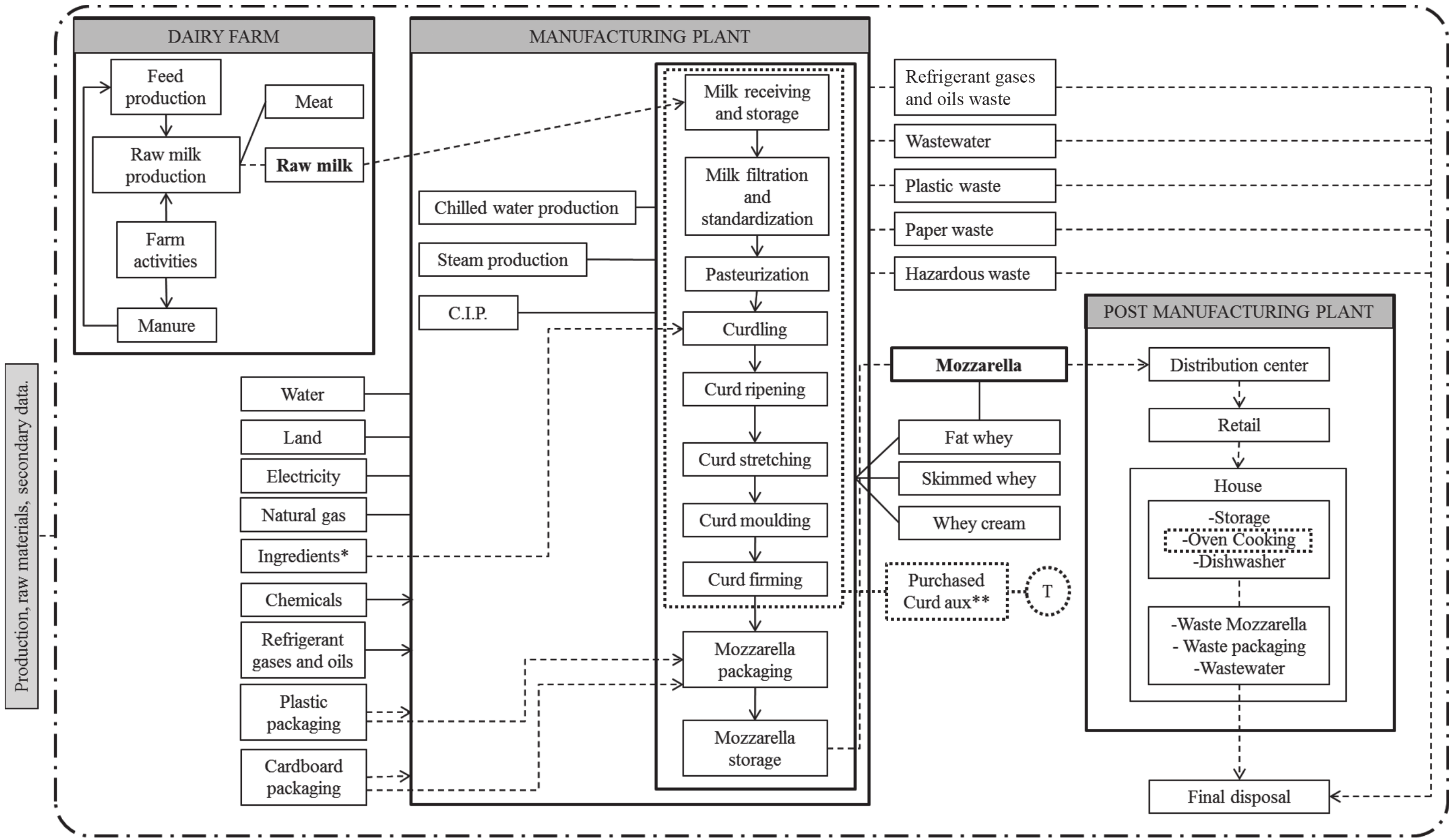
System Boundaries

The system boundaries encompassed raw milk production (feed production and on-farm activities), raw milk transport, mozzarella manufacturing, transport of mozzarella, packaging, distribution, retail, consumption, and disposal (Figure 1). Infrastructure was included in the system boundaries, but employee commuting and other ancillary activities were not considered (Kim et al., 2013). Although the LCA was a cradle-to-grave analysis, emphasis was given to manufacturing plant and processes. All the quantifiable material and energy flows were considered in the facility inventory and impact assessment. To reach the highest resolution in the description of mozzarella production, the individual manufacturing operations were characterized by energy, heat, or material requirements, whereas plant-specific information was used to assign specific inputs to each product. Importantly, our study is not a detailed engineering analysis, and some information was available only at the whole-plant scale, not directly assigned to a specific operation.

Allocation

Allocation at the dairy farm level was performed using the IDF (2015) methodology, where the emissions are allocated between milk and animal live weight, considering the energy content of the feed required to produce each product (Dalla Riva et al., 2015). Fat, protein, lactose, and ash are the main solid components in milk (Walstra et al., 2006) and in mozzarella cheese, so it is reasonable to consider the movement of milk solids through the plant as a factor to allocate resources and environmental burdens to mozzarella and co-products. The choice of allocation model can influence the assessment results (Flysjö et al., 2011); therefore, in our study, allocation was still required because many of the operations, such as pasteurization, are relevant for all of the valuable products, although data were provided for individual operations within the facility rather than for the facility as a whole. Where information was available for specific products (e.g., primary packaging) values were assigned directly to that product without allocation. When allocation was required for individual operations within the plant, the milk solids content of the exiting streams was used as the basis for allocation (Kim et al., 2013; Vergé et al., 2013). Additionally, a scenario analysis was performed to detect the variation in emissions assigned to the main product, using different allocation models at the manufacturing plant.

Figure 2 summarizes the scenario analyses for mozzarella allocation used in our study. Case 1 represents the default allocation model; the inputs were allocated using plant-specific information to assign specific inputs to specific products. Case 2 and Case 3 are presented as scenarios to compare the final results and to



*salt, rennet, curdling salt mix, starter cultures, milk protein.

** packaging, storage, cooking, waste and transport (T) of purchased curd for manufacturing LM mozzarella

Figure 1. System boundaries for the high-moisture (HM) mozzarella life cycle. Dashed arrows represent specific transport information; continuous arrows represent default transport. The dotted figures include the low-moisture (LM) mozzarella phases (production of purchased curd in a specialty plant, transport, storage, packaging, curd cooking, waste, and oven cooking). C.I.P. = clean in place.

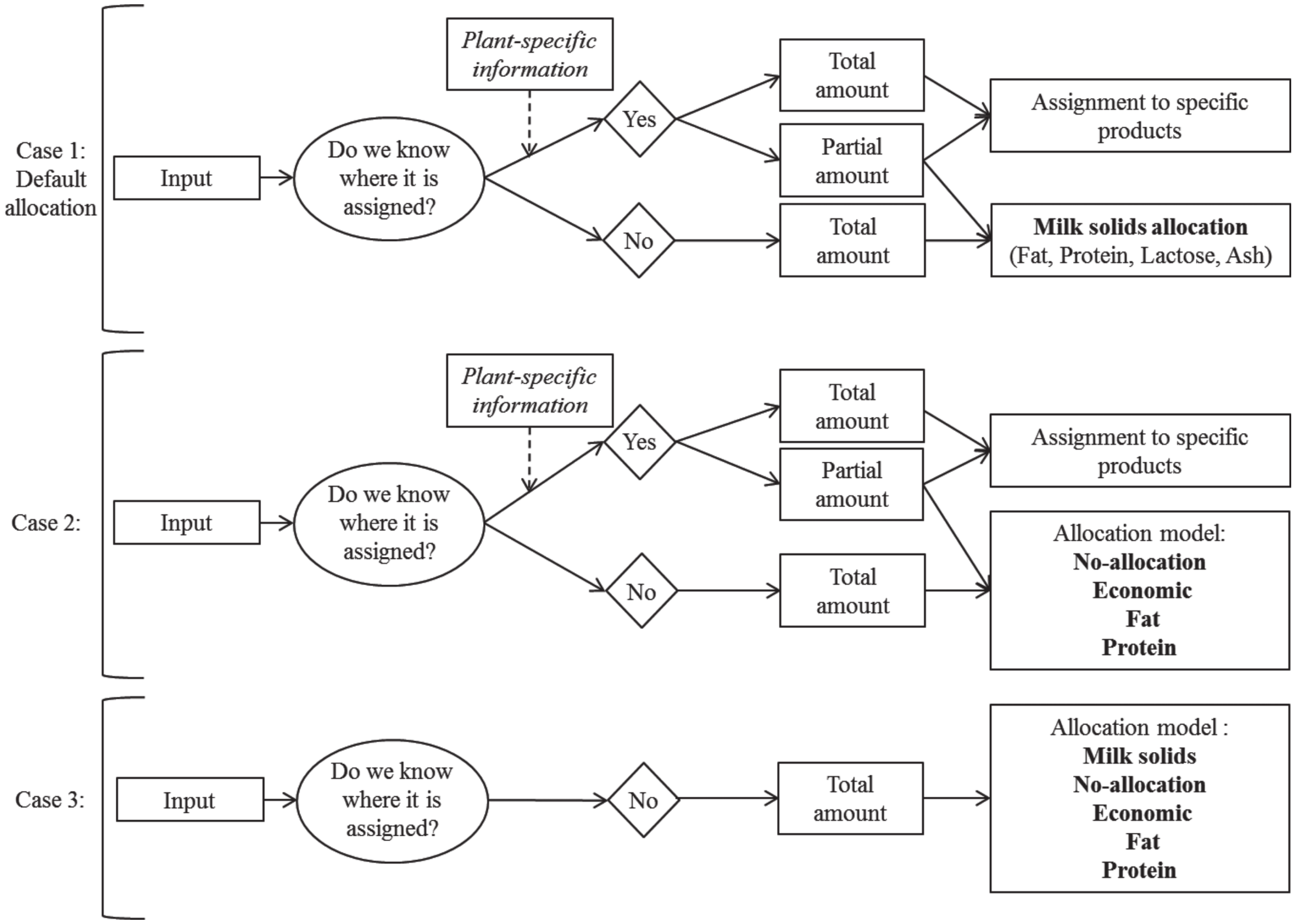


Figure 2. Scenario analysis for allocation models used to allocate resources and emissions between mozzarella and co-products.

test the robustness of Case 1. Case 2 follows the same process of Case 1, but 4 different allocation models (no-allocation, economic, fat, and protein) were applied to the inputs, which were not assigned using plant-specific information. Finally, Case 3 tested 5 allocation models (milk solids, no-allocation, economic, fat, and protein), considering a hypothetical situation where no plant-specific information was available to assign the inputs to the specific products, but assuming all input data were at the whole-plant level.

Life Cycle Inventory

Our study maintained a perspective focused on the mozzarella manufacturing plant. During 2015, the third-largest Italian mozzarella plant was surveyed to collect primary data for the calendar year 2014. The survey included questions regarding resources (materials, energy, water, and land), production (mozzarella and co-products), and waste (liquid and solid). The mozzarella plant used raw milk from both Italian regions and other European states. Notably, a previous study on raw milk production was used as background data for Italian milk (Dalla Riva et al., 2015). The Ecoinvent v3.2 (Weidema et al., 2013) was used to represent

European raw milk production and secondary data. Uncertainty of inputs was assigned using the Ecoinvent pedigree matrix approach, with variability and consistency being checked for primary survey data, whereas the uncertainty distribution provided by Ecoinvent was used unaltered for secondary data. SimaPro 8.1 (PRé Consultants, 2014) was used as the modeling software. Table 1 shows data inventories per kilogram of HM mozzarella before allocation.

Table 1. Farm gate-to-plant gate life cycle inventory flows per kilogram of high-moisture (HM) mozzarella before allocation, and default allocation model at the manufacturing plant

Inputs	Input flow,[1] per kg of HM mozzarella	Transport,[2] km	Assignment of input: Plant-specific information	Assignment of input: Milk solids allocation
Land, m^2a	1.78E-03	—	—	√
Well water, kg	25.1	—	√	√
Electricity, kWh	0.48	—	√	√
Natural gas, kWh	0.94	—	√	√
Lubricant oil, kg	8.35E-06	Default[3]	—	√
R507 and R134a gas, kg	8.74E-05	Default[3]	—	√
Soda, kg	0.01	Default[3]	√	√
Hydrochloric acid, kg	1.57E-04	Default[3]	√	√
Nitric acid, kg	3.86E-03	Default[3]	√	√
Peracetic acid, kg	1.98E-04	Default[3]	√	√
Sodium chlorite, kg	1.54E-04	Default[3]	√	√
Foaming, kg	1.64E-03	Default[3]	—	√
Cleanser, kg	6.55E-04	Default[3]	—	√
Water softener (salt), kg	3.14E-03	1,000	√	√
Label, kg	5.46E-04	300	√	—
Cardboard, kg	0.09	186	√	√
Plastic PP,[4] kg	0.05	255	√	√
Plastic PVC,[4] kg	0.04	26	√	√
Plastic HDPE,[4] kg	6.96E-06	30	√	√
Hazardous products, kg	1.66E-05	300	—	√
Italian raw milk, kg	1.58	65	—	√
Foreign raw milk, kg	3.43	413	—	√
Italian curd, kg	0.02	103	—	√
Foreign curd, kg	0.24	1,397	—	√
Salt, kg	0.02	1,000	√	—
Milk protein, kg	6.91E-03	300	√	—
Starter culture, kg	2.00E-04	300	√	—
Rennet, kg	1.53E-03	3.4	√	—
Curdle salt mix, kg	1.93E-04	1,000	√	—
Cardboard waste, kg	5.46E-03	2.1	—	√
Plastic waste, kg	6.21E-03	2.1	—	√
Hazardous waste, kg	1.66E-05	120	—	√
Refrigerant loss, kg	8.74E-05	Default[3]	—	√
Lubricant oil waste, kg	8.35E-06	Default[3]	—	√
Wastewater, m^3	0.03	—	—	√
Mozzarella loss, kg of milk solids	0.19	—	—	√

[1]The data at whole plant level are divided by total amount of mozzarella.

[2]Transport by EURO 5 truck

[3]Default transport included in the market processes from Ecoinvent v3.2 database (Weidema et al., 2013).

[4]PP = polypropylene; PVC = polyvinyl chloride; HDPE = high-density polyethylene.

Life Cycle Inventory

HM Mozzarella Manufacturing Plant Data. Surveyed plants produced mozzarella, liquid fat whey, liquid skimmed whey, and whey cream. Data collection was performed on individual operations within the plant to separate the manufacturing process into distinct operations to reduce the need, as much as possible, for allocation of whole-plant data among the multiple products. The plant operations were separated as shown in Figure 3. Specific life cycle inventory unit processes were created to represent each operation (i.e., brine production, water purification, steam and chilled water production, and clean-in-place). Loss of milk solids was considered during the manufacture, which was accounted for through collection in the wastewater. The loss was estimated by the difference in milk solids entering the plant with the raw milk and milk solids delivered by the plant with the mozzarella and the co-products.

Transportation. The study included transport of raw milk from farm to manufacturing plant, transport of mozzarella to distribution and retail centers, as well as transport to consumer's house. Transportation was characterized by the distance driven by refrigerated trucks and the loading of products on the truck. The modeled emission class was EURO 5

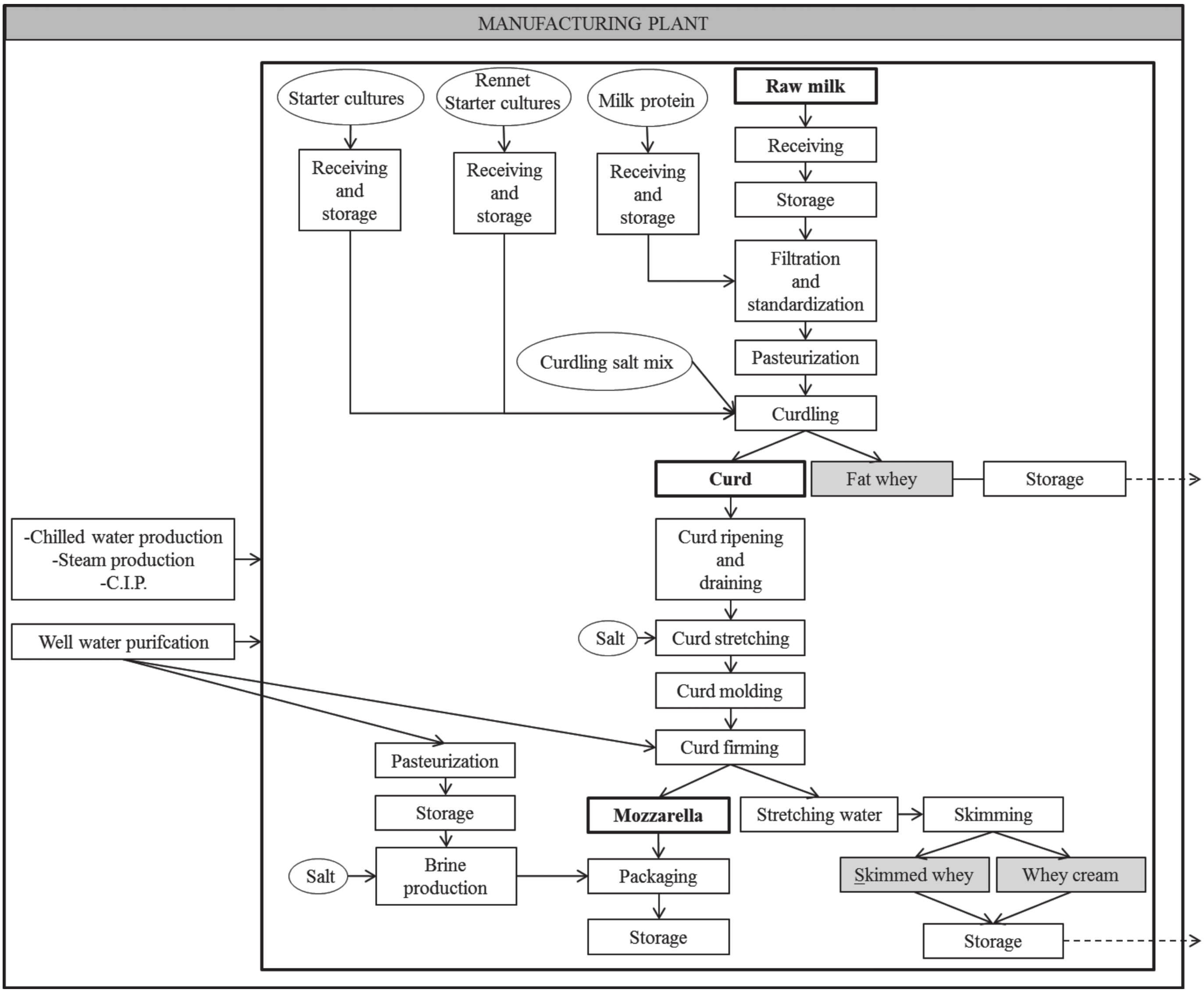


Figure 3. Operations modeled in the manufacturing plant and product outputs along the manufacturing processes for high-moisture (HM) mozzarella (gray rectangles are co-products). C.I.P. = clean in place.

, with an average 11.8-t transport lorry for Italian transport and a 24.0-t lorry for foreign transport. Transport of other manufacturing inputs was modeled using the specific distance, if information was available; otherwise, in case the transport information was not available or the inputs had multiple origins, the market processes from the Ecoinvent database were used, which included production and transport (Weidema et al., 2013). Also, transport of raw milk and other inputs were allocated among products using the milk solids default allocation. Post-dairy transport was directly assigned to mozzarella and included a small percentage of transport by ship and by aircraft. Notably, transport of mozzarella from retail to the consumer's house was by passenger car. The foreign transport of mozzarella from retail to the consumer's house was assumed to be the same as Italian transport due to the low percentage of exported mozzarella (13% of production) and the limited foreign primary data about that life cycle phase. The average consumer transport distance was assumed to be 10 km roundtrip. According to Istat (2015a), 1.12% (mass) of average Italian grocery shopping is composed of dairy products, and 28.6% of these items are cheese, which includes 37% of mozzarella (CLAL, 2016), so 0.11% of the consumer transport impact was attributed to mozzarella, or 0.011 km/kg per of mozzarella.

Distribution, Retail, Consumption, Disposal. Data on distribution center, retail, and consumption and disposal phases were derived from the published literature and assumptions, given the limited primary data related to mozzarella production and consumption (Table 2). Of the produced mozzarella, 87% was sold in Italy and 13% was exported. An average package of mozzarella has a shelf-life of 30 d. In the present study, we assumed mozzarella was consumed just at the end of the shelf-life period to estimate the greatest impact from storage; obviously if the consumption occurs sooner, the impact will be lower. Generally, mozzarella was stored 1 d at the dairy plant and then delivered to a distribution center. The distribution, retail, consumption, and disposal phases happening abroad have been assumed the same of the equivalent Italian phases due to the low percentage of exported mozzarella and the limited foreign primary data about those life cycle phases. Once mozzarella reached the distribution center, it was stored at 2 to 4°C; the maximum period of storage was 10 d. Importantly, the same storage temperature and duration were considered for retail. According to Flysjö (2011), 0.042 kWh are necessary to store the cheese for 10 d, so 0.0042 kWh/kg of mozzarella per day were used to model our distribution center and retail processes. To estimate the energy consumption of home refrigeration, an average refrigerator was assumed to have a 200 L capacity and an annual electricity consumption of 320 kWh, which equates to 0.0043 kWh/L per day; with the share of refrigerator occupied by mozzarella being 12.7% (de Angelis, 2016), 0.00055 kWh are used by home refrigerators per kilogram of mozzarella per day, and mozzarella was stored an average of 5 d before consumption. A dishwasher was also considered, and according to Kim et al. (2013), 1.51 kWh and 22 L of water per cycle were used; 5 percent of dishwasher load room was destined per kilogram of mozzarella.

We accounted for mozzarella packaging waste (cardboard boxes and plastic), with recycling, municipal incineration, and landfilling as the waste treatments for cardboard waste and plastic packaging. The percentage of cardboard and plastic waste accumulating in different waste treatments were assumed from ISPRA (2014) for waste treated in Italy; meanwhile data from Plastic Europe (2015) and ERPC (2014) were used for waste treated in other European states. The waste treated in European countries not accounted for in the data was a negligible amount, so it was modeled as European waste. Furthermore, a 50-km transport by truck was assumed to dispose of the waste mozzarella and packaging after the consumption phase, both for Italian and foreign distribution. The dairy plant used a small number of hazardous products (syringes, containers, reagents, and other various materials, mainly derived from routine laboratory analyses on raw milk and mozzarella), which were classified and treated as hazardous waste after use, and this waste was transported 120 km and disposed in an incineration plant. The plant under study was not equipped to treat wastewater, so the wastewater was modeled as being directly discharged into a municipal treatment system and eventually treated at a municipal wastewater treatment plant. We accounted for mozzarella waste during both distribution and retail phases; primary data were not available, so we considered a mozzarella waste of 2% (FAO, 2011) for both Italian and foreign phases. However, mozzarella waste at food service establishments and restaurants was not included in the analysis due to lack of available data. According to WRAP (2014), a mozzarella household waste of 9% was assumed, both for Italian and foreign consumption. The brine included in the package was assumed to be discharged into the kitchen sink and treated as wastewater in a municipal treatment system.

Table 2. Plant gate-to-grave life cycle inventory flows per kilogram of high-moisture (HM) mozzarella

Inputs	Input flow, per kg of HM mozzarella	Transport,[1] km
Distribution		
Italian transport, km	—	524
Foreign transport, km	—	1,092
Foreign airplane transport, km	—	8,735
Foreign ship transport, km	—	17,100
Electricity, kWh	0.04	—
Retail		
Transport, km	—	50
Electricity, kWh	0.09	—
Consumption		
Transport,[2] km	—	10
Electricity, kWh	0.1	—
Dishwasher water, kg	1.1	—
Disposal		
Waste mozzarella, kg	0.09	50
Paper waste, kg	0.11	50
Plastic waste, kg	0.03	50
Wasted brine, kg	0.78	—

[1]Transport by EURO 5 truck

[2]Transport by car.

LM Mozzarella (From Purchased Curd). The whole process of the manufacture of HM mozzarella occurred inside 1 dairy plant. The LM mozzarella, however, is manufactured using 2 dairy plants; the curd is manufactured in a specialty plant and transported to a mozzarella manufacturing plant, where it is transformed into mozzarella. Comparatively, LM mozzarella is generally used as an ingredient, such as a pizza topping, so cooking is a required process, whereas mozzarella from raw milk is generally consumed fresh and without cooking. In our study, HM and LM mozzarella were produced in the same dairy plant, and the production lines were completely separate, so it was possible to consider the 2 production lines as 2 separate dairy plants. The plant purchased 92% of its curd from other European countries, whereas the remaining percentage came from Italian dairy plants. Further, the environmental impacts of LM mozzarella were estimated and then compared with the environmental impacts of HM mozzarella. The comparison between HM and LM mozzarella was shown on the basis of DM content of the products because the comparison is not appropriate for products with different moisture contents when allocation is based on solids content.

The operations from receiving the raw milk to ripening curd during the manufacturing of HM mozzarella were used to model the purchased curd production for LM mozzarella manufacturing, which may have occurred in either Italian or foreign dairy plants before transport to the manufacturing facility under study. After the ripening and draining, the curd was shaped into blocks, packaged with plastic bags, and refrigerated before delivery. After delivery to the mozzarella plant, the curd was refrigerated for up to 10 d. To produce LM mozzarella, the curd was cut in pieces, warmed with hot water (curd cooking) to soften it, and, finally, stretched and manufactured into mozzarella. Data required for curd production (both domestic and foreign) and the processes following curd ripening and draining (packaging, storage, delivery, and mozzarella production) were taken from data provided for HM mozzarella production. Skimmed whey and whey cream were co-products of LM mozzarella production, whereas the fat whey was a co-product in the curd manufacturing. The loss of milk solids during LM mozzarella manufacturing (milk solids entering in the plant with the curd minus milk solids delivered by the plant with the mozzarella and the co-products) was included. The same data used for the HM mozzarella post-dairy plant phases were assumed for LM mozzarella; for consumption, however, LM mozzarella was assumed to be a pizza topping and thus required heating and electricity to be cooked in an electric oven [29% mass allocation factor to mozzarella STG (2016)], obtaining 0.58 kWh/kg of LM mozzarella from cooking. Waste of LM mozzarella was assumed the same as HM mozzarella; the mozzarella waste at food service establishments and restaurants was not included in the analysis due to the lack of available data, whereas the mozzarella waste at the in-home consumption phase was set at 9%. According to the dairy plant, the shelf-life of LM mozzarella is the same as HM mozzarella. Table 3 shows the additional data inventory per kilogram of LM mozzarella before allocation.

Table 3. From farm gate-to-grave, additional input flow per kilogram of low-moisture (LM) mozzarella before allocation

Inputs	Input flow, per kg of LM mozzarella	Transport,[1] km
Packaging		
Electricity, kWh	2.85E-03	—
Plastic, kg	2.04E-03	Default[2]
Storage predelivering		
Electricity, kWh	0.02	—
Delivering to mozzarella plant		
Italian transport, km	—	103
Foreign transport, km	—	1,397
Storage postdelivering		
Electricity, kWh	0.02	—
Curd cooking		
Well water, kg	0.23	—
Salt, kg	0.01	1,000
Natural gas, kWh	0.12	—
Electricity, kWh	0.03	—
Mozzarella loss, kg of milk solids	0.15	
Waste		
Plastic waste, kg	2.04E-03	50
Cooking at consumption		
Electricity, kWh	0.58	—

[1]Transport by EURO 5 truck

[2]Transport included in the market processes from the Ecoinvent database (Weidema et al., 2013).

Life Cycle Impact Assessment

The impact categories were assessed using the ReCiPe midpoint (H) V1.11 framework (Goedkoop et al., 2009). The inventory indicator categories of land occupation and water depletion were also assessed with the ReCiPe framework, and the cumulative energy demand inventory indicator category was assessed by the method of Frischknecht et al. (2007) (Table 4).

RESULTS

Results of HM Mozzarella

Figure 4 presents the life cycle impact assessment results from cradle-to-grave and from farm gate-to-grave. Table 5 presents the quantitative results for the full supply chain of HM mozzarella consumption. Raw milk production contributed the largest effects for most impact categories. Feed production was the main contributor at the farm phase for all impact categories, and farm activities were relevant in climate change (**CC**), terrestrial acidification, and photochemical oxidant formation (**POF**). Ozone depletion (**OD**), human toxicity (**HT**), and cumulative energy demand (**CED**) were the only 3 categories where post-farm gate activities contributed more than 50% of the final impact; OD was

Table 4. Inventory and impact categories analyzed in the study and acronyms used in the text

Life cycle impact category	Life cycle inventory indicator category
CC = climate change, kg of CO_2 equivalents	CED = cumulative energy demand, MJ
OD = ozone depletion, kg of CFC = 11 equivalents	LO = land occupation, m^2a
TA = terrestrial acidification, kg of SO_2 equivalents	WD = water depletion, m^3
FE = freshwater eutrophication, kg of P equivalents	
ME = marine eutrophication, kg of N equivalents	
HT = human toxicity, kg of 1,4-DCB equivalents	
ET = ecotoxicity,[1] kg of 1,4-DCB equivalents	
POF = photochemical oxidant formation, kg of NMVOC	

[1]Ecotoxicity is reported as cumulative of 3 impact categories affecting the environmental sphere: terrestrial, freshwater, and marine ecotoxicity. All 3 impact categories have the same unit of measure, kg of 1,4-DCB equivalents, according to Goedkoop et al. (2009). Whereas, human ecotoxicity was considered by itself due to its repercussion on human health

mainly determined by manufacturing operations, HT was mainly related to transport activities, and CED was determined by energy usage, packaging, and transport activities. Furthermore, manufacturing and packaging had the largest contribution in the post-farm supply chain, except for HT, POF and ME. Indeed, more than 40% of post-farm gate HT and POF was caused from raw milk transport and transport of mozzarella, whereas the same percentage for marine eutrophication (**ME**) was derived from retail, consumption, and waste, which signals an important contribution along the post-farm chain. Energy production and utilization were the main drivers in several impact categories, primarily for CC and CED, whereas the production and use of packaging contributed to land occupation (**LO**), CED, and water depletion (**WD**).

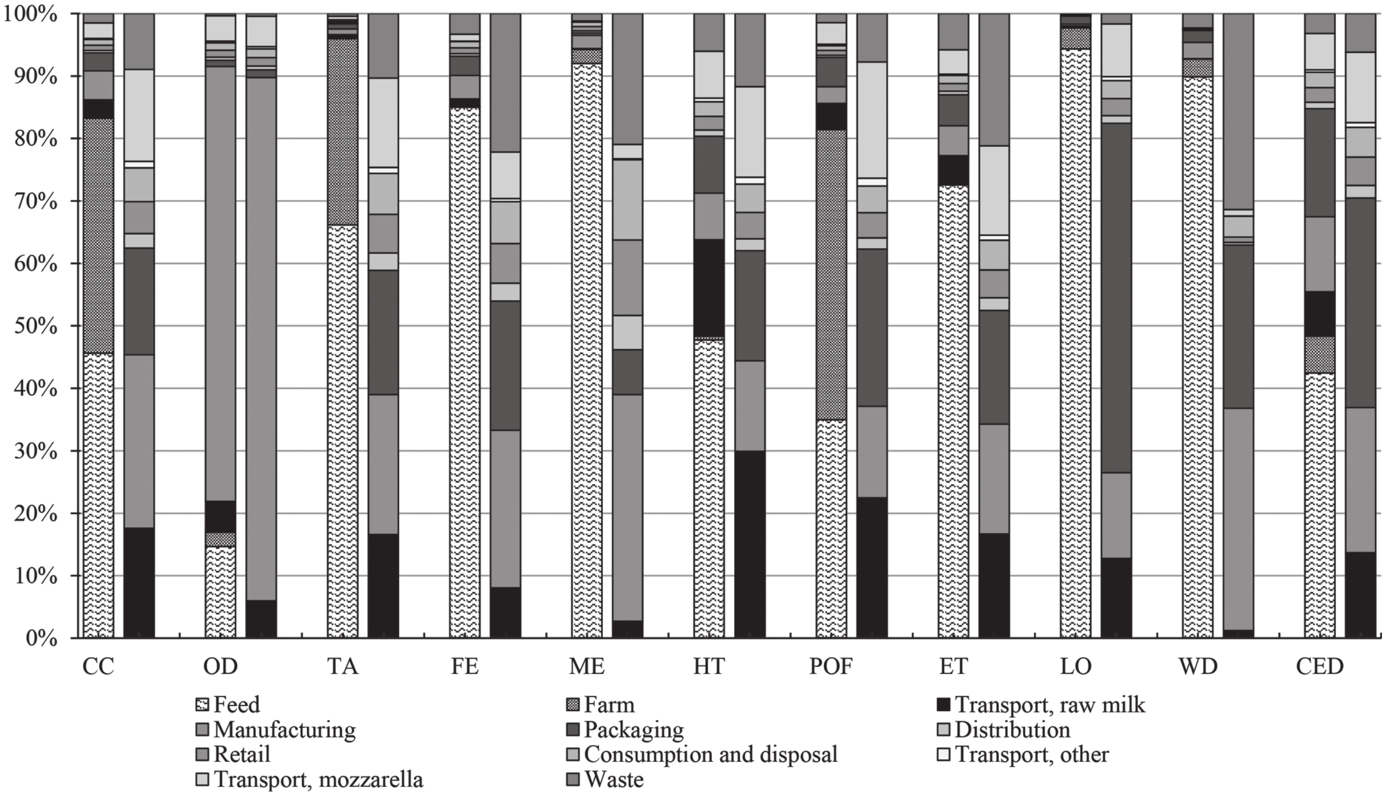


Figure 4. Life cycle impact assessment results for the supply chain of high-moisture (HM) mozzarella: cradle-to-grave (left column) and farm gate-to-grave (right column) perspectives. CC = climate change; OD = ozone depletion; TA = terrestrial acidification; FE = freshwater eutrophication; ME = marine eutrophication; HT = human toxicity; POF = photochemical oxidant formation; ET = ecotoxicity; LO = land occupation; WD = water depletion; CED = cumulative energy demand. Color version available online.

Table 5. Cradle-to-grave life cycle impact assessment results per kilogram of high-moisture (HM) mozzarella consumed

Item[1]	Feed	Farm	Transport, raw milk	Manufacturing	Packaging	Distribution	Retail	Consumption and disposal	Transport, other	Transport, cheese	Waste	Total
CC	3.04	2.50	0.20	0.31	0.19	0.03	0.06	0.06	0.01	0.16	0.10	6.66
OD	1.07E-07	1.63E-08	3.59E-08	5.05E-07	7.31E-09	3.67E-09	8.06E-09	8.57E-09	2.04E-09	2.94E-08	2.54E-09	7.25E-07
TA	6.32E-02	2.85E-02	6.39E-04	8.62E-04	7.66E-04	1.08E-04	2.37E-04	2.52E-04	3.64E-05	5.51E-04	3.97E-04	9.55E-02
FE	9.73E-04	1.38E-06	1.37E-05	4.29E-05	3.52E-05	4.89E-06	1.08E-05	1.14E-05	8.64E-07	1.27E-05	3.77E-05	1.14E-03
ME	4.37E-02	1.07E-03	7.40E-05	9.90E-04	1.95E-04	1.50E-04	3.29E-04	3.50E-04	4.29E-06	6.25E-05	5.71E-04	4.75E-02
HT	2.25E-01	2.86E-03	7.30E-02	3.53E-02	4.29E-02	4.70E-03	1.03E-02	1.10E-02	2.72E-03	3.54E-02	2.85E-02	4.72E-01
POF	6.66E-03	8.84E-03	7.96E-04	5.17E-04	8.90E-04	6.45E-05	1.42E-04	1.51E-04	4.42E-05	6.59E-04	2.74E-04	1.90E-02
ET	5.97E-02	1.02E-04	3.75E-03	3.95E-03	4.08E-03	4.57E-04	1.01E-03	1.07E-03	1.77E-04	3.22E-03	4.75E-03	8.23E-02
LO	4.12E+00	1.46E-01	1.28E-02	1.38E-02	5.61E-02	1.23E-03	2.71E-03	2.88E-03	6.67E-04	8.47E-03	1.64E-03	4.4
WD	5.68E-01	1.78E-02	5.72E-04	1.64E-02	1.21E-02	1.82E-04	4.00E-04	1.53E-03	3.33E-05	4.78E-04	1.45E-02	6.03E-01
CED	19.17	2.67	3.19	5.42	7.81	0.48	1.05	1.11	0.18	2.63	1.44	45.1

[1]CC = climate change (kg of CO_2 equivalents); OD = ozone depletion (kg of CFC-11 equivalents); TA = terrestrial acidification (kg of SO_2 equivalents); FE = freshwater eutrophication (kg of P equivalents); ME = marine eutrophication (kg of N equivalents); HT = human toxicity (kg of 1,4-DCB equivalents); POF = photochemical oxidant formation (kg of NMVOC); ET = ecotoxicity (kg of 1,4-DCB equivalents); LO = land occupation (m^2a); WD = water depletion (m^3); CED = cumulative energy demand (MJ

Manufacturing and packaging are directly controlled by the mozzarella manufacturer, and given their relatively large contribution to final effects after the farm gate, it is reasonable to analyze gate-to-gate impacts and contribution for the dairy plant (Figure 5). Electricity, natural gas, and secondary packaging (cardboard boxes) were the main drivers from mozzarella manufacturing, excluding OD and WD. Refrigerant losses were the main contributors to OD, with its largest contribution after the farm gate related to storage and transport of mozzarella, whereas wastewater treatment and well water for processes were main contributors for WD. Land occupation was mainly determined by secondary cardboard packaging; that is, the boxes that transport the packaged mozzarella to a distribution center and then to retail. This result was somewhat unanticipated, as the delivery of packaged mozzarella required a large number of cardboard boxes, so the cardboard box usage had repercussions on environmental impacts. Notably, wastewater particularly affected WD, ME, freshwater eutrophication (**FE**), and ecotoxicity (**ET**). Nitrogen and phosphate in wastewater were a significant source of eutrophication, both for FE and ME. Finally, the post-dairy plant phases were mainly driven by electricity usage for cooling and storage of mozzarella and secondarily by transport, whereas wastewater produced during mozzarella consumption, including the brine used to preserve the freshness of mozzarella, were relevant for WD, FE, and ME in the post-dairy plant analysis.

Normalization

Normalization is useful to identify the impact categories, which are important for this specific sector (Kim et al., 2013). ReCiPe Midpoint (H) V1.11 European normalization factors (Goedkoop et al., 2009) were used to normalize emissions from the Italian annual per capita HM mozzarella consumption, determined by the total Italian annual mozzarella consumption (280,643,295 kg; Assolatte, 2015) divided by the Italian population (60,795,612 citizens; Istat, 2015b). Normalized results represent the fractional contribution of mozzarella consumption by Italians, to an average European Union citizen's cumulative annual environmental impact. Normalization results are shown in Figure 6. Ecotoxicity represented 4.2% of the annual ecotoxicity impact, whereas ME was 2.2% of the annual marine eutrophication impact. Both ET and ME were derived mainly from feed production at farm, waste treatment, and transport activities along the supply chain. Meanwhile the third and fourth largest impact categories (both 1.3%) were the terrestrial acidification and FE, mostly originating from the use of phosphorus fertilizer. Ap-

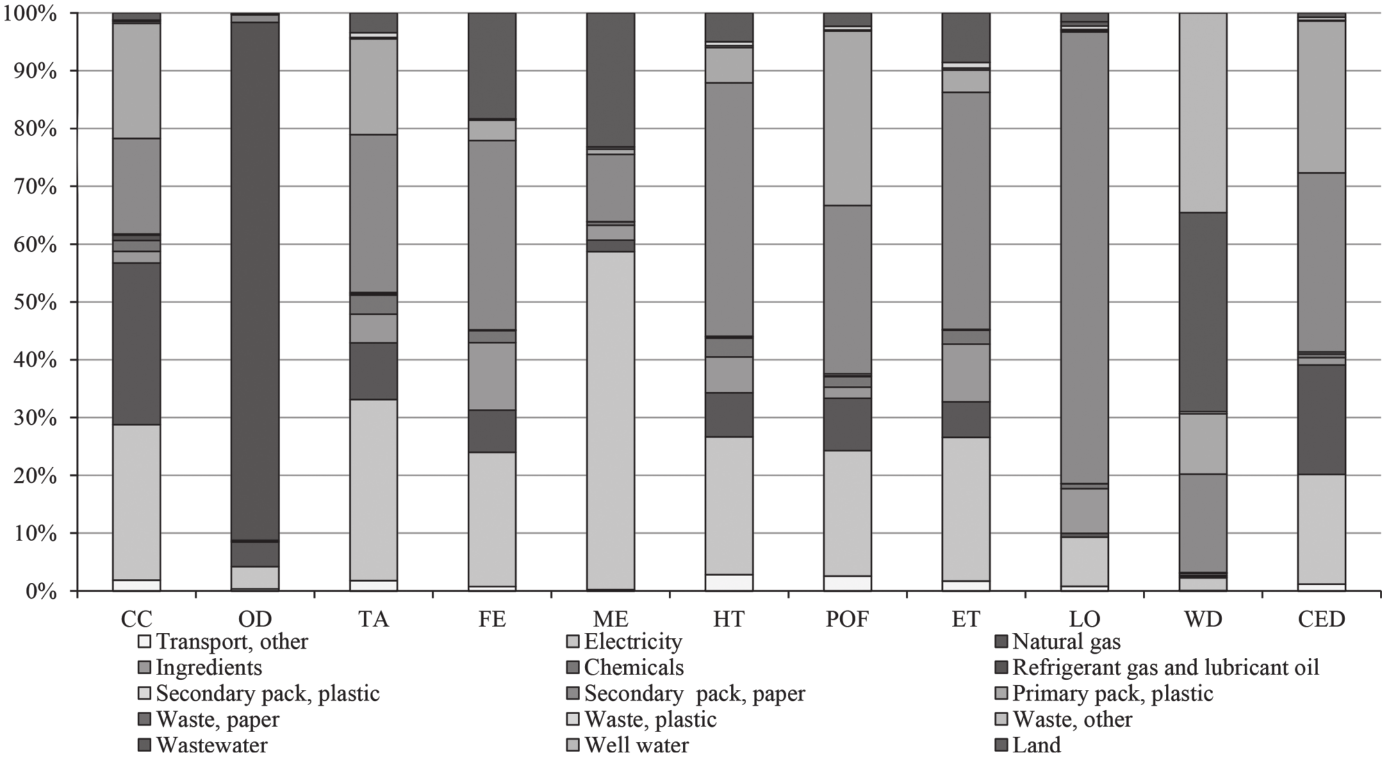


Figure 5. Contribution to environmental impacts from gate-to-gate at manufacturing plant of high-moisture (HM) mozzarella. CC = climate change; OD = ozone depletion; TA = terrestrial acidification; FE = freshwater eutrophication; ME = marine eutrophication; HT = human toxicity; POF = photochemical oxidant formation; ET = ecotoxicity; LO = land occupation; WD = water depletion; CED = cumulative energy demand. Color version available online.

plying normalization in a farm gate-to-grave perspective shows that the ET, FE, and HT still occupied the first positions with regard to contribution to impacts, whereas ME was third. These results were all mainly driven by transport activities, waste treatment, and electricity usage.

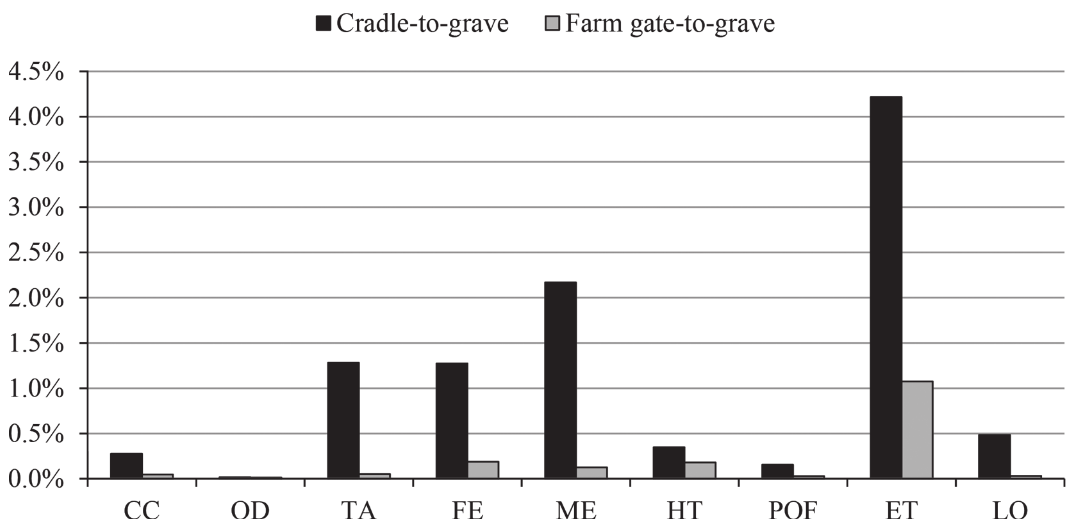


Figure 6. Normalization of cradle-to-grave (black bar) and farm gate-to-grave (gray bar) effects for 4.6 kg of high-moisture (HM) mozzarella consumed. CC = climate change; OD = ozone depletion; TA = terrestrial acidification; FE = freshwater eutrophication; ME = marine eutrophication; HT = human toxicity; POF = photochemical oxidant formation; ET = ecotoxicity; LO = land occupation.

Table 6. Uncertainty analysis using 1,000 Monte Carlo simulation runs of 1 kg of high-moisture (HM) mozzarella consumed from cradle-to-grave

Impact category	Unit	Mean	CV, %	95% CI	
Climate change	kg of CO_2 equivalents	6.66	7.94	5.86	7.93
Ozone depletion	kg of CFC-11 equivalents	7.25E-07	2.40E+01	4.56E-07	1.14E-06
Terrestrial acidification	kg of SO_2 equivalents	9.55E-02	1.28E+01	7.75E-02	1.26E-01
Freshwater eutrophication	kg of P equivalents	1.14E-03	2.75E+01	9.44E-04	1.48E-03
Marine eutrophication	kg of N equivalents	4.75E-02	1.11E+01	3.94E-02	6.08E-02
Human toxicity	kg of 1,4-DCB equivalents	4.72E-01	9.20E+03	0.00E+00	9.56E+01
Photochemical oxidant formation	kg of NMVOC	1.90E-02	1.03E+01	1.57E-02	2.36E-02
Ecotoxicity	kg of 1,4-DCB equivalents	8.23E-02	1.63E+03	0.00E+00	7.30E-01
Land occupation	m^2a	4.4	46.9	3.8	5.3
Water depletion	m^3	6.03E-01	8.81E+01	5.88E-01	1.56E+00
Cumulative energy demand	MJ	45.1	105.4	38.6	54.1

Uncertainty Analysis

The LCA results for 1 kg of HM mozzarella consumed were analyzed using 1,000 Monte Carlo simulation runs (Table 6). Ecoinvent v3 pedigree matrix (Weidema et al., 2013) was used to assign the quality of individual data; CC, CED, and WD were relevant impact categories for dairy production. The 95% confidence interval was 5.86 to 7.93 kg of CO_2 equivalents and 38.6 to 54.1 MJ for CC and CED per kilogram of mozzarella consumed, respectively. The average emissions were 6.66 kg of CO_2 equivalents and 45.1 MJ

per kg of mozzarella consumed. Both CC and CED were derived at 14 and 45% from the dairy plant to grave perspective, respectively; whereas 0.94 kg of CO_2 equivalents and 20.3 MJ were the impacts per kilogram of mozzarella at the dairy plant. The water depletion per kilogram of mozzarella consumed was 0.60 m^3, whereas the water depletion from the dairy farm gate-to-grave perspective was 3% of the total WD, equivalent to 18 L/kg of mozzarella consumed; 80% of this water was used during mozzarella manufacturing in the dairy plant.

DISCUSSION

Our study is an analysis from cradle-to-grave of mozzarella consumption. In line with published literature of LCA of dairy production (Kim et al., 2013; Vergé et al., 2013; Broekema and Kramer, 2014; Palmieri et al., 2016), most of the effects were related to raw milk production; therefore, immediate suggestions for impact improvement are related to dairy farm activities. Farm effects related to feed production (fertilization, transport, processing, and land and water use) and animals (enteric methane, nitrous oxide, and methane from manure management) are the hotspots for improvements, as stated previously by Berlin (2002), Rotz et al. (2010), Kim et al. (2013), Thoma et al. (2013), Vergé et al. (2013), and Palmieri et al. (2016).

The normalization suggests that ET and ME are the main impact categories where environmental mitigations should be focused, as the relative contribution of mozzarella production and consumption was larger than other impact categories. The ME was closely related to nitrogen, which was released in water after nitrogen fertilizer application during feed production. The ET was derived mainly from feed used at the farm phase, mainly from production and use of purchased feed, both for Italian and foreign raw milk production. In particular, soybean and corn, used as main ingredients in concentrate feed for lactating cows, represented more than 80% of the purchased feed-related ET. After the purchased feed contribution, ET was determined by on-farm feed production, primarily corn silage for Italian milk and grass silage for foreign milk. Pesticides (mainly for purchased feed production), heavy metals (contained in fertilizers), and transport of off-farm inputs and fields operation, in order, were the main contributing substances and activities to ET associated with feed; similar to the results reported by Eide (2002) and Ledgard et al. (2016). Considering the post-farm phases, fossil fuels used for electricity production and mozzarella transport were the primary contributors to ET. Moreover, considerable ET was associated with waste management, particularly from heavy metals released by landfilling; again, in line with Eide (2002). Therefore, efforts to reduce electricity and fuel consumption in post-farm mozzarella life cycle will lead to broad impact reduction, as suggested by Kim et al. (2013).

Water use is an important aspect of dairy production (Ridoutt et al., 2010). In our study, more than 90% of WD arose from feed production and farm activities. Notably it is interesting to analyze water use using the recent method AWARE (Available WAter REmaining) v1.02, which is a recommended method from the WULCA (Water Use in LCA) Group to assess water scarcity impact in LCA, the method is also endorsed by the EU Joint Research Center (WULCA, 2017). A full comparison between the method to assess the WD in our study (Goedkoop et al., 2009) and the full implementation of the AWARE method is complex and falls outside of the current study's goal; moreover, the software SimaPro 8.1 (PRé Consultants, 2014) has a limited implementation of the AWARE method. However, we consider that the application of AWARE method increases the value of our analysis and it is a starting point for future research. We maintained the same mozzarella life cycle phases

Considering the cradle-to-grave perspective, the AWARE method identified 1.58 m^3 of water scarcity per kilogram of mozzarella consumed. In contrast to the baseline method, the AWARE result shows that packaging (mainly cardboard boxes used during mozzarella transport) was the main driver (54%), followed by feed production for animals (20%), farm activities (13%), and mozzarella manufacturing (6%). Distribution, retail, and consumption contributed 4% of impact, and waste and transport (mainly milk and mozzarella) caused 1 and 2% of water scarcity, respectively. Feed production for animals was the main driver of water scarcity for both Italian and foreign raw milk. Purchased feed, mainly protein feed (such as soybean) was the main contributor (70%) to water scarcity in the feed production phase, whereas fertilizer production, irrigation, and energy used in the feed mill were the main processes consuming water; secondarily, water scarcity occurred from on-farm feed production (25%) of corn silage for Italian milk and grass silage for foreign milk. Finally, drinking water for animals and a minor contribution from energy usage were the main drivers at the farm phase (5%).

Importantly, manufacturing was the phase of the mozzarella life cycle mainly analyzed in our study. We evaluated 1 mozzarella plant, yet we considered the model to be a suitable representation of the Italian mozzarella production, excluding special mozzarella production such as aged or smoked mozzarella, due to the limited production level and the artisanal rather than industrialized production technology. Manufacturing operations were the main contributors for OD, whereas transport of raw milk and mozzarella were important contributors for HT and ET, from the post-farm gate perspective, as also reported by Kim et al. (2013). This situation is different than reported by Palmieri et al. (2016), where negligible effects of transport activities (mainly raw milk) were found due to the short distance between farm and factory. Comparatively, in our study, 68% of the raw milk was imported from other European countries, increasing the distance from the farm to the mozzarella facility. Further, whereas 87% of mozzarella had a national market, the remainder was internationally distributed (1,561 km).

Climate change and CED were mainly determined by energy usage, where mozzarella-making and packaging production were the 2 main energy-consuming phases in the post-farm gate supply chain, and energy was primarily linked to electricity usage. Effects of energy usage, its linkage with electricity, and its relevance after farm gate were determined by several authors (Guinard et al., 2009; Kim et al., 2013; Vergé et al., 2013; Palmieri et al., 2016). Moreover, the effects of packaging were relevant, in agreement with EPD (2013), where mozzarella packaging was a main driver after farm and manufacturing phases for resource depletion, photochemical oxidant formation, acidification, and eutrophication. The same impacts were derived from packaging in our study and in the study of Sonesson and Berlin (2003); whereas González-García et al. (2013a) and Broekema and Kramer (2014) estimated low impacts from packaging, and its contribution is mainly present for land occupation. In our study, land occupation and CED were mainly caused by cardboard packaging; in fact, land was occupied for many years (up to 30 yr) to grow trees for cardboard-making, and electricity was used to process both cardboard and plastic packaging.

Large amounts of small cardboard box packaging were used to deliver the mozzarella; this can be considered as an inefficiency in the use of packaging because small amounts of mozzarella were packaged in each box, whereas a large packaging would use less packaging per unit volume of mozzarella and lead to impact reduction (Marsh and Bugusu, 2007). Nevertheless, it is important to take into consideration the type of mozzarella market, which is characterized by a wide network of small Italian and foreign retailers. These retailers are supplied with the most common packaged shape (HM mozzarella balls, 0.125 kg, packaged using a plastic film); therefore, a small quantity of mozzarella delivered using small cardboard boxes is better managed by the retailers, although this leads to increase of packaging use and, in turn, impacts. At the manufacturing plant, wastewater treatment together with energy and packaging usage presented a considerable driver to WD, FE, ME and ET, as reported by Kim et al. (2013), Broekema and Kramer (2014) and Palmieri et al. (2016). Phosphate, nitrogen, and COD

contained in the wastewater were the key substances contributing to freshwater and marine eutrophication and ecotoxicity, in line with González-García et al. (2013b).

Another suggestion is that the manufacturing phase could be targeted for emission improvements. Cheese manufacturing and cheese distribution by trucks consumes a lot of energy; thus, a reduction of energy consumption, an increase in renewable source fuels and energy, and an emissions reduction for trucks could improve the environmental profile of mozzarella (González-García et al., 2013a). Additionally, packaging is one of the main contributors for several categories in that packaging presents a wide variation of impact contribution based on its type, especially for dairy products (Foster et al., 2007). Williams and Wikström (2011) studied the relevance of packaging effect of different food items and determined there is a high contribution of packaging for cheese. Those authors found that reduction in packaging for cheese is not always a good solution for impact improvement. In fact, a tradeoff exists between packaging and food waste—insufficient packaging may increase spoilage losses, ultimately leading to greater effects for the supply chain (Marsh and Bugusu, 2007; Williams and Wikström, 2011). Research on food packaging with low environmental burdens suggests biomaterial-based packaging and recycling technology as the most promising options (Chiellini, 2008), together with lightweight packaging (Marsh and Bugusu, 2007). In our case, plastic packaging is fundamental to preserve the freshness and the long shelf-life of mozzarella, whereas the cardboard box packaging was used for delivery and storage. Research on the reduction of packaging amount per kilogram of mozzarella and new eco-sustainable packaging could be a starting point to reduce the impact of packaging in the mozzarella life cycle.

Compared with farm and manufacturing phases, the post-dairy plant and consumption phases played a minor role, as also reported by Broekema and Kramer, (2014) and Palmieri et al. (2016). However, Broekema and Kramer (2014) found that distribution, retail, and consumption contribute mainly to climate change, eutrophication, and energy depletion, which is primarily determined by energy for cooling and lighting. Similarly, in our study, the energy used (mainly electricity) for refrigeration was the main driver at the distribution and consumption phase, which is another key area for reduction and improvement. Finally, our study does not provide information on the co-products' impacts because all of the co-products were sold by the plant and destined for further transformation and utilization, such as animal feed, protein and sugar extraction, and utilization as ingredients for other dairy products. The subsequent use of co-products has been evaluated by several authors as a way to reduce emissions (Flysjo et al., 2014), although in some cases the further processing of co-products can increase the overall emissions, as shown by González-García et al. (2013a), where the drying process of liquid whey from Portuguese cheesemaking increased the total effects at the cheese plant. Notably, a detailed assessment of the potential valorization of co-products is necessary to obtain specific measures of reduction and improvement from this reuse, but this falls outside of our research aims for the current paper.

Allocation Scenario Analysis

Testing different allocation models is a good way to test the robustness of the results. Table 7 and Figure 7 shows the comparison between the default allocation (Case 1) and the 2 allocation scenario analyses (Case 2 and Case 3). Moving from milk solids allocation through protein and fat allocation, as well as economic allocation and no-allocation, the CC and CED ranged from 6 to 13 kg of CO_2 equivalents and from 37 to 80 MJ /kg of mozzarella consumed, respectively. Comparing the 2 scenario analyses, Case 3 assigned lower emissions than Case 2 to overall impacts, except when no-allocation was applied. The lower values of Case 3 suggest that assuming the data at the whole-plant level, without plant-specific information, determines a lower assignment (i.e., a lower allocation factor) of resources to mozzarella than Case 2. This observation suggests that Case 2 better represents the resource assignments inside the dairy plant because these assignments represent the main aim of dairy plant, which is mozzarella production. Moreover, the ISO requirement (ISO 2006a,b) suggests resource attribution to plant operations and products, using specific plant information as a means of system separation to avoid allocation. The results show the no-allocation model is the best model to evaluate the impacts at the whole-plant level, without considering co-products and their further processes, which indicates better strategies for reduction at the plant to the manufacturers. Meanwhile, the milk solids allocation may be more appropriate to follow the resource flows inside the plant and their assignments to each product. The economic model remains one of the most-used models for allocation (FAO, 2016), which clearly reflects the first aim of the manufacturers, although it does not necessarily reflect the material and energy flows of the production system (Ayer et al., 2007).

Impacts of LM Mozzarella

Mozzarella from purchased curd (LM) had larger impacts than mozzarella produced directly from raw milk (HM). This finding was anticipated, as adding phases to the life cycle will increase environmental burdens. To compare the 2 types of mozzarella, it is important to note 2 facts. First, HM and LM mozzarella are 2 different products, having different moisture contents; therefore, a direct comparison considering the kilograms of mozzarella consumed is not appropriate. Second, the 2 mozzarella processes result in different allocation factors at the manufacturing plant due to different moisture contents and different amounts of co-products. For these reasons, we present the comparison of the 2 mozzarella on a dry basis. In this case, the comparison between the 2 types of mozzarella were made without the use of allocation, to better represent the phases and operations determining differences of LM mozzarella with respect to HM mozzarella, as well as to remove bias from the allocation results. Importantly, the impacts are overstated because no impacts are assigned to co-products; however, even if an allocation were applied, such as milk solids allocation, which is the correct procedure in multioutput systems (Milani et al., 2011), the larger emissions of LM mozzarella compared with HM mozzarella will be invariant (results not shown).

Table 8 illustrates the comparison of emissions and the phases influencing differences between the 2 mozzarella types (dry basis). The farm phase effects were the same for both types because the same raw milk can supply both types of mozzarella, so the effect of raw milk variability was negligible, although the impact variability of milk production is well established and is the first contributor for environmental impacts (Guerci et al., 2013; Thoma et al., 2013). Notably, the farm phase analysis was not our study's goal. The post-dairy plant phases were also identical to HM mozzarella with the exception of oven cooking at the consumption phase. Oven cooking determined the main differences between mozzarella types, and it was particularly related to electricity usage. Importantly, oven cooking is an assumption, so it may be possible to have different kinds of consumption phases, such as no cooking or a different way of cooking; however, considering the most common situation, LM mozzarella is mainly produced and used as a pizza topping, it is reasonable to consider oven cooking to represent the whole life cycle. For manufacturers, it is important to highlight the differences in the manufacturing processes, in that transport of curd led to larger effects of LM mozzarella over HM mozzarella. Ozone depletion, HT, POF, and land occupation were strongly influenced by transport. Additionally, curd cooking was the second source of the increase, having the greatest contribution for WD, CED, CC, OD, FE, and terrestrial acidification. Additional storage was the third-largest contributor to LM mozzarella effects. The extra plastic packaging used to package the curd and the waste generated from the additional operations of LM mozzarella production had minimal contribution to the impacts.

Generally, LM mozzarella is manufactured with purchased imported curd. The milk produced in Italy represents 70% of the whole Italian milk supply chain (CLAL, 2015), so Italy imports milk and curd to cover the whole national consumption. The 60% of Italian milk is used to produce high-quality and traditional cheese

Table 7. Impact results per kilogram of high-moisture (HM) mozzarella consumed with allocation scenario analyses (Case 2 and Case 3)[1]

	Case 1[2]	Case 2[3]				Case 3[4]				
Impact	Milk solids	No allocation	Economic	Fat	Protein	Milk solids	No allocation	Economic	Fat	Protein
CC	6.66	11.36	10.88	9.13	8.96	6.27	13.4	10.53	8.79	8.59
OD	7.25E-07	1.24E-06	1.18E-06	9.94E-07	9.75E-07	7.80E-07	1.67E-06	1.20E-06	1.05E-06	1.01E-06
TA	9.55E-02	1.68E-01	1.60E-01	1.33E-01	1.31E-01	9.40E-02	2.01E-01	1.59E-01	1.32E-01	1.29E-01
FE	1.14E-03	1.95E-03	1.87E-03	1.57E-03	1.54E-03	1.07E-03	2.28E-03	1.79E-03	1.49E-03	1.46E-03
ME	4.75E-02	8.32E-02	7.95E-02	6.63E-02	6.49E-02	4.63E-02	9.90E-02	7.82E-02	6.51E-02	6.37E-02
HT	4.72E-01	7.36E-01	7.08E-01	6.11E-01	6.00E-01	3.80E-01	8.11E-01	6.28E-01	5.29E-01	5.15E-01
POF	1.90E-02	3.22E-02	3.09E-02	2.60E-02	2.55E-02	1.77E-02	3.78E-02	2.97E-02	2.48E-02	2.43E-02
ET	8.23E-02	1.35E-01	1.30E-01	1.10E-01	1.08E-01	7.20E-02	1.54E-01	1.20E-01	1.01E-01	9.83E-02
LO	4.4	7.7	7.4	6.1	6	4.3	9.2	7.3	6.1	6
WD	6.03E-01	1.06E+00	1.01E+00	8.43E-01	8.26E-01	5.97E-01	1.28E+00	1.01E+00	8.39E-01	8.21E-01
CED	45.1	69.6	67.1	58	57	37.3	79.6	60.7	51.6	50.1

[1]CC = climate change (kg of CO_2 equivalents); OD = ozone depletion (kg of CFC-11 equivalents); TA = terrestrial acidification (kg of SO_2 equivalents); FE = freshwater eutrophication (kg of P equivalents); ME = marine eutrophication (kg of N equivalents); HT = human toxicity (kg of 1,4-DCB equivalents); POF = photochemical oxidant formation (kg of NMVOC); ET = ecotoxicity (kg 1,4-DCB equivalents); LO = land occupation (m^2a); WD = water depletion (m^3); CED = cumulative energy demand (MJ).

[2]Default allocation model: plant-specific information and milk solids allocation.

[3]Allocation scenario analysis: plant-specific information and no allocation, economic, fat, protein allocations.

[4]Allocation scenario analysis: inputs data at whole plant level allocated using milk solids, no allocation, economic, fat, protein allocations.

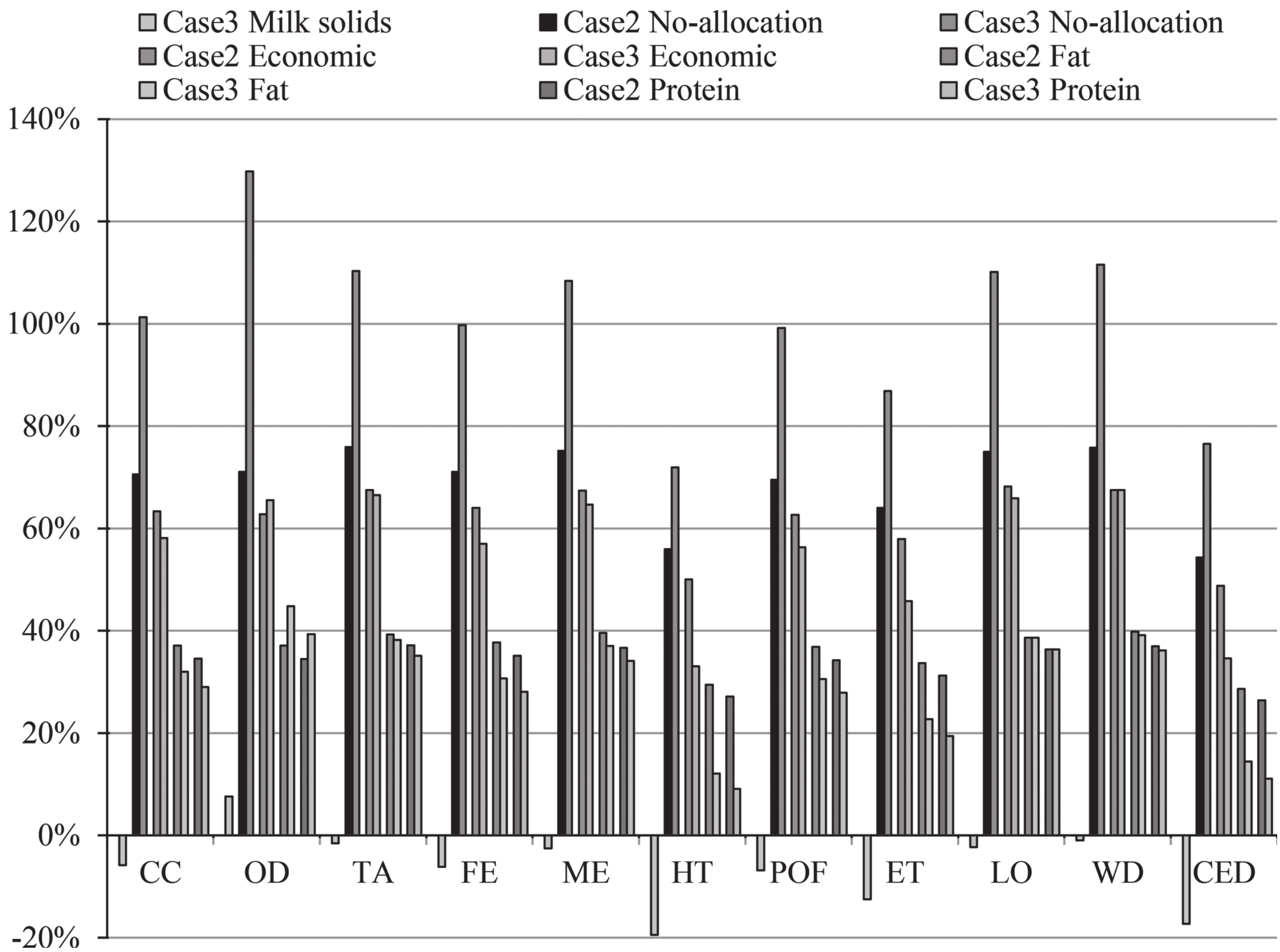


Figure 7. Percent variation of allocation scenario analyses Case 2 (plant-specific information and un-allocation, economic, fat, protein allocations) and Case 3 (inputs data at the whole-plant level allocated using milk solids, un-allocation, economic, fat, protein allocations) with respect to Case 1 (0%; plant-specific information and milk solids allocation) in high-moisture (HM) consumption. CC = climate change; OD = ozone depletion; TA = terrestrial acidification; FE = freshwater eutrophication; ME = marine eutrophication; HT = human toxicity; POF = photochemical oxidant formation; ET = ecotoxicity; LO = land occupation; WD = water depletion; CED = cumulative energy demand. Color version available online.

(CLAL, 2015); therefore, the majority of imported milk and curd is used to produce general industrial cheese, such as LM mozzarella. Transport of raw milk, other inputs, and mozzarella were all relevant contributors to several effects; moreover, they were the first cause of higher impacts of LM mozzarella than HM mozzarella from a gate-to-gate perspective. This situation suggests consideration of a scenario analysis where LM mozzarella is produced using raw milk (**LMm mozzarella**) instead of curd. In this scenario, the foreign (94%) and Italian milk is delivered to mozzarella plants and LMm mozzarella is produced normally, as in case of HM mozzarella; therefore, the additional phases to manufacture curd are avoided. Meanwhile, an increase in transport is required; in fact, generally 10 kg of milk is necessary to produce 1 kg of curd (Walstra et al., 2006). In this scenario, LMm mozzarella had higher emissions than LM mozzarella from a cradle-to-grave perspective (Figure 8), ranging from 38% for CED to 1% for land occupation. Clearly, the transport of raw milk played a fundamental role in increasing emissions; the transport of milk determined an increase, especially for OD, HT, and CED. This result suggests that the production of LM mozzarella using purchased curd is environmentally better than using imported raw milk. Although the curd production requires more manufacturing phases, the effects are not relevant when compared with the transport of imported milk, where the

Table 8. Environmental impacts (dry basis) of high-moisture (HM) and low-moisture (LM) mozzarella from farm gate-to-grave and source of variation of LM mozzarella before allocation

Item[1]	HM[2]	LM[2]	Source of variation from additional phases, %					
			Storage	Packaging	Transport	Cooking[3]	Waste	Oven cooking
CC	1.81	3.37	3.6	1.1	34.7	8.2	0.3	52.0
OD	1.29E-06	1.72E-06	3.2	0.3	44.5	8.2	0.0	43.8
TA	6.43E-03	1.20E-02	4.0	1.2	30.6	5.1	0.0	59.1
FE	4.68E-04	8.14E-04	4.4	0.8	13.0	5.8	0.0	76.0
ME	1.72E-03	2.26E-03	2.5	0.6	19.0	3.1	0.0	74.8
HT	5.14E-01	9.47E-01	2.7	0.5	50.3	4.2	0.2	42.1
POF	5.12E-03	9.51E-03	2.7	1.5	48.4	4.2	0.0	43.1
ET	4.96E-02	8.39E-02	3.8	0.6	33.9	5.3	0.9	55.6
LO	0.14	0.25	4.2	1.5	34.8	4.5	0.0	55.0
WD	4.48E-02	6.55E-02	6.2	1.9	13.1	11.1	0.1	67.6
CED	46.2	76.3	3.8	2.0	32.6	8.5	0.0	53.1

[1]CC = climate change (kg of CO_2 equivalents); OD = ozone depletion (kg of CFC-11 equivalents); TA = terrestrial acidification (kg of SO_2 equivalents); FE = freshwater eutrophication (kg of P equivalents); ME = marine eutrophication (kg of N equivalents); HT = human toxicity (kg of 1,4-DCB equivalents); POF = photochemical oxidant formation (kg of NMVOC); ET = ecotoxicity (kg of 1,4-DCB equivalents); LO = land occupation (m^2a); WD = water depletion (m^3); CED = cumulative energy demand (MJ).

[2]The results are expressed as DM.

[3]Curd warming before LM mozzarella making.

average transport was 1,397 and 103 km for foreign and Italian imported milk (the same as purchased curd), respectively. Therefore, in a hypothetical situation where the manufacturer has to decide to produce LM mozzarella purchasing curd or liquid milk, the more sustainable decision is to import curd, which requires

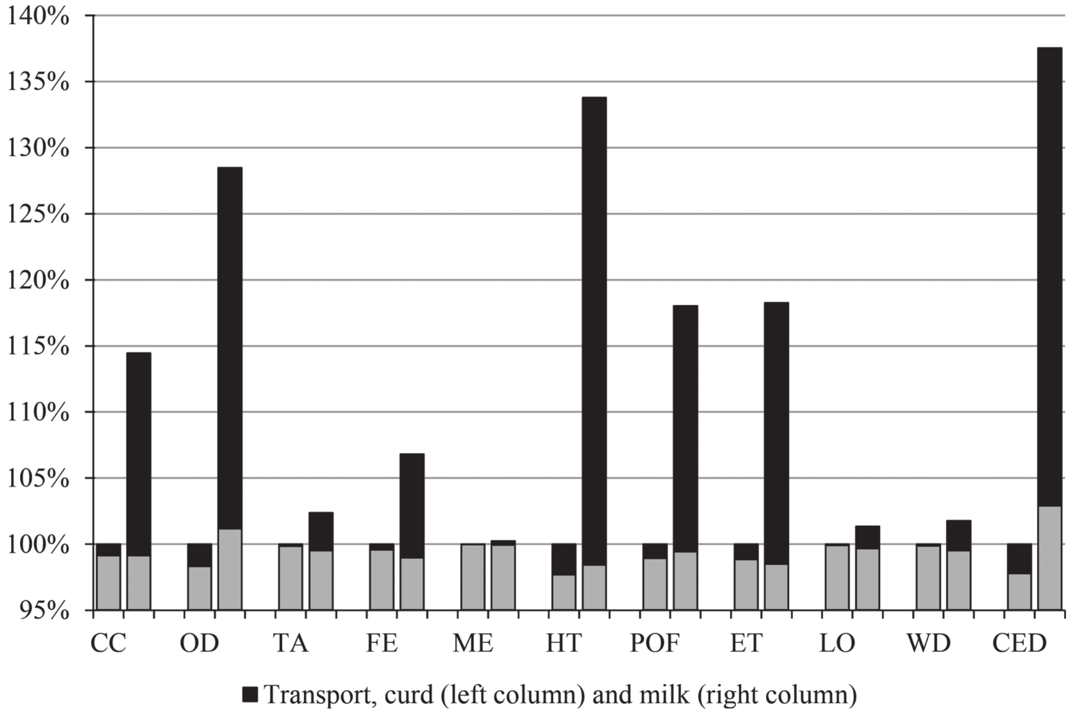


Figure 8. Comparison of low-moisture (LM) mozzarella (left column, 100%) and an assumption of LM mozzarella produced from imported raw milk (LMm mozzarella; right column), respectively, from a cradle-to-grave perspective and a relative contribution of curd and milk. CC = climate change; OD = ozone depletion; TA = terrestrial acidification; FE = freshwater eutrophication; ME = marine eutrophication; HT = human toxicity; POF = photochemical oxidant formation; ET = ecotoxicity; LO = land occupation; WD = water depletion; CED = cumulative energy demand

less transport. In fact, curd production represents a kind of milk concentration, which is a practice that helps reduce impact from milk transport (Flysjö, 2012).

CONCLUSIONS

Our study is an LCA of Italian mozzarella cheese, which was performed to evaluate the environmental burdens associated with the mozzarella life cycle for the purpose of identifying practices to improve environmental sustainability of the Italian dairy sector. Mozzarella cheese is particularly important in light of its increasing trends in production, as it is recognized as one of the most commonly produced dairy products. Our study emphasized the processes and impacts of the mozzarella manufacturing plants, which can be easily controlled by the mozzarella manufacturer. Energy and fuel consumption drove several impacts, such as climate change and cumulative energy demand. Moreover, energy and fuel usage were main contributors for many manufacturing and post-dairy plant environmental burdens, which involved activities such as storage, refrigeration, and transport. Furthermore, animal feed production and raw milk production were hot spots for all impact categories except for ozone depletion. Therefore, effort should be invested to reduce impacts from agricultural phases of the life cycle including reduction of methane emissions, improvement of manure management, fertilization and chemical treatments to reduce run-off, and volatilization of noxious substances. Improvements in these areas have the potential to significantly reduce several environmental impacts of the mozzarella life cycle.

Manufacturing and packaging had the largest post-farm contribution, with their largest influence being on freshwater and marine eutrophication, cumulative energy demand, and land occupation. Water used for cleaning, mozzarella production, and wastewater management had the greatest contribution to water depletion and relevant contributions to marine eutrophication. Further, electricity and natural gas usage were main contributors for post-farm phases. Additionally, transport of milk and mozzarella is relevant for human toxicity and photochemical oxidant formation. Notably, distribution, retail, house, and disposal phases had smaller contributions to final impacts, where the main drivers were transport and cold storage of mozzarella.

Furthermore, this study analyzed the differences between mozzarella produced directly from raw milk (HM mozzarella) and mozzarella from purchased curd (LM mozzarella). This analysis demonstrates an incremental increase in emissions for LM mozzarella compared with HM mozzarella, particularly due to the additional transport to deliver the curd to mozzarella plants, as well as the additional operations to process the curd into mozzarella, which were estimated as main contributors increasing the impacts. However, performing a scenario to compare LM mozzarella production using curd or using imported milk from the same location of the curd, the results shows that the more sustainable choice was to import curd instead of import milk. In fact, milk import required much more transport, considering the liquid status of the milk.

Overall, the production of mozzarella directly from raw milk appears to be more environmentally sustainable than using purchased curd. Moreover, HM mozzarella, being classified as a high-quality mozzarella—normally produced with Italian milk—can also obtain a Protected Designation of Origin label, which can improve the visibility of the HM mozzarella as having lower environmental burdens.

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7 General Conclusions

The Ph.D. Project applied the LCA methodology to the Italian dairy industry. The impact estimation was performed at three different level of perspective analyzing three different products: raw milk production from cradle-to-farm gate, Asiago PDO cheese from cradle-to-dairy plant gate, and Mozzarella from cradle-to-grave. This Project was performed in close relation to Italian dairy farms and dairy factories, indeed 34 dairy farms, one Asiago cheese plant and one Mozzarella cheese plant have been surveyed to collected the primary data for LCA study. Thank to this relationship a large amount of real primary data were used to build the LCA models and to obtain a real and specific impacts per kg of dairy product. Considering the results for raw milk production at farm gate the hotspot were feed production and animal emissions (mainly enteric methane and nitrous oxide from manure management). The LCA on milk was fundamental to perform the LCA on Asiago PDO cheese, in fact the analyzed raw milk was the milk utilized to manufacture the Asiago cheese in the plant. In the Asiago cheese production milk production was the main contributor to several impacts, while the main drivers of impacts occurring during cheese-making were electricity, fuel and water usage. These two LCAs represent a first case study for Asiago PDO cheese production in Italy. The third LCAs study performed a complete LCA including all the phase of Mozzarella lifecycle, although the post plant phase are modelled considered data derived by literature and national inventories and assumption. The importance to include all phases into the assessment was driven by the fact that the environmental sustainability can be improve along the whole dairy chain, and not including all the phases can determine less possibility to apply strategies for reduction and the possibility to not recognized shifting of impacts from one phase to another phase. The LCA on Mozzarella confirmed the raw milk production as hot spot for several impact categories, and the Mozzarella cheese making processes was the second driver of impacts, mainly determine by energy usage. Moreover, packaging and transport of milk and mozzarella had relevant importance when raw milk phase was excluded from the analysis. Meanwhile distribution, retail, consumption and disposal contributed mainly to energy and water demand, waste treatment, and mozzarella losses at consumption phase had relevant influence on the final impacts.

The LCA methodology has been confirmed as a fundamental tool to perform environmental analysis. Moreover, the LCA has been discovered as an importance method to control material and energy flow in dairy farms and dairy plant, in fact it helped to build a sort of input/output balance for dairy producers involved into the Project.

LCA application has strategic position in the future of the Italian dairy sector: reduction of impacts is fundamental to preserve the environment, thus the production, and at the same time the LCA results lead to improve of efficiency in the traditional production methods and to increase sustainability during production and consumption phase. Moreover, the LCA of PDO cheese can help to gain new market areas, supporting production and consumption of these traditional and local cheese, which represent a large part of the Italian cheese sector. Finally, the LCA results can determine more value to the PDO cheese, adding the environmental quality-value, to the already known nutritional and organoleptic quality.

In the future, we consider that the LCA study should be related to economic analysis in order to give a complete package to producer, considering the environmental impacts, but at the same time the cost of impacts and more importance strategies for their reduction.

LCA is fundamental tool to estimate the impacts related to change in the production chain and to find the best strategies for reduction. It is clear there is not “silver bullet” for improvements (Flysjö, 2012). The possibility to reduce the impacts is possible and the tools are ready. First of all, the reduction pass through the efficiency: several authors highlighted as knowing the resources flows and understanding the strength and the weak point of the production can determine an immediate improvements of emissions without surplus cost and investments. Secondly, considering the whole spectrum of impacts associate to dairy sector attention has to be taken to apply the improvements, because some strategies can have positive and negative aspect at the same time. Thoma et al. (2013) highlighted the risk to apply an improvement to reduce emissions (i.e. GHG emissions), but it could be only a shift of the emissions in the system, without a real reduction. So, it is important to show the possibility of reduction but to test each strategies in order to obtain a real benefit. Moreover, it is important to weight and normalize the results in order to detect the first impact to focus the strategies (Kim et al., 2013).

Improvement of the sustainability should become a key factor in the future of Italian dairy sector.

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