Literature review of beef production systems in Europe

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Commissioned by the European Roundtable for Beef Sustainability, a literature review was conducted on the environmental impact of beef and leather production systems in Europe. The literature review was restricted to the studies that applied attributional LCA methods. The average carbon footprint of 20.5 kg CO_2eq per kg carcass (ranged between 7.0 and 45.7 kg CO_2eq per kg carcass) was found for beef production in Europe. Our literature scan showed the higher greenhouse gas (GHG) emissions per kg carcass for suckler-based systems compared to the dairy-based system. The GHG emissions of organic farms was almost similar to the non-organic farms. Comparison of a concentrate-based diet with the roughage-based diet showed the lower GHG emissions for concentrate-based diet. The review of studies for beef production systems showed a high potential for mitigating the GHG emissions. Due to high turnover and environmental impacts of leather industry, the literature review was extended to leather production. A high variation was seen in results of leather carbon footprint because of methodological differences (e.g., system boundary and functional unit), quality of product and final use of finished leather. The average carbon footprint of reviewed papers was 24.6 kg CO_2eq per m^2 finished leather ranged between 7.75 and 53.7 kg CO_2eq per m^2 finished leather.

Key words: Beef, leather, carbon footprint, life cycle assessment, Europe, suckler-based, dairy-based.

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Table of contents

Foreword

Climate change is the major challenge for humanity in the 21st century and to overcome it, reduction of greenhouse gas (GHG) emissions is essential. Livestock production plays an important role in climate change by emitting GHG either directly (from enteric fermentation and manure management) or indirectly (from feed production and conversion of forest into pasture). More attention has been paid to reduce production of GHG emissions of beef production systems.

There is a high variation in the reported GHG emissions of beef production where different factors (e.g., intensive or extensive systems, origin of calves, organic or non-organic systems, diet composition, animal species, local or regional socioeconomic and market context) and also different methodological choices play a role in the variation of reported carbon footprint of beef in Europe.

The European Roundtable for Beef Sustainability (ERBS) is a multi-stakeholder platform, hosted by SAI Platform, focused on European beef sustainability from farm to fork. The ERBS unites and coordinates sustainability programmes around a common agenda to deliver positive impact within the beef value chain. One of the key outcome areas the ERBS is focused on is the reduction of GHG as part of improving the environmental footprint of farming systems.

The Sustainable Agriculture Initiative Platform (SAI Platform) is a not-for-profit organisation transforming the global food and drink industry to source and produce more sustainably. With over 150 members, from companies and organisations in the food and drink value chain, SAI Platform is at the forefront in pioneering solutions to common challenges and promoting sustainable agriculture in a pre-competitive environment.

The Beef sector in Europe recognises that GHG emissions produced at farm level are contributing to climate change. The European Roundtable for Beef Sustainability (ERBS) is committed to having a positive impact on driving down GHG emissions in the sector, and our members are actively working on this. To further enable this change, the ERBS created a project dedicated to identifying known and practical solutions to mitigate GHG emissions at farm level, and as part of this, understanding GHG impact studies at farm level in Europe. This literature search on beef impact studies helps to understand the environmental impact of different beef production systems and therefore where the opportunity for improvements are. For the next phase of the project, the content of both reports will be translated into a simpler toolbox format to reach a wider audience.

Summary

Livestock, specifically beef sector has a high contribution to environmental impacts. The Food and Agriculture Organization (FAO) estimation showed that from 4.6 Gt CO_2eq per year of livestock sector emissions, 2.5 Gt CO_2eq per year was from beef cattle. The most important sources of greenhouse gas (GHG) emissions in the beef sector are feed production (51% of the sector emissions) and enteric fermentation (43% of the sector emissions). Manure storage and processing (in total around 5% of the sector emissions) and other off-farm and post-farm activities including transportation (around 1% of total emissions) are the other important sources of GHG emissions in beef production systems (Opio et al., 2013).

Over the last decade, more attention has been paid to reduce production of GHG emissions of beef production systems. There is a high variation in the reported GHG emissions of beef production. Different factors (e.g., intensive or extensive systems, origin of calves, organic or non-organic systems, diet composition, animal species, local or regional socioeconomic and market context) and also different methodological choices are the main reasons of the differences. Assessing different beef production systems by doing a comprehensive literature review, helps to identify the environmental hotspots in beef production systems, and where further improvements can be made.

Studies which applied life cycle assessment (LCA) methodology and Intergovernmental Panel on Climate Change (IPCC) emission guidelines to estimate GHG emissions and conducted for beef production in Europe were considered in this literature review. To make the results comparable, carbon footprints (CFs) were calculated per kg carcass as functional unit (FU). Moreover, since the majority of LCA studies on beef production assessed the environmental impacts up to the farm gate, we limited the system boundary from cradle to farm gate. Therefore, for studies assessing post-farm stages, results were adopted to farm gate.

To perform a LCA, two approaches can be applied: attributional and consequential. An attributional LCA quantifies the environmental burdens of a product (e.g., beef) while a consequential LCA estimates how the environmental burdens are affected by a change in the production and use of the product. The majority of LCA studies in livestock production systems applied the attributional LCA approach rather than consequential. Thus, we restricted our review to attributional LCA studies. Therefore, based on the considered criteria, the literature review was limited to publications that evaluated beef production systems in Europe, used an attributional LCA, included a system boundary at least from cradle to farm-gate, and included beef and/or milk as the main product of the system. Among the 60 scientific publications reviewed, 21 studies met the defined criteria. To compare different beef production systems, three classifications were defined as following:

- Origin of calves; including dairy-based and suckler-based systems. In a dairy-based system, the surplus male calves are separated from dairy cows and fattened and finished. However, in a suckler-based system beef originates from the suckler cows and their offspring.
- Diet composition; including concentrate-based diet (a diet with an average proportion of at least 50% concentrate and grain crops) and roughage-based diet (less than 50% concentrate in diet).
- Production method; including organic and non-organic beef production systems.

Our literature scan showed the higher GHG emissions per kg carcass for suckler-based systems compared to the dairy-based system. In a dairy-based system, the emissions related to maintaining the mother cows are allocated to both products (milk and meat) while in a suckler-based system, emissions are attributed to just meat. The GHG emissions of organic farms were almost similar to the non-organic farms. However, the average GHG emission of organic farms in Europe was slightly lower than the non-organic farms due to fewer GHG emissions associated with the production of animal feeds. Because of the variation of reported CFs, the difference between organic and non-organic farms were not statically different in terms of GHG emissions. Comparison of a concentrate-based diet with the roughage-based diet showed the lower GHG emissions for concentrate-based diet. The higher enteric methane of roughage digestion and lower growth rate (longer finishing time) of calves in roughage-based systems can be the reasons for the higher GHG emissions of roughage-based diets compared to the concentrate-based one. Applying better feeding management to increase the growth

rate in a roughage-based system and also shifting from low productive grasslands to the high productive ones reduces the CF of grass fed or pasture reared beef.
Recently, carbon sequestration has been paid attention to in livestock production due to use of grass as one of the important feed components to provide nutritional animals' needs. Few studies took into account carbon sequestration in LCA of beef production. Different and contradictory results have been reported for the impact of carbon sequestration on total GHG emissions, as has been presented in this report. Although grazing results in mitigating emissions, its high potential on overall livestock emissions is still under discussion.
The review of studies for beef production systems showed that there is a high potential for mitigating the GHG emissions. Different studies have shown the potential for mitigating GHG emissions in beef systems i.e., dairy- and concentrate-based beef systems. However, the feed-food competition issues should be considered when a concentrate-based system is recommended. In addition to changing the production system, some specific strategies can be considered including i) increasing the production efficiency by applying different feeding groups (based on the animal nutritional need), ii) reducing overfeeding by providing more fibre-rich roughages (in case the dairy × beef crossbred cattle is growing in herd with a higher feed efficiency), iii) reducing the number of unproductive animals and iv) modifying the dietary composition (e.g. use of feed additives, use of dietary supplements, reduction of N excretion by optimization of N content of diet).
Due to high turnover and environmental impacts of leather industry, the literature review was extended to leather production. Similarly, to beef, we restricted the literature review to those studies that applied attributional LCA methods. Because there was a wide range for the defined system boundaries in previous leather studies, we limited the system boundary to production of finished leather (i.e., cradle to factory gate). Among the two common FUs (kg and m^2 of finished leather), m^2 of finished leather was applied for comparison of the results. The literature scan showed that most of LCA leather studies in Europe were carried out in Italy, Spain and Turkey. A high variation was seen in results because of methodological differences (e.g., system boundary and FU), quality of product and final use of finished leather. Therefore, it was difficult to compare the studies in terms of GHG emissions. We applied some conversion factors to make the comparison possible. The average Carbon footprint (CF) of reviewed papers was 24.6 kg CO_2eq per m^2 finished leather ranged between 7.75 and 53.7 kg CO_2eq per m^2 finished leather. Supplying energy and chemicals contributed most to the total GHG emissions of leather production. Conventional production systems had higher environmental impacts than the production systems with new technologies and applying new technologies was mentioned as the main strategy to reduce CF of leather. To overcome the high variations in the reported results, it is recommended to apply standard approaches such as PEFCR for environmental assessments of leather product for future studies.

1 Introduction

Climate change is the major challenge for humanity in the 21st century and to overcome it, reduction of greenhouse gas (GHG) emissions is essential. In 2015, all nations reached an important agreement to tackle the climate change problems, accelerate the actions and investments, and to support developing countries to do so. The central aim of the Paris Agreement was setting a global framework to avoid the threats of climate change by keeping the global average temperature rise below 2ºC and pursuing efforts to limit it even further to 1.5ºC. To achieve these ambitious goals, an appropriate mobilisation and provision of financial resources, a new technology framework and enhanced capacity-building needs to be considered. This takes place through "nationally determined contributions" (NDCs) in which each country should express their national mitigation target. Therefore, countries have been committed to determine, plan and report regularly on their emissions and implement efforts to mitigate global warming. In this regard, the member states of the EU have committed themselves to reduce the GHG emissions by at least 40% (1990 baseline) by 2030, and the European Commission recently proposed to increase the ambition to 55% reduction. The longer-term ambitious goal for the EU is to be climate-neutral by 2050. To achieve the net zero carbon target, first the human induced emissions should be reduced as close to zero by applying mitigation strategies. Next, the remaining human induced emissions should be removed from the atmosphere by applying carbon removal technologies or processes (e.g., afforestation or air capture and storage technologies). However, most of the national targets have not yet been made sector specific, which makes it complicated to translate these overall targets to individual targets at sector, company or farm level. Moreover, not all NDCs or national targets are yet Paris compliant. This is however also part of the set-up of the Paris Agreement. Countries can and have to strengthen their target every 5 years based on a periodic stock taking.

The agricultural sector including livestock and crop production, forestry and other land use was estimated to be responsible for about 30% of GHGs. According to FAO, the livestock sector is responsible for 14.5% of the global GHG emissions directly (e.g., from enteric fermentation and manure management) and indirectly (e.g., from feed production activities and land use change) (Gerber et al., 2013a; Gerber et al., 2013b; Buratti et al., 2017). The livestock sector contributes to about 7.1 Gt CO_2eq per year of which about 4.6 Gt CO_2eq comes from the cattle sector (milk and beef production) with beef production being responsible for about 2.5 Gt CO_2eq per year (35% of GHG emissions from the livestock sector) (Opio et al., 2013). The environmental impact of livestock production has received increasing attention over the last years due to the high contribution to environmental impacts (Steinfeld et al., 2006).

As a protein source, meat has been a part of the human diet for thousands of years. Beef production has doubled over the last 40 years (Herrero et al., 2016). Based on FAO data, cattle meat production has more than doubled since 1961, increasing from 28 million tonnes per year to 68 million tonnes in 2014 (FAO, 2020). To meet the growing demand for animal protein products, the livestock sector and specifically the beef sector is under high pressure. However, due to animal welfare and environmental issues, a large number of people around the world are turning to a plant-based diet instead, to reduce the consumption of meat. The European Union (EU) ranked third in world beef production in 2018 (Hocquette et al., 2018). Not only the beef production system is important for European food security but also for socioeconomic reasons and the livelihood of European rural communities. Figure 1 shows the beef production trend in Europe from 1992 to 2018. As can be seen, the production was more than 16 million tonnes in 1992 and declined to 10.2 million tonnes in 2013. However, production was almost stable in the EU and varied between 10.4 million tonnes (highest production in 1992) and 7.4 million tonnes (lowest production in 2013). Based on FAO statistics, beef production from the whole of Europe in 2018 was 10.6 million tonnes of which the production in Western, Eastern, Northern and Southern European countries was 3.6, 3.1, 2.1 and 1.8 million tonnes, respectively (Figure 1) (FAO, 2020).

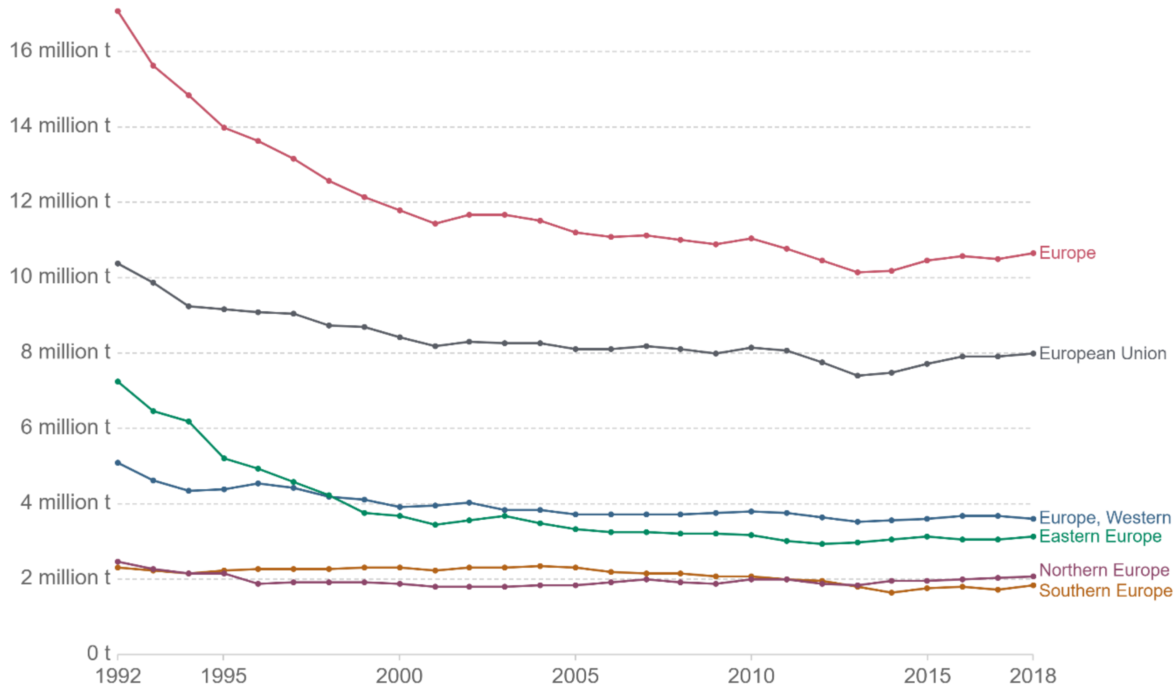

Figure 1 *Beef production in Europe, 1992-2018. Note: data are given in terms of dressed carcass weight, excluding offal and slaughter fats. Source: Food and Agricultural Organization of the United Nation (FAO) (FAO, 2020).*

Figure 2 illustrates the beef production situation in EU (FAO, 2020). As shown, Russia, France and Germany were the main producers in Europe with a production of 1.6, 1.4 and 1.1 million tonnes, respectively, followed by the UK, Spain, Ireland and Poland with a production of 0.92, 0.67, 0.64 and 0.60 million tonnes, respectively.

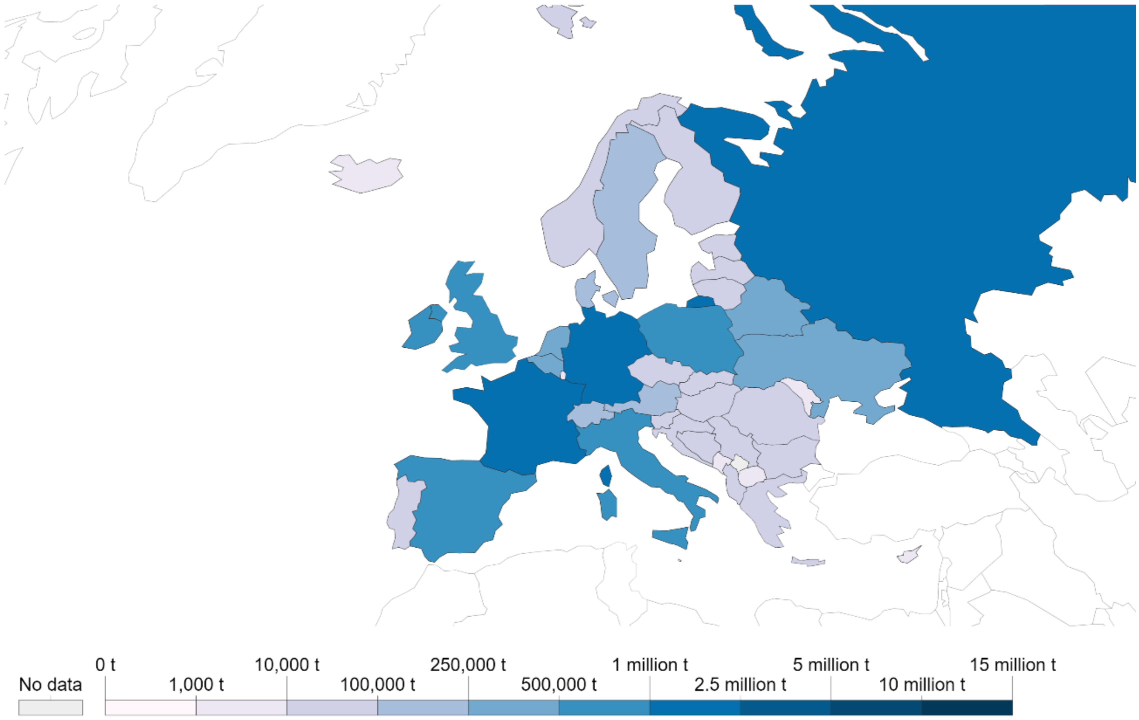

Figure 2 *Beef production in European countries in 2018. Note: data are given in terms of dressed carcass weight, excluding offal and slaughter fats. Source: Food and Agricultural Organization of the United Nation (FAO) (FAO, 2020).*

Over the last years, more attention has been paid to reduce the environmental impacts of the meat production system. Beef was the subject of different research studies. Previous studies showed that GHG emissions of beef production systems vary largely (from 8.6 to 35.2 kg CO_2eq per kg of edible beef) (De Vries et al., 2015). This variation can be due to different production systems (e.g. intensive or extensive systems, origin of calves, organic or non-organic systems, diet composition, animal species, local or regional socioeconomic and market context) and also different methodological choices (De Vries et al., 2015; Bragaglio et al., 2018). Much research has been conducted to evaluate the environmental impacts of different beef production systems. Some of these studies illustrated the lower GHG emissions of intensive beef production systems (Bragaglio et al., 2018).
An environmental assessment of beef production requires an approach to quantify the total emission. LCA is a widely accepted method to assess the environmental impacts of a product during the whole life cycle (Guinée et al., 2002). Many research studies applied LCA to determine the environmental impacts of beef production (Hocquette et al., 2018; McAuliffe et al., 2018; Presumido et al., 2018; Vitali et al., 2018; Hessle et al., 2019). Assessing different beef production systems by doing a comprehensive literature review gives a better insight into the environmental hotspots in beef production systems. Such an assessment is also crucial for further improvements in beef production. The main objective of this literature review is assessing the CF of different beef production systems in Europe. Therefore, we reviewed the LCA studies focused on beef production in Europe to assess and compare environmental impacts of various production systems.
An important by-product of livestock production systems is leather. Leather production is an important industry with a high turnover. Around 10,000 tanneries are active in the world with a turnover of almost US$ 50 billion (Giannetti et al., 2015; Tasca and Puccini, 2019). The leather and related goods sector in Europe comprises about 36,000 enterprises and generates a turnover of EUR 48 billion. These enterprises employ around 435,000 people in Europe (LEI, 2008). Italy, with an average production of 135 million m^2 of leather and hides, is the leading country in Europe and in the world. The leather production of Italy accounts for about 65% of EU production. Spain ranks second with a production of 28 million m^2 which accounts for about 13% of EU production (Notarnicola et al., 2011), and France ranked third among the main EU producers.
The leather tanning industry converts the raw hide and skin into finished leather which is used as raw material by different manufacturers. The most important EU products from finished leather are footwear (41%), leather goods (19%), furniture (17%), automotive products (13%), clothes (8%) and other (2%) (EC, 2021).
During the last century, the leather industry evolved from the traditional vegetable-tanned leather to the modern chrome-tanned leather. Many innovations have been introduced in the leather industry in terms of chemicals, new processing methods and finished properties (Saravanabhavan et al., 2004; Covington, 2008; Navarro et al., 2020).
Along with the growth and development of the leather industry, environmental concerns have increased regarding this industry. Many questions have been raised about environmental impacts of leather production such as water consumption and wastewater treatment, solid-waste recovery and the avoidance or reduction of some chemicals like chromium, sodium sulphide, etc (Hu et al., 2011). Generally, the leather industry in Europe is under lots of environmental (strong environmental regulations) and economic (high labour costs) pressures and these pressures led to a move of leather production from Europe to other countries (such as India, China, Latin America, etc.) (Notarnicola et al., 2011; Navarro et al., 2020).
To mitigate the environmental impacts of this sector, the first step is assessing the current situation to provide a comprehensive view of the leather industry. Many attempts have been made to address the environmental issues related to the leather industry and in this report, we aim to review them to provide a holistic evaluation and further help to improve the production in terms of environmental aspects.

2 Material and methods

As has been mentioned before, there are some variations between the beef production systems. Beef can be produced in different systems, the two principal ones being dairy systems and specialised beef production systems. In a dairy system, dairy cows produce milk and meat and surplus calves are fattened for meat production (De Vries et al., 2015). In contrast, in a specialised beef production system, meat is the main product and produced from beef cows and their calves. In Europe, beef from dairy cows is very common. For example, a high portion (60%) of Swedish beef originates from dairy cattle (Hessle et al., 2019). In England, around half of total beef is a product of dairy cattle (Pick, 2020). However, in some countries like Norway, specialised beef production systems are common (Samsonstuen et al., 2020).
Besides the difference in the origin of the calves, depending on whether the production is intensive or extensive, the type of feeding can be different. For instance, in Brazil, most beef calves are fattened in pastures (Dick et al., 2015) while in the USA, beef calves are commonly fattened on feedlots and the main feed component is concentrate (Pelletier et al., 2010).
These differences in beef production may have an impact on the CF of beef. Therefore, we will also consider these differences to have a better insight into the impacts they have on the CF of beef production systems in Europe.

2.1 Life cycle assessment

To quantify the environmental impacts of beef production systems, different approaches can be used. LCA, which is the most popular method, is used to quantify the environmental impacts of a product through the whole life cycle. For the literature review it is important to compare results which are based on the same methodology or approach. We considered the studies which applied LCA methodology and IPCC emission guidelines (IPCC, 2006) to estimate the GHG emissions. This is the most accepted approach for the environmental assessment of livestock products.
Depending on the goal of study, different function units (FUs) can be used for the LCA of beef production including 1 kg of live weight, carcass weight, or edible beef (Pishgar-Komleh et al., 2019). One kg of protein can also be applied when the aim of production is meeting a human body's protein requirements. The FU is the main function of a production system and all the environmental impacts in a LCA study are expressed based on it. Given that the GHG emissions are presented in different FUs, to make the results comparable all the GHG emissions were calculated per kg carcass. In other words, 1 kg carcass weight was defined as the main FU in this study and the results of studies used different FUs (kg live weight or edible beef) were updated to 1 kg of carcass. It was assumed that 57.5% of live weight is carcass (LEI, 2008; De Vries et al., 2015) and around 60% of carcass is boneless meat (Extension, 2021).
The system boundary can be defined from cradle to farm gate, slaughter, processing factory door, or to end market gate. Figure 3 shows the system boundary for the whole life cycle of beef production. The majority of LCA studies on beef production assessed the environmental impacts until the farm gate. Because the level of variations for the post-farm stages (e.g., live animal transport, slaughtering and processing operations and market) is high, we limited the system boundary from cradle to farm gate. For studies which assessed post-farm stages (such as slaughtering, packaging, transporting to retail and etc.,), results were adopted to farm gate.
For the life cycle impact assessment (LCIA) phase, various impact categories such as global warming potential (GWP), acidification potential and eutrophication have been quantified. However, this literature review focuses on GWP (also known as the CF). To aggregate the CO_2, N_2O and CH_4 emissions, almost all LCA studies used conventional GWP equivalence, however, recently GWP* has been introduced as a new concept. In this report GWP* was not studied since this new approach is based on changes in CH_4 emissions rates and is not applicable in attributional LCA and also because comparing the impact of GWP and GWP* on environmental impacts of beef was not in scope of this study.

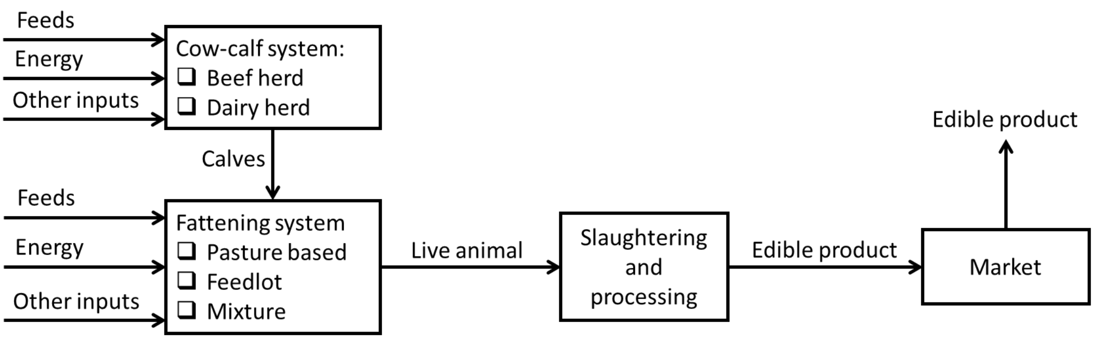

Figure 3 *System boundary of a beef production system (De Vries et al., 2015).*

To perform a LCA, two approaches can be applied; attributional and consequential (Thomassen et al., 2008a). An attributional LCA quantifies the environmental burdens of a product (e.g., beef) while a consequential LCA quantifies how the environmental burdens are affected by a change in the production and use of the product. The majority of LCA studies in livestock production systems apply attributional LCA. Some studies applied consequential LCA to study the impacts of different strategies on reduction of GHG emissions. However, to the best of our knowledge all of them focused on dairy production systems (Thomassen et al., 2008a; Nguyen et al., 2013a; Styles et al., 2018). Because the aim of this study is identifying the CF of beef products, we considered the studies which applied attributional LCA. However, for the GHG mitigation options the results of consequential LCA studies were also considered.

One of the most challenging issues in modelling the environmental impacts in a system with multiple outputs is the method for partitioning the total environmental burdens to different products. For this reason, ISO 14044 provides a mandatory hierarchy for dealing with co-production and suggests process subdivision, system expansion, bio-physical allocation, physical allocation (e.g. mass allocation) and economic allocation as the methods for the partitioning issue (ISO, 2006). Partitioning in a beef production system is applied for the production of feed (e.g. soybean meal and oil), for the milk and meat products (in a dairy-based system) and for the meat and other co-products (after the slaughtering and processing stage) in case slaughtering and processing is involved in the system boundary (De Vries et al., 2015). Economic allocation is the most commonly used method which is also suggested by the European Commission (Product Environmental Footprint Category Rules - PEFCR) for the production of feed, husbandry stage (in case manure has economic value) and for post-slaughtering stage (Zampori and Pant, 2019). In a dairy-based beef system, biophysical allocation method is applied to allocate emissions between milk, culled cows and surplus calves based on the factors recommended by International Dairy Federation (IDF, 2015).

In addition to the specified methodological choices which might affect the CF of beef products, other assumptions and choices such as diet calculations, manure handling, slaughter age and weight, and construction and maintenance of capital goods such as buildings might influence the LCA results (De Vries et al., 2015). These issues should be considered as possible factors explaining differences in results.

One of the important issues regarding environmental impacts of agricultural activities is land use (the use of land for current human or economic activities) and land use change (the process of converting a land from one application to another) which affects carbon sequestration. In most LCA studies, land use or land use change is presented as how much area is required in a certain period to produce a unit of product. This evaluation is a useful way to assess the efficiency use of land when different production systems can be applied. Two ways can be applied to quantify the value of lands. The first way is called "opportunity cost of land" which shows the value of land for alternative use e.g. forestry (Garnett, 2009). Transforming the land to forest would have high positive impact on carbon sequestration. Therefore, the loss of carbon sequestration for land used for forage and cereal crops needs to be considered. Second is the potential of land use change due to an increased demand for land-based products. The growing demand for feed to support meat production increases the pressure on land use globally and results in land use change (Stehfest et al., 2009). Because land use and land use change were out of the scope of this literature review, we did not focus on its impact on beef

production. However, we tried to provide some brief discussion about land use impacts by applying grazing.
For the environmental impacts of leather production, also the LCA approach was applied. It is the main approach for assessing the environmental impacts of leather products. In this study we provided an overview of LCA studies such as scientific papers and reports related to leather production which have been published in peer-reviewed journals.
Generally, depending on the purpose of leather and the preference of the tanner, there would be between 20 and 40 process steps involved in the production of finished leather (Laurenti et al., 2017). Tanners can be classified based on the processes which are carried out in their tannery. The Leather working group (LWG) classifies the tanners into six categories as follows (Laurenti et al., 2017):

- Raw hide to tanned hide
- Raw hide to crust leather
- Raw hide to finished leather
- Tanned hide to finished leather
- Crust leather to finished leather
- Tanned hide to crust leather

Therefore three main steps can be considered for tanners i.e. raw hide to tanned hide, tanned hide to crust leather, and crust leather to finished leather (Laurenti et al., 2017). In this literature review we considered the studies in which the final product was the finished leather.
As mentioned before, LCA is a useful approach which provides a better understanding of the materials and energy flows throughout the complete life cycle of a product, service or system (which may include technologies or organizations), and their related environmental impacts (ISO, 2006). We considered leather studies which applied attributional LCA. Because the subsystem boundary in LCA studies of leather may cover all steps of production and consumption (i.e., "cradle to grave"), and because there was a wide range for the defined system boundaries in previous studies, we limited the system boundary to production of finished leather (i.e., "cradle to factory gate"). Generally, the whole production chain of finished leather is presented in **Figure 4**. Two most common FUs which applied in previous studies were kg and m^2 of finished leather. Because the thickness of the final product is also important, thickness was also included in the selected FUs (Chen et al., 2014). For the final comparison m^2 of finished leather was used as the main FU.
For the impact assessment several impact categories including global warming, eutrophication, ozone depletion, smog, human toxicity, etc. can be considered. Product environmental footprint category rules (PEFCR) suggests climate change (or global warming), ozone depletion, human toxicity-cancer, human toxicity-non cancer, particulate matter, ionisation radiation-human health, photochemical ozone formation-human health, acidification, eutrophication terrestrial, eutrophication fresh water, eutrophication marine, ecotoxicity freshwater, land and water use and abiotic resource depletion (minerals and fossil fuels) impact categories for assessing environmental impacts of leather production (De Rosa-Giglio et al., 2018). The main focus in this study was evaluating the GHG emissions of leather product so we only considered climate change (global warming potential).

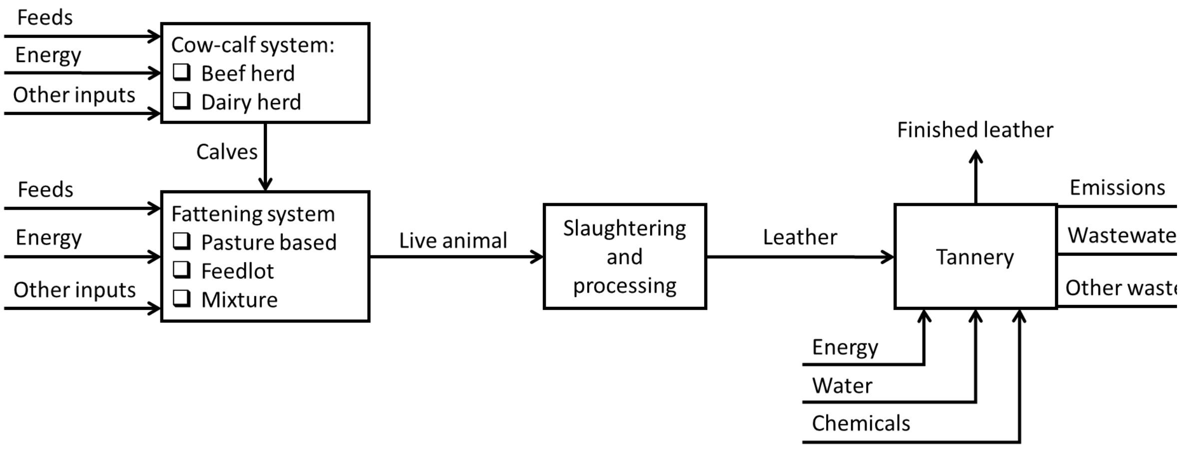

Figure 4 *System boundary of a leather production system.*

2.2 LCA studies of beef production

The search for the LCA studies of beef production was limited to the scientific reports and scientific papers which have been published in peer-reviewed journals. Different key words (such as life cycle assessment, environmental impacts, beef production, suckler, meat, etc.) were used as the subject for the papers and LCA studies were included in this literature review which:

- Evaluated beef production system in Europe
- Used attributional LCA
- Included a system boundary at least from cradle to farm-gate
- Included beef and/or milk as the main product of the system

According to the above criteria, 21 LCA studies were selected among 55 papers (which assessed the beef production systems) for further evaluations.

2.3 Comparison of production system

As mentioned before, environmental impacts of beef production vary depending on the production system (e.g., intensive or extensive system, origin of calves, organic or non-organic system, diet composition, animal species, local or regional socio economic and market context). To enable a systematic comparison, farms were classified based on three main characteristics suggested by De Vries et al. (2015), namely origin of calves, diet composition and production method (conventional or organic).

2.3.1 Origin of calves (dairy-based and suckler-based systems)

With regard to the origin of calves, we considered dairy-based and suckler-based systems. In a dairy-based system, the surplus male calves are separated from dairy cows and fattened and finished. However, in a suckler-based system beef originates from the suckler cows and their offspring (Nguyen et al., 2010). In case both suckler and dairy-based systems were included in a beef production, the system was classified based on the source of the majority of calves.

2.3.2 Type of production (organic and non-organic production)

The second grouping of previous LCA studies was based on the organic and non-organic production. Based on a general definition in an organic beef production system, animals must be raised using organic management practices and organically raised livestock must be separated from their conventional animals. The main differences between organic and non-organic beef production systems are related to feed production and grassland management (e.g., absence of inorganic fertilisers and pesticides) and animal husbandry (e.g., absence of antibiotics).

2.3.3 Diet composition (concentrate-based and roughage-based diet)

The third classification was based on the diet composition during the fattening period. Because of high variations in the diet compositions of beef production we applied the approach proposed by De Vries et al. (2015) where the portion of concentrate and grain crops in a diet was used for classification. Therefore, two categories were defined as: i) concentrate-based diet (a diet with an average proportion of at least 50% concentrate and grain crops), ii) roughage-based diet (less than 50% concentrate in diet).
The main impact of diet composition is on GHG emissions associated with the enteric fermentation and production of feed. The methane (CH_4) rate is highly dependent on the diet composition where a concentrate-based diet produces less CH_4 emissions compared with a roughage-based diet (Nguyen et al., 2010).

2.4 LCA studies of leather production

For the literature scan of leather production, we used various key words such as life cycle assessment, environmental impacts, leather, etc. as the subject of the papers. Some of the found papers assessed one step of a leather production process or studied leather waste treatments or recycling or provided some discussion regarding the methodology development. To have a better assessment we limited our study to the papers which:

- Assessed the whole leather production process (including at least tanning process)
- Evaluated leather production in Europe
- Used attributional LCA

Based on these criteria few numbers of studies have been found, therefore it was decided to highlight some studies from outside the EU and we came to 9 LCA studies.

3 Results and discussion

Based on the literature scan and according to the defined criteria, 21 and 9 LCA studies analysing beef and leather production were selected for further evaluations. In the next sections, a short review of them is presented, and the results are compared.

3.1 The main contributors to GHG emissions of beef production

A key starting point for assessing the GHG emission of beef production system is understanding the main contributors of total GHG emission. According to estimations from 1995 to 2005, between 5.6 and 7.5 Gt CO_2eq per year were emitted by the livestock sector (Herrero et al., 2016). Cattle production contributed 64-78% (depending on the study (MacLeod et al., 2013; Opio et al., 2013)) to the whole sector's total emissions. An FAO estimation showed that from 4.6 Gt CO_2eq per year of livestock sector emissions, 2.5 Gt CO_2eq per year were from beef cattle while 2.1 Gt CO_2eq per year were from dairy cattle (Gerber et al., 2013a; Opio et al., 2013; Herrero et al., 2016). The breakdown of global GHG emissions from the beef sector showed that feed production contributed most (51%) to the total emissions and followed by enteric fermentation (43%). Manure management (5%) and other off-farm and post-farm activities including transportation (around 1%) were ranked as other sources of GHG emissions (Opio et al., 2013). Between the GHGs, methane (CH_4) accounts for 43% of total livestock sector emissions while the share of nitrous oxide (N_2O) and carbon dioxide (CO_2) was 29% and 27%, respectively (Herrero et al., 2016). It should be noted that the estimation does not include carbon sequestration in grasslands.

3.2 Literature review results for beef production

Based on the literature scan, 21 studies were found in the databases including Scopus, Web of Science, ScienceDirect, etc. which used attributional LCA to determine the GHG emissions of beef production systems in Europe (**Table 1** shows the detailed information). Given that the GHG emissions are presented in different FUs, to make the results comparable all the GHG emissions were calculated per kg carcass based on conversion factors discussed in previous sections. To have a better insight into GHG emissions of different beef systems, the selected studies were classified according to the chosen criteria (origin of calves (dairy or pure beef), type of diet and the production method). As mentioned before, studies which covered both on-farm and off-farm emissions (cradle to at least farm gate) were considered for further evaluation. A short description of selected studies is described in the following.

Due to the high variation in beef production and subsequently the environmental impacts, Bragaglio et al. (2018) compared the cradle to farm gate sustainability of four different Italian beef production systems, in terms of global warming, using the LCA methodology. The primary data were obtained from 25 farms for: a) Native breed - cow-calf suckling (grazing + Grain diet fattening at barn); b) Specialised extensive – cow-calf suckling (grazing + Grain diet fattening at barn); c) Cow-calf Intensive - cow-calf suckling at barn with high-grain diets fattening at barn; d) Fattening system - high-grain diets fattening of imported calves at barn. FU was 1 kg of live weight of marketed beef cattle. Results showed the higher GHG emissions for intensive production than the extensive system (pasture-based system). This has been outlined in the next sections of this report.

In a study conducted by Casey and Holden (2006b) the GHG emissions of Irish suckler-beef production were quantified. Different scenarios were developed to examine the impacts of using both beef-bred animals (Charolais, Simmental and Limousin) and dairy-bred animals (Holstein-Frisian) on total GHG emissions of beef production systems. The specific fraction (96.6% to milk and 3.4% to meat) based on mass allocation was applied for partitioning the total GHG emissions of a dairy system

to beef. Results showed the 11.26 kg CO_2eq per live weight per year for a typical suckler-beef system. Scenario analysis showed higher GHG emissions for suckler-based system than for dairy-based system.
In order to study the impact of increasing milk production on GHG emissions in dairy-based beef systems, the link between milk and beef production was studied by Flysjö et al. (2012). To this aim, the correlation between the CF of milk and the amount of milk delivered per cow for both organic and conventional systems was investigated for 23 dairy farms in Sweden. A fixed allocation ratio based on economic value was applied for partitioning the total GHG emissions to the milk and beef products. Results showed almost equal CFs (8.2 and 7.0 kg CO_2eq per kg carcass weight) for both organic and conventional systems. Results indicated that increasing milk production per cow does not necessarily reduce the CF per kg milk, when also considering the alternative production of the by-product beef.
Nguyen et al. (2010) studied the environmental impacts of beef meat production in the EU. Four beef production systems including three dairy-based systems and one suckler-based system. The difference between these systems is presented in **Table 1**. The systems were further classified into three categories based on their diet composition: i) calves reared indoor on concentrates; ii) calves, fattened indoor on a mixed ration of concentrates and roughage (the share of roughage was more than 50%); and iii) steers, fattened on roughage. FU was defined as one kg slaughter weight delivered from farms. The system boundary was from cradle to farm gate. Results showed the greater CF for suckler-based systems (27.3 kg CO_2eq per kg slaughter weight) compared to the dairy-based systems (on average 17.9 kg CO_2eq per kg slaughter weight). Comparison of production systems based on diet composition illustrated the lower CF (16.0 kg CO_2eq per kg slaughter weight) for concentrate based. The CF of calves fattened indoor on a mixed ration of concentrates and roughage was 17.9 while for steers, fattened on roughage, the CF was calculated as 19.9 kg CO_2eq per kg slaughter weight.
Buratti et al. (2017) applied LCA to calculate the CF of two typical Italian beef production systems (organic and conventional) from "cradle to farm gate". Given that no direct land use change occurs in lands used for feed production emissions from direct land use change were excluded from the analysis. Because of lack of site-specific data, soil carbon changes were not included in GHG calculations. The main feed components were maize silage, hay (e.g., ryegrass and alfalfa), barley, maizemeal, faba bean, sorghum meal, triticale meal etc. The LCA results showed that an organic system produces more GHG emissions (24.62 kg CO_2eq per kg live weight) than a conventional system (18.21 kg CO_2eq per kg live weight). Enteric fermentation contributed most (50–54%) to the total GHG emissions. The difference between the production systems was due to the higher methane emissions from enteric fermentation and manure management in organic systems. Despite the absence of synthetic fertilizers that led to lower GHG emissions for feed production, the longer finishing period and the type of diet caused the higher total emissions in organic systems compared to the conventional system.
In a study conducted by Mogensen et al. (2015) the GHG emissions of the typical beef production systems in Denmark and Sweden were assessed and compared. The beef production from both dairy-based and suckler-based systems were evaluated. The impact of diet composition on GHG emissions was also assessed. The system boundary covered all emissions in the production chain to the farm gate where the animals left the farm. Results for the environmental assessment of typical beef production systems in Denmark showed higher GHG emissions for suckler-based systems (23.1 and 29.7 kg CO_2eq per kg carcass weight) than the dairy-based systems (8.9, 9.0 and 16.6 kg CO_2eq per kg carcass weight). Higher GHG emissions in dairy-based systems was reported for systems based on a roughage-based diet. Like Denmark, higher GHG emissions (25.4 kg CO_2eq per kg carcass weight) was reported for suckler-based systems in Sweden compared to the dairy-based systems (9, 11.5 and 17.0 kg CO_2eq per kg carcass weight). The highest GHG emissions in a dairy-based system was reported for a system based on a roughage-based diet. Based on the obtained results it was revealed that in addition to the production system (dairy or suckler-based), feed use per kg carcass weight is a main driver for variations in GHG emissions.
Presumido et al. (2018) evaluated a semi-intensive system (SIS) and an extensive organic system (EOS) of beef production systems in Portugal. The diet for animals consisted of forage (local hay) and concentrated feeds. In the EOS, cows spent their whole life in the pasture. The assessment considered all the emissions related to the production chain of cattle from feed production to the slaughterhouse i.e., the system boundary was from "cradle to slaughterhouse gate". The total GHG emissions for SIS and EOS were 22.3 and 16.4 kg CO_2eq per kg carcass weight, respectively. Methane and nitrous oxides from enteric fermentation and manure management contributed most to the total GHG

emissions. The share of carbon dioxide produced from use of energy and fuel was low compared to other sources of emissions. The main difference between two system was related to the enteric fermentation and manure management. The difference of emissions related to the slaughter of animals and feed production for SIS and EOS was not significant. Lower weight gain in a shorter time in SIS had also impact on higher footprint compared to the EOS. Therefore, increasing the animal weight gain in a shorter time and improving animal production efficiency can be considered to reduce environmental impacts of SIS. Given that the system boundary was up to the slaughterhouse gate we adjusted the obtained result for up to the farm gate boundary. Therefore the reported CF was subtracted by 0.19 kg CO_2eq per kg carcass (which was the average GHG emission for the slaughtering process based on Mogensen et al. (2016) and Desjardins et al. (2012) studies).
Roer et al. (2013) studied the environmental burdens from combined milk and meat production in Norway. Three typical farms in the most important regions (central, central southeast and southwest) for milk and meat production in Norway were selected and GHG emissions of all activities at the farm gate were determined. The total GHG emissions were reported based on one kg carcass (calculated as live weight multiplied by 0.5) as FU. An economic allocation approach was used to allocate the GHGs to milk, carcass, surplus offspring and manure. Because the share of total energy intake from concentrates for the studied farms was less than 50% (34%, 40% and 48% for southwest, central and central southeast, respectively), the production system was considered as a forage-based system. The total GHG emissions per kg carcass for central, central southeast and southwest was 18.4, 17.7 and 18.2 kg CO_2eq, respectively. Based on the obtained results it was revealed that field emissions from forage production and enteric fermentation contribute most to the environmental burdens of meat production.
A study was carried out by Vitali et al. (2018) to assess the GHG emissions associated with a local organic beef supply chain. An organic Italian farm (in central Italy) where cows are fattened for meat production was evaluated. The system boundaries included the fattening of animals, slaughtering operations, meat processing (e.g., production of packaging, retail activities, transport), consumption (e.g., home storage, cooking and waste disposal) phases. Since live animals are the only product in a suckler-based beef production system, no allocation was made for farm activity (breeding and fattening). The overall burden was 24.46 kg CO_2eq per kg cooked meat. The breeding and fattening phase was the main source of GHG emissions in the production chain, accounting for 86% of the total emissions. Among the fattening phase, enteric methane emission was the greatest source of GHG (47%). In order to calculate the GHG emission per kg carcass, it was assumed that 60% of carcass is boneless meat (Extension, 2021). Therefore, the GHG emission of beef production was calculated to be 12.59 kg CO_2eq per kg carcass.
Webb et al. (2013) compared the meat product produced in the UK (in a dairy-based beef production system) and imported from Brazil (mostly produced in a suckler-based beef production system) from an environmental perspective. A roughage-based diet was considered for comparison of beef production in Brazil and the UK. The system boundary included all production inputs up to the retail distribution centre. Environmental burdens were allocated based on the economic value. Results showed a greater GHG emission for beef production in Brazil than the UK due to greater enteric CH_4. Another reason for lower GHG emissions in beef production in the UK was the origin of the calves. Around 30% of the beef calves finished in the UK originate from the dairy sector and due to allocation, the emissions related to the breeding were less in a dairy-based system. The estimated GHG emission for the UK was 16 kg CO_2eq per kg carcass at farm gate. Enteric fermentation was the main source of GHG emission. Besides enteric fermentation, substantial emissions were calculated for production of forages and the maintenance of grazed pastures due to the application of fertilizers. It was concluded that extensive beef production essentially does not lead to smaller GHG emissions per kg product than intensive production.
McAuliffe et al. (2018) determined the emission intensity of on-farm beef cattle reared on three pasture-based production systems (permanent pasture (PP), white clover/high sugar grass mixture (WC), and high sugar grass monoculture (HS)). In PP system no field was reseeded for at least 20 years, in WC system around 30% of ground cover is white clover and in HS system the latest improved grass varieties are planted. The background emissions (including feed and diesel production) were not considered. The potential effect of changes in soil carbon stock on total emissions was not considered in this study. Since the system boundary was limited to the on-farm activities we removed this study from the listed studies and do not present it in Table 1. Results showed the higher emission intensity for HS (20.17 kg CO_2eq per kg live weight) compared to the PP (18.47 kg CO_2eq per kg live

weight) and WC (15.96 kg CO_2eq per kg live weight). In all three production systems enteric fermentation contributed most (varying between 38 and 48%) to the total GHG emissions. Emissions associated with manure management were the other main contributor.

In a study conducted by Cederberg and Stadig (2003), environmental impacts of a Swedish organic suckler-based system were determined. The system was based on roughage, of which 50% of fodder (dry matter basis) must be home grown. The GHG emissions of 22.3 per kg bone free meat was reported.

Nguyen et al. (2013b) evaluated the effects of farming practice scenarios (modified grassland and herd managements, replacing protein sources, and increased n-3 fatty acid content) aiming to reduce GHG emissions of a beef cattle production system in France. The baseline scenario included a standard cow-calf herd (a diet based on grazing) and a standard bull-fattening herd (a diet mainly based on maize silage). GHG emissions of 27.8 kg CO_2eq per kg carcass were reported for the baseline scenario. The CF ranged from 24.2 to 27.9 kg CO_2eq per kg carcass for different scenarios.

The environmental performance of five Charolais beef production systems (three specialised beef production systems in grassland and two mixed crop-livestock farms with a more intensive production system) in France was assessed by Veysset et al. (2010). The GHG emissions varied from 14.9 to 17.1 kg CO_2eq per kg live weight for the specialised beef production system in grassland. For the mixed crop-livestock farms a range of 14.3 to 19.0 kg CO_2eq per kg live weight was reported.

In a study conducted by Veysset et al. (2014) 59 Charolais suckler-cattle farms in France were investigated in terms of the GHG emissions and non-renewable energy (NRE) consumption over the years 2010 and 2011. The system boundary covered all the direct and indirect emissions (i.e., cradle to farm gate). The main factors impacting the GHG emissions and NRE consumption per kg of live weight beef were: (i) animal productivity (kg of live weight produced per livestock unit); (ii) farm size and stocking rate (area and herd); and (iii) degree of specialisation in beef production. Results indicated that increasing the herd size reduces the animal productivity and leads to higher environmental impacts per product. Findings also showed that the large and diversified farms (mixed crop-livestock farming systems) have more environmental impact than the moderate-sized and specialised beef farms. Comparison of beef farms with the highest and lowest GHG emissions showed that there is a potential to reduce 50% of the GHG emissions through better management. The average GHG emissions amounted to 12.79 kg CO_2eq per kg live weight. Enteric fermentation and manure management contributed most to the total GHG emissions by 78%.

The environmental impacts of different organic and conventional beef production systems in South Tyrol was examined by Angerer et al. (2021). GHG emissions of conventional calf-fattening, organic suckler and conventional heifer/steer fattening farms were determined. The organic suckler and conventional heifer/steer fattening farms aimed to produce marketed beef while the purpose of conventional calf fattening system was marketed veal. Results showed higher GHG emissions for conventional calf-fattening (32.7 kg CO_2eq per kg live weight) than the other two systems (19.8 and 17.1 kg CO_2eq per kg live weight). The higher GHGs of calf fattening system can be explained by the low live weight of calves when they were sent to the slaughterhouse. Due to high GHG emissions we decided to not include it in **Table 1**. No significant difference was seen between the organic and the conventional systems. Due to the high feed consumption and very low output (189 kg live weight per calf) high CF was reported for the conventional calf-fattening farms. Among different sources of emissions, enteric fermentation contributed most to the total GHG emissions, followed by feed production (e.g., permanent grassland and concentrate production).

Table 1 *Characteristics of LCA studies on beef production system in Europe.*

Reference	country	type of beef system	Origin of calves (Dairy/ Suckler)	Type of production (Organic/non-organic)	Diet (roughage/ concentrate)	FU	CF (kg CO_2eq per FU)	CF (kg CO_2eq per kg carcass)
Cederberg and Darelius (2002)	Sweden	Conventional dairy-bred bulls fattened on forage/grain	Dairy	Non-organic	Roughage	kg bone free meat	17.0	10.20
		Conventional dairy-bred bulls fattened on mainly concentrate	Dairy	Non-organic	Concentrate	kg bone free meat	16.2	9.72
		Organic dairy-bred bulls	Dairy	Organic	Roughage	kg bone free meat	16.9	10.14
		Organic suckler-bred calves	Suckler	Organic	Roughage	kg bone free meat	20.1	12.06
Cederberg and Stadig (2003)	Sweden	Organic beef production	Suckler	Organic	Roughage	kg bone free meat	22.3	13.38
Williams et al. (2006)	United Kingdom	Organic, non-organic, suckler, dairy	Dairy	Non-organic	N.A.[1]	t Carcass weight	15,433	15.43
			Suckler	Non-organic	N.A.	t Carcass weight	25,300	25.30
			Dairy	Organic	N.A.	t Carcass weight	14,168	14.17
			Suckler	Organic	N.A.	t Carcass weight	24,541	24.54
Casey and Holden (2006a)	Ireland	Conventional	Suckler	Non-organic	Roughage	kg carcass weight	13.0	13.00
		Organic	Suckler	Organic	Roughage	kg carcass weight	11.1	11.10
Casey and Holden (2006b)	Ireland	Beef-bred males in intensive indoor feedlot	Suckler	Non-organic	Concentrate	kg live weight	10.8	18.78
		Typical Irish beef-suckler system	Suckler	Non-organic	Roughage	kg live weight	11.3	19.65
		Dairy-bred males in an intensive indoor feedlot	Dairy	Non-organic	Concentrate	kg live weight	7.6	13.22
		Dairy-bred system	Dairy	Non-organic	Roughage	kg live weight	9.8	17.04
Nguyen et al. (2010)	Europe		Suckler	N.A.	Roughage	kg carcass weight	27.3	27.30
			Dairy	N.A.	Concentrate	kg carcass weight	16.0	16.00
			Dairy	N.A.	Roughage	kg carcass weight	17.9	17.90
			Dairy	N.A.	Roughage	kg carcass weight	19.9	19.90
Veysset et al. (2010)	France	Specialised (beef) in grassland area (A: calf-to-weanling and fattened females; B: calf-to-weanling 100% grassland farm; C: calf-to-beef. Beef steers production)	Suckler	Non-organic	Roughage	kg live weight	16.00	27.83
		Mixed crop-livestock (D: calf-to-beef. Intensive baby beef production; E: calf-to-weanling and cereals production)	Suckler	Non-organic	Roughage	kg live weight	16.55	28.78

Reference	country	type of beef system	Origin of calves (Dairy/ Suckler)	Type of production (Organic/non-organic)	Diet (roughage/ concentrate)	FU	CF (kg CO_2eq per FU)	CF (kg CO_2eq per kg carcass)
Alig et al. (2012.)	Switzerland	Bull-fattening	Dairy	Non-organic	Roughage	kg live weight	8.8	15.30
		Suckler cow	Suckler	Non-organic	Roughage	kg live weight	15.3	26.61
		Organic suckle cow	Suckler	Organic	Roughage	kg live weight	14.8	25.74
Flysjö et al. (2012)	Sweden	Swedish conventional system	Dairy	Organic	N.A.	kg carcass weight	8.2	8.24
		Swedish conventional system	Dairy	Non-organic	N.A.	kg carcass weight	7.0	7.02
Opio et al. (2013)	Western Europe	Western Europe dairy meat	Dairy	Non-organic	N.A.	kg carcass weight	12.9	12.90
	Western Europe	Western Europe beef	Suckler	Non-organic.	N.A.	kg carcass weight	31.0	31.00
	Eastern Europe	Eastern Europe dairy meat	Dairy	Non-organic.	N.A.	kg carcass weight	8.0	8.00
	Eastern Europe	Eastern Europe beef	Suckler	Non-organic.	N.A.	kg carcass weight	29.1	29.10
Roer et al. (2013)	Norway	Norwegian typical farm in central	Dairy	N.A.	Roughage	kg carcass weight	18.4	18.40
		Norwegian typical farm in central southeast	Dairy	N.A.	Roughage	kg carcass weight	17.7	17.70
		Norwegian typical farm in southwest	Dairy	N.A.	Roughage	kg carcass weight	18.2	18.20
Webb et al. (2013)	UK	A dairy-based beef production system	Dairy	N.A.	Roughage	kg carcass weight	16.0	16.00
Clarke et al. (2013)	Ireland	grass-based suckler beef production systems (Bull/heifer system)	Suckler	Non-organic	Roughage	kg carcass weight	20.54	20.54
		grass-based suckler beef production systems (Steer/heifer system)	Suckler	Non-organic	Roughage	kg carcass weight	22.70	22.70
Nguyen et al. (2013b)	France	cow-calf and a bull-fattening herd	Suckler	Non-organic	Roughage	kg carcass weight	26.91	26.91
Veysset et al. (2014)	France	Charolais suckler-cattle farms	Suckler	Non-organic	Roughage	kg live weight	12.79	22.24
Mogensen et al. (2015)	Denmark	Danish beef breed extensive	Suckler	Non-organic	Roughage	kg carcass weight	29.7	29.70
		Danish beef breed intensive	Suckler	Non-organic	Roughage	kg carcass weight	23.1	23.10
		Danish bull calves (slaughter at 9.4 months)	Dairy	Non-organic	Concentrate	kg carcass weight	8.9	8.90
		Danish bull calves (11.5 months)	Dairy	Non-organic	Concentrate	kg carcass weight	9.0	9.00
		Danish steers (25.0 months)	Dairy	Non-organic	Roughage	kg carcass weight	16.6	16.60
	Sweden	Swedish beef breed intensive	Suckler	Non-organic	Roughage	kg carcass weight	25.4	25.40
		Swedish bull calves (slaughter at 9.0 months)	Dairy	Non-organic	Concentrate	kg carcass weight	9.0	9.00
		Swedish bull calves (19.0 months)	Dairy	Non-organic	Concentrate	kg carcass weight	11.5	11.50

Reference	country	type of beef system	Origin of calves (Dairy/ Suckler)	Type of production (Organic/non-organic)	Diet (roughage/ concentrate)	FU	CF (kg CO_2eq per FU)	CF (kg CO_2eq per kg carcass)
		Swedish steers (25.4 months)	Dairy	Non-organic	Roughage	kg carcass weight	17.0	17.00
Buratti et al. (2017)	Italy	Conventional beef production	Suckler	Non-organic	Roughage	kg live weight	18.2	31.67
		Organic beef production	Suckler	Organic	Roughage	kg live weight	24.6	42.82
Bragaglio et al. (2018)	Italy	Native breed – Cow-calf suckling (grazing + Grain diet fattening at barn)	Suckler	N.A.	Roughage	kg live weight of marketed beef cattle	26.3	45.74
		Specialized extensive-Cow-calf suckling (grazing + Grain diet fattening at barn)	Suckler	N.A.	Roughage	kg live weight of marketed beef cattle	25.41	44.19
		Cow Calf Intensive-Cow-calf suckling at barn + high-grain diets fattening at barn	Suckler	N.A.	Concentrate	kg live weight of marketed beef cattle	21.94	38.16
		Fattening System-High-grain diets fattening of imported calves at barn	Suckler	N.A.	Concentrate	kg live weight of marketed beef cattle	17.62	30.64
Presumido et al. (2018)	Portugal	Extensive organic system (EOS)	Suckler	Organic	Roughage	kg carcass weight	16.2	16.21
		Semi-intensive system (SIS)	Suckler	Non-organic	Roughage	kg carcass weight	22.1	22.11
Vitali et al. (2018)	Italy	A local organic beef supply chain	Suckler	Organic	N.A.	kg cooked meat	20.98	12.59
		A local organic beef supply chain	Suckler	Organic	N.A.	kg carcass weight	12.59	12.59
Angerer et al. (2021)	Italy	Organic and conventional beef production in Alpine mountain regions	Suckler	Organic	Roughage	kg live weight	19.80	34.43
			Suckler	Non-organic	Roughage	kg live weight	17.1	29.74

[1] N.A.: detailed information was not available

3.3 Comparison of different beef production systems

In this section, GHG emissions of different beef production systems are compared based on the origin of calves, diet composition and production method (conventional or organic). Besides different categories defined in the present study for comparison, beef systems may differ in terms of beef breed, applying growth hormones in production and etc., which were not considered in our comparisons.

3.3.1 Origin of calves

Among the selected studies, seven studies specifically compared the environmental impacts of beef systems in terms of origin of calves (Cederberg and Stadig, 2003; Casey and Holden, 2006b; Williams et al., 2006; Nguyen et al., 2010; Alig et al., 2012.; Opio et al., 2013; Mogensen et al., 2015). **Figure 5** shows the variability of CF (kg CO_2eq per kg carcass) for the suckler and dairy-based system in previous studies. Variation of CF in suckler-based systems was greater than in dairy-based systems. As can be seen, the CF of suckler-based systems was consistently higher than that of the dairy-based systems. Based on the literature review, the average CF of dairy and suckler-based systems was 13.50 and 25.46 kg CO_2eq per kg carcass, respectively. In suckler-based systems, all the emissions related to maintaining the mother cows are attributed to beef while in dairy-based systems the majority of dairy farm emissions are allocated to milk and not to beef (i.e. 83-97%, Cederberg and Darelius (2002); Casey and Holden (2006b); Alig et al. (2012.); Opio et al. (2013); Mogensen et al. (2015)). Therefore, the contribution of the cow-calf stage can explain the higher CF for suckler-based systems (De Vries et al., 2015). It was also concluded by Zehetmeier et al. (2012) and Hessle et al. (2019) that the environmental impacts of systems with dual purpose (meat and milk) is lower compared to the suckler-based systems in which meat is the only product. Despite the lower GHG emissions of dairy-based systems per kg of beef, the other issues such as possible lower quality of beef from dairy-bred calves or culled dairy cows needs to be taken into account. Meat products from dairy-based systems often receive criticism for their meat quality (Grunert et al., 2004; van Selm et al., 2021). However, Bown et al. (2016) believed that under similar growing conditions, the difference in meat quality will be small. Integration of dairy and beef production by changing sire breed can be an option to overcome the issue. However, calving difficulty of beef sires compared to dairy breeds such as Jersey makes application of this option difficult (Oliver and McDermott, 2005). Selective breeding for easy-calving offers opportunities to solve this issue (Burggraaf and Lineham, 2016). According to van Selm et al. (2021) findings integrating dairy and beef production through dairy beef calves would lead to 2 Mt kg CO_2eq reduction in annual GHG emission of New Zealand beef production. One of the reasons for a preference of suckler-beef systems over dairy-based systems is that suckler cow farming is less labour intensive and gives more flexibility to the farmer to manage the farm (Angerer et al., 2021).

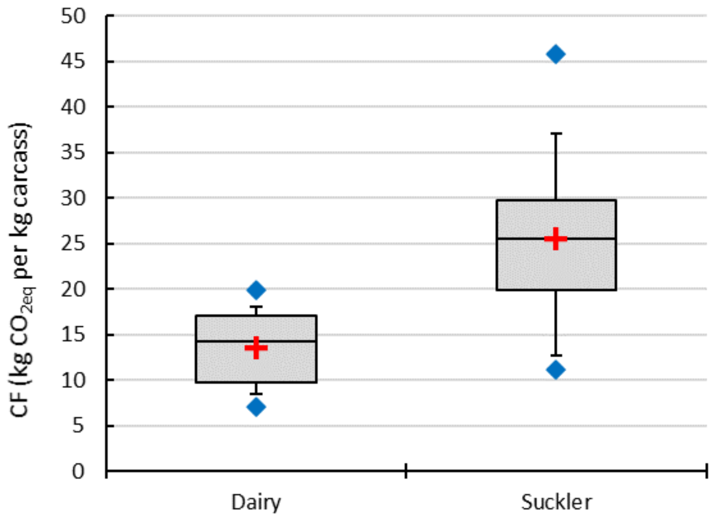

Figure 5 *Variability of GHG emissions per kg carcass of the suckler and dairy-based system for the selected studies. The midpoints of each box plot represent median (the 50th percentile); lower and upper edges of the boxes show the 25th and 75th percentiles, respectively; and the whiskers denote the 10th and 90th percentiles. The red cross (+) is the average value and blue diamonds (◆) show the minimum and maximum values of the CF for the selected studies.*

3.3.2 Type of production

Among the selected studies eight of them compared the environmental impacts of organic and non-organic beef production systems (Cederberg and Darelius, 2002; Casey and Holden, 2006a; Williams et al., 2006; Flysjö et al., 2012; Alig et al., 2012.; Buratti et al., 2017; Presumido et al., 2018; Angerer et al., 2021) (**Table 1**). **Figure 6** shows the variability of reported CF for organic and non-organic systems in all LCA studied conducted for beef production in Europe. Results showed almost similar variation of CF for both organic and non-organic systems. On average CF for organic and non-organic farming systems was 18.31 and 19.13 kg CO_2eq per kg carcass, respectively. Due to high variation of CF for both organic and on-organic farming systems it is difficult to conclude that beef organic farming has less environmental impact. The difference was not statistically significant. Less use of synthetic fertiliser and pesticides in production of feeds in an organic beef production system results in lower CO_2 and N_2O emission compared to the non-organic production system. Generally, in organic beef systems the share of roughage in rations is higher than in non-organic systems, which leads to higher enteric methane production. Therefore, the reduction of CO_2 and N_2O in organic systems is higher than the increase of enteric CH_4. The same argument was reported by Casey and Holden (2006a); Thomassen et al. (2008b); De Vries et al. (2015); Buratti et al. (2017) for the lower GHG emissions of organic beef production systems. Besides the impact of inclusion of higher roughage in rations, the lower use of concentrate and the types of concentrate were found by Casey and Holden (2006a) to be the reasons behind less GHG emissions of organic systems. In organic systems, the feed components are mainly unprocessed feed products and produced locally which have a lower CF (Williams et al., 2006; Alig et al., 2012.; De Vries et al., 2015). Generally, inclusion of concentrate results in lower enteric fermentation while the GHG emissions associated with the production of concentrate is higher than roughages. The comparison of concentrate- and roughage-based diets will be discussed in the next section where concentrate-based beef system has lower GHG emissions. Although, roughages result in higher CF of beef product, the organic roughages (mainly home-made roughages) may have lower GHG emissions compared to processed feed products (e.g., concentrate). Based on the study conducted by Picasso et al. (2014), productivity of grassland plays an important role in the reduction of GHG emissions on organic farms. The CF of suckler calves raised on low productive pastures in Uruguay, was more than twice higher than the calves pastured on seeded grasslands and finished in feedlots. The higher CF can be explained by the lower weight of calves and longer growth period. Shifting from low productive grasslands to high productive ones (intensive farming) can be considered as an option for GHG reduction in beef production systems (Dick et al., 2015; Ruviaro et al., 2015). However, it should be noted that intensive farming may cause other environmental impacts such as habitat and wildlife loss, soil erosion and nutrient run-off (Angerer et al., 2021).

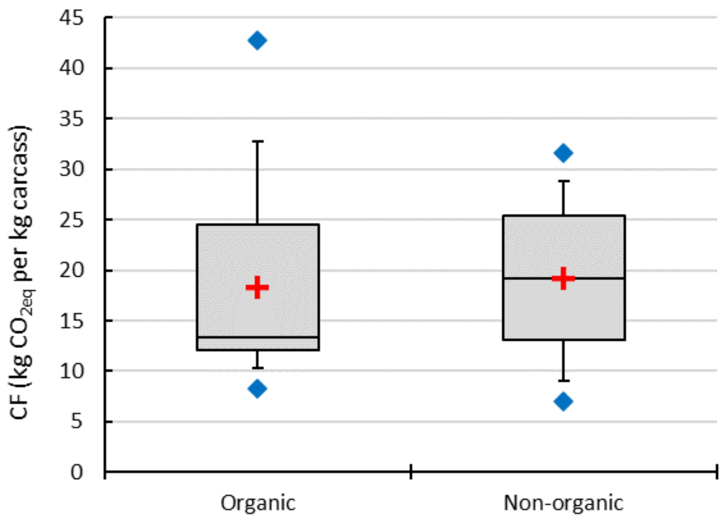

Figure 6 *Variability of GHG emissions per kg carcass of the organic and non-organic systems for the selected studies. The midpoints of each box plot represent median (the 50th percentile); lower and upper edges of the boxes show the 25th and 75th percentiles, respectively; and the whiskers denote the 10th and 90th percentiles. The red cross (+) is the average value and blue diamonds (♦) show the minimum and maximum values of the CF for the selected studies.*

3.3.3 Diet composition

Figure 7 shows the average and range of GHG emissions per kg carcass for the concentrate and roughage-based systems in previous studies conducted in Europe. The average CF of roughage-based systems was 23.43 kg CO_2eq per kg carcass (varied between 12.62 and 37.79) while for the concentrate-based system the CF was 17.47 kg CO_2eq per kg carcass (varied between 9.00 and 30.64). Among the selected studies, a number of them (Cederberg and Darelius, 2002; Casey and Holden, 2006b; Nguyen et al., 2010; Mogensen et al., 2015; Bragaglio et al., 2018) compared the GHG emissions of concentrate and roughage-based diets in beef production systems in their studies. The first reason for the lower GHG emissions of concentrate-based systems compared to the roughage-based might be the lower enteric methane of concentrate digestion than from roughage. The feed components of a roughage-based diet are very diverse but the main components can be grass (fresh grass and grass silage), maize silage and straw (Casey and Holden, 2006b; Nguyen et al., 2010; Mogensen et al., 2015). It was reported that there is no difference between a diet consisting of grass products only and a diet including both grass and non-grass roughage products in terms of GHG emissions (De Vries et al., 2015). The lower CF for concentrate-based systems can also be explained by the higher growth rate of calves in this system compared to the roughage-based system. Lower finishing weight or longer finishing time means higher GHG emissions per kg carcass (Lovett et al., 2006; De Vries et al., 2015; Mogensen et al., 2015). The average daily gain of 1.2 and 0.8 kg per day was determined for concentrate and roughage-based systems (De Vries et al., 2015).
In most of the studies reviewed, the roughage yield (both grazing and harvesting yields) was assumed to be high. The high yields are achieved by use of high levels of fertilisers in grassland. If a lower productive grassland is used for a roughage-based beef system, the CF of beef products will be even higher. The animal growth and reproduction will reduce significantly in a low-productive grassland (due to low diet quality). This leads to higher CF of beef products. Therefore, shifting from low-productive to high-productive grasslands can be considered as an option for reduction of roughage-based beef production systems (De Vries et al., 2015; Dick et al., 2015; Ruviaro et al., 2015).

However, the negative impacts (e.g., nutrient leaching and loss of habitats) of fertiliser application on ecosystems should be also considered.
Carbon sequestration is an important environmental factor which should be taken into account when the roughage- and concentrate-based systems are compared. Carbon sequestration capacity strongly depends on the age of pasture. Old pastures have a high level of SOC but their capacity for carbon sequestration is low. In a favorable condition, soil sequesters carbon until equilibrium is reached and after equilibrium level the carbon sequestration is stopped. In many parts of the world, the potential of carbon sequestration via grazing management is limited or absent (Garnett et al., 2017). Many factors including soil types and quality, grazing level, climate conditions, precipitation level, etc. will influence the level of carbon sequestration. Some studies evaluated the impacts of soil organic carbon (SOC) sequestration on GHG emissions (Nguyen et al., 2010; Pelletier et al., 2010; Beauchemin et al., 2011; Lupo et al., 2013; Mogensen et al., 2015). In a study commissioned by National Trust (2012), the carbon sequestration rate of 0.88 t CO_2 per year was assumed for permanent grassland (whether animal is on pasture or not) and the results showed that conversion from conventional to organic farming leads to carbon gain of 1.5 t CO_2 per year for grassland. Regarding the impact of SOC sequestration on total GHG emissions, different and contradictory results have been reported. Nguyen et al. (2010) and Pelletier et al. (2010) found the lower GHG emissions in roughage-based systems compared to those of concentrate-based when the SOC sequestration potential was taken into account in GHG calculations. Contrary to these findings, the GHG emissions of concentrate-based systems were found to be lower compared to the grass-based systems, even when SOC sequestration is accounted for (Lupo et al., 2013; Mogensen et al., 2015). Based on Garnett et al. (2017), the carbon sequestration potential from grazing is between 295 and 800 Mt CO_2eq per year which offsets between 20% and 60% of annual emissions of grazing cattle sector and compared to the whole livestock sector, its potential is not high. One important issue regarding carbon sequestration is that the sequestration potential reduces over time until the equilibrium level is achieved. There is a discussion about the difference between sequestration in forage and concentrate production, how soil carbon sequestration decreases, permanence of soil carbon, and the wider potential benefits to agricultural production through increased SOC. In addition to high potential for carbon sequestration in grass and arable lands, the positive impacts of woodlands and hedges on carbon sequestration needs to be taken into account to mitigate the GHG emissions. More information regarding carbon sequestration can be found in Koopmans et al. (2020); Lesschen et al. (2020). Overall, although carbon sequestration can be considered as a measure to reduce GHG emissions in the beef sector, there is genuine scientific uncertainty around the role of grazing systems in affecting soil carbon (Garnett et al., 2017).
Although the lower GHG emissions were reported for concentrate-based systems compared to the roughage-based systems, the other aspects of concentrate-based diets need to be taken into account. Given that cereal is the main feed component in concentrate-based systems which also can be consumed by humans, the feed food competition should be considered as an important factor in terms of sustainability.

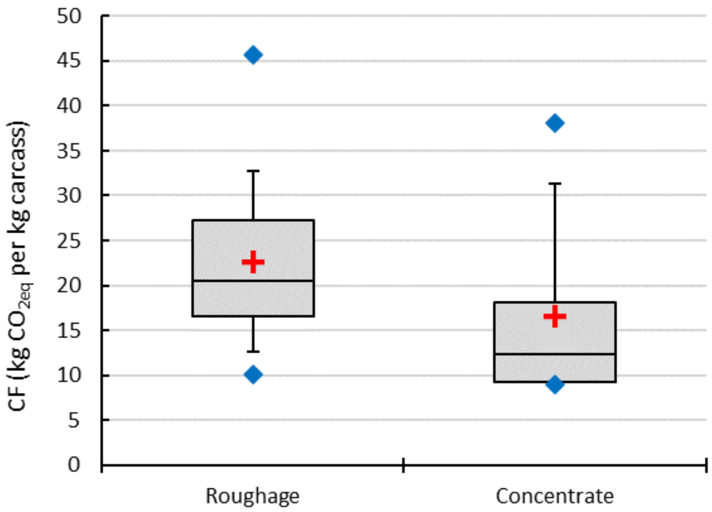

Figure 7 *Variability of GHG emissions per kg carcass of the concentrate and roughage-based systems for the selected studies. The midpoints of each box plot represent median (the 50th percentile); lower and upper edges of the boxes show the 25th and 75th percentiles, respectively; and the whiskers denote the 10th and 90th percentiles. The red cross (+) is the average value and blue diamonds (♦) show the minimum and maximum values of the CF for the selected studies.*

3.4 GHG mitigations in beef production

Following the Paris Agreement where the countries committed to tackle the climate change problems by planning and implementing efforts to mitigate the GHG emissions, efforts should also be implemented in beef production in Europe to mitigate emissions. The review of studies for beef production systems showed that there is a high potential for mitigating the GHG emissions. Based on the conducted literature review, it was concluded that the amount of GHG emissions highly depends on the origin of calves (dairy or suckler-based systems), types of production (organic or nonorganic systems) and diet composition (roughage or concentrate-based systems).
Obtained results from reviewed papers showed the higher potential to produce beef with lower CF in concentrate-based systems compared to roughage-based systems. The average GHG emissions of organic systems were slightly lower than the non-organic systems in the reviewed papers. However, due to high variation of results, the difference was not statistically significant. Lower fertilizer application rates play an important role in lower GHG emissions of organic production systems. It should be noted that extensive organic farming leads to higher GHG emissions of organic farming. Shifting from extensive organic beef farming (low productive grasslands) to intensive organic farming (high productive grasslands) increases the daily weight gain of calves and reduces the growth period (Peters et al., 2010). This leads to lower GHG emissions per kg of beef.
Shifting from low productive grasslands to the high productive ones reduces the CF of beef. Based on previous studies, the CF of beef in low productive pastures was more than two times higher than the seeded grasslands. It should be noted that the available lands can be applied for both crop (used for animal feeding purpose) and grass production. Based on previous studies and evaluations, grazing in beef production in countries where the land is less suitable for crop production can be an appropriate option, otherwise allocating available land (which are suitable for crop production) for crop production might lead to reduction of GHG emissions in beef systems.
A deeper comparison showed that in both roughage and concentrate-based diets, dairy-based beef systems had lower emissions compared to the suckler-based systems (Casey and Holden, 2006b; Nguyen et al., 2010). Given the preference of dairy-based beef production systems over suckler-based systems in terms of GHG emissions, more focus on beef production may be essential through e.g. increased cross-breeding with beef breeds or optimizing dairy and beef production (De Vries et al., 2015). Generally, since dairy and beef systems are connected to each other, the potential for reduction of GHG emission in both systems needs to be analysed simultaneously. For example,

applying more efficient dairy production strategies (e.g. increasing dairy cow longevity) results in reduction of beef products and in the production of calves (Vellinga and De Vries, 2018). To maintain the needs, more beef from suckler-based systems should be supplied, which means higher GHG emissions per kg meat product.
GHG impacts of beef production systems can be further reduced by improving the growth performance and feed efficiency of dairy-bred beef cattle (Hietala et al., 2014; De Vries et al., 2015). Increasing the production efficiency is the main and most important factor for reduction of environmental impacts of livestock production (both dairy and beef) (Roer et al., 2013; Mogensen et al., 2015; Vitali et al., 2018). Moreover, reducing the number of unproductive animals in the farm is also beneficial (Vitali et al., 2018).
Adapting the ration based on the animal requirements and applying different feeding groups increases the time required to manage the herd and needs attention to detail to achieve a higher feed efficiency of animals. The feed can also be adjusted based on the environmental impacts of the individual feeds (e.g., change in ration to allow for better crop rotation and providing environmental benefits). According to Hessle et al. (2019), for suckler cows, the feed adjustments can be about reducing overfeeding (energy and protein) by providing more fibre-rich roughages, whereas dairy cows and growing cattle need to get more digestible (earlier harvested) forages. At the crop and forage production step, reduction of emissions associated with the feed production is also critical (Hessle et al., 2019).
Carbon removal or carbon sequestration is a strategy in livestock sector to remove CO_2 from the atmosphere by increasing the soil carbon storage. Because carbon sequestration has long-term impact, there are many discussions in the techniques to measure its impact. Although inclusion of carbon sequestration into LCA calculations of beef studies provides additional information regarding the environmental impacts, typically, due to high uncertainty regarding the rates and permanence, it is excluded (McConkey et al., 2019). Garnett et al. (2017) also showed that the potential of carbon sequestration on reduction of GHG emissions in beef production system is low. To calculate the carbon sequestration, further work and testing on the ground needs to be done. In a study carried out by McConkey et al. (2019) the average carbon sequestration for rangelands and non-permanent pastures in France were reported as 570 and 80 kg C per ha per year, respectively (McConkey et al., 2019). Additionally, growing legume fodder crops in grasslands makes it possible to eliminate the use of synthetic fertilisers in grasslands. Shifting from temporary to permanent grasslands provides better environmental performance because permanent grasslands creates higher levels of carbon sequestration compared to the temporary grasslands (Hessle et al., 2019). However, it should be considered that older pastures have lower capacity for carbon sequestration because the soil has achieved the equilibrium level.
Besides the options mentioned in this study, some other options are available and can be considered as GHG mitigation strategies for beef production. The methane emissions from enteric fermentation, which are the main source of GHG emissions in beef production, can be reduced by modifying the dietary composition and increasing the feed conversion efficiency (Doreau et al., 2011; Gollnow et al., 2014). To this aim, several actions are applicable such as i) the use of feed additives to reduce the methane emission up to 30% by modifying the rumen microbial fermentation (Luo et al., 2015; Buratti et al., 2017), ii) the use of dietary supplements such as tannins and saponins or forage additives, such as ionophores and defaunation (Williams et al., 2009; Luo et al., 2015; Buratti et al., 2017), iii) reduction of N excretion and subsequently nitrous oxide emissions from manure management by optimisation of N content of diet (reducing/optimising the crude protein content of diet) (Powell et al., 2008; Buratti et al., 2017).
Applying manure management techniques can also contribute to reduction of GHG emissions from beef production. Manure separation immediately after excretion reduces the production potential of methane and nitrous oxide from manure. Besides using biogas digester to extract the methane from manure, promoting or avoiding anaerobic conditions in solid manure storages by decreasing the storage time underneath pit or frequent turning of manure piles will be helpful. Chadwick et al. (2011) reported a 0.5% reduction of initial C content of manure due to frequent turning of the manure pile.

3.5 LCA studies of leather production

Table 2 shows the description of found papers in the scientific literature related to the leather production in Europe and some other studies carried out outside Europe. In Europe, most of the leather LCA was carried out in Italy, Spain and Turkey. It should be noted that some of the studies compared environmental impacts of conventional tanning processes and alternative processes focusing on a specific process. Since these studies cannot provide a holistic view of the whole production, we ignored them for further evaluations. As can be seen, the variation between the studies was high. System boundaries were different and different FUs were applied for reporting the GHG emissions. To make the results comparable we used conversion factors to convert the different FUs to m^2 finished leather (the last column of **Table 2**). However, it should be mentioned that the uncertainty of this approach is high. In the next section we provide some detailed information about the reviewed studies.

Table 2 *Characteristics of LCA studies on leather production system.*

Reference	Country	Type of study	Production process F: farming S: slaughterhouse T: tannering	FU	CF (kg CO_2eq per FU)	CF (kg CO_2eq per m^2)
Milà i Canals et al. (1998)	Spain	LCA of footwear	F+S+T	N.A.	N.A.	N.A.
Milà i Canals et al. (2002)	Spain	LCA for ecolabel of leather	F+S+T	kg of salted hide	19.80	146.7 b
			F	kg of salted hide	12.53	92.8 b
			S	kg of salted hide	0.66	4.9 b
			T	kg of salted hide	6.59	48.8 b
Notarnicola et al. (2011)	Italy	Italian and Spanish leather production systems	T	m^2 with thickness of 1.3 mm	8.93 a	8.93 b
	Spain			m^2 with thickness of 1.3 mm	7.71 a	7.71
Kılıç et al. (2018)	Turkey	CF of a tanning company in Turkey	T + waste management	m^2 finished calf leather	63.16	63.16
			T	m^2 finished calf leather	45.77	45.77
Chen et al. (2019)	Chile		T	kg finished leather	3.98	18.43 c
	China		T	kg finished leather	5.33	24.68 c
	India		T	kg finished leather	7.26	33.61 c
	Italy		T	kg finished leather	5.41	25.05 c
	Spain		T	kg finished leather	3.41	15.79 c
Joseph and Nithya (2009)	India	LCA of leather	S+T	m^2	152	152
Chen et al. (2014)	Taiwan	LCA of leather	F+S+T	m^2 with thickness of 1.5 ± 0.1 mm	64.8	64.8
				m^2 with thickness of 1.7 ± 0.1 mm	74.5	74.5
				m^2 with thickness of 1.9 ± 0.1 mm	79.6	79.6
				m^2 with thickness of all thicknesses	73	73
Tasca and Puccini (2019)	Italy	LCA of leather production	T (including retanning, fatliquoring, and dyeing processes)	kg tanned leather	2.64	12.22 c

Reference	Country	Type of study	Production process F: farming S: slaughterhouse T: tannering	FU	CF (kg CO_2eq per FU)	CF (kg CO_2eq per m^2)
Laurenti et al. (2017)	Spain	LCA of raw hide to finished leather (limited to energy and fuel)	T (chromium tanning)	m^2 with thickness of 1.2-1.4 mm	2.5	2.5
	Taiwan		T (chromium tanning)	m^2 with thickness of 1.2-1.4 mm	4.95	4.95
	Australia		T (chromium tanning)	m^2 with thickness of 1.2-1.4 mm	12	12
	Argentina		T (vegetable tanning)	m^2 with thickness of 1.2-1.4 mm	2.3	2.3
	Spain		T (vegetable tanning)	m^2 with thickness of 1.2-1.4 mm	4.97	4.97

a. slaughtering stage is not included

b. using conversion factor of 7.41 kg raw hides or skins per m^2 finished leather (De Rosa-Giglio et al., 2018)

c. using conversion factor of 4.63 kg finished leather per m^2 finished leather (De Rosa-Giglio et al., 2018)

d. N.A.: detailed information was not available

The first application of LCA for calculating the environmental impacts of leather belonged to Milà i Canals et al. (1998) where the Spanish leather industry was evaluated and the environmental hotspots in the footwear production were identified. Cattle raising, slaughterhouse, tannery and footwear manufacture were in the system boundary. Results showed that cattle raising, tanning, waste management and footwear manufacture are the main polluters in the leather industry. Because detailed inventory data was not provided in this study, deeper evaluation was not possible. Only the share of environmental impacts for leather production were presented for different impact categories.
The environmental hotspots in the chrome-tanned leather production used for shoe uppers in Spain were identified in a study carried out by Milà i Canals et al. (2002). The LCA covered all processes in the animal production (including feed production stage), slaughtering and tanning stages. The FU of slated hide was chosen instead of finished leather because it was more common. Among the different stages it was concluded that tannery is an important stage in terms of environmental impacts. Also, animal production had an important role in total GHG emissions. The total GHG emissions were calculated as 19.8 kg CO_2eq per kg salted hide. Cattle raising, tannery, agriculture stage (feed production) and slaughterhouse (including storage) had the highest contribution to total GHG emissions by 6.99, 6.59, 5.54 and 0.66 kg CO_2eq per kg salted hide, respectively.
Notarnicola et al. (2011) assessed environmental impacts of Italian and Spanish bovine leather production systems to identify the hotspots and compare different production technologies and cooperative managements. The FU was defined as delivery of the surface area of a typical leather delivery to a shoe company. Therefore, FU was 185.8 m^2 of chrome-tanned bovine leather with a thickness of 1.3 mm to be used for the manufacture of women's shoes, which is equivalent to a leather mass of 200 kg. The system boundary included all materials and inputs related to the slaughtering, storage, transport and leather production processes. The husbandry was kept out of the system boundary. As shown in Figure 8, tannery contributed most to the total GHG emissions (global warming potential - GWP) of leather production in both countries, followed by solid and water waste treatment. The impacts of the slaughterhouse and storage phases were low. In the tanning process the main environmental impacts belonged to the chemical supply (67-80%) and energy load (19-4%). Obtained results showed the high contribution of tanning to total GHG emissions. Energy consumption, industrial processes and solid waste managements were identified as the main levels which need more consideration when the aim is to mitigate the GHG emissions of leather production. The results underlined the higher GWP for Italian tannery (8.93 kg CO_2eq) compared to the Spanish system (7.71 kg CO_2eq) per m^2 chrome tanned with thickness of 1.3 mm.

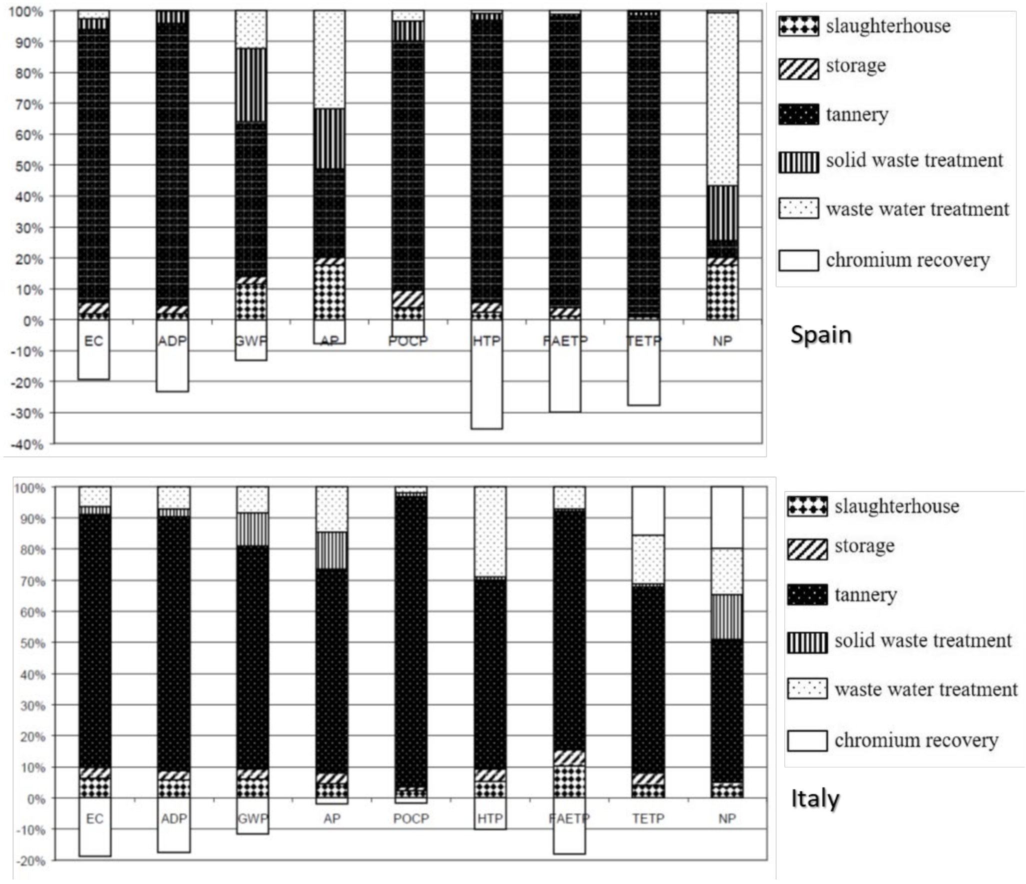

Figure 8 *LCA of a Spanish and Italian leather (from slaughterhouse to finished leather) (Notarnicola et al., 2011). Impact categories were energy consumption (EC), abiotic resource depletion potential (ADP), global warming potential (GWP), acidification potential (AP), photochemical oxidant creation potential (POCP), human toxicity potential (HTP), fresh aquatic eco-toxicity potential (FAETP), terrestrial eco-toxicity potential (TETP), and nutrification potential (NP).*

The environmental impact of leather production in Turkey was studied by Kılıç et al. (2018). The LCA included beamhouse, retaining and finishing processes. Beamhouse operation in the production of leather is between curing and tanning and includes some activities such as soaking, liming, removal of extraneous tissues. The reference unit of m^2 of finished leather was used for reporting the results of environmental assessments. GHG emissions were calculated for three scopes. Scope 1 included the emissions which arise directly from the tannery process, Scope 2 is the emissions associated with the production of material and energy inputs which are used in leather production and finally Scope 3 related to emissions associated with the production of material and energy inputs which are not controlled by the tannery. Results showed the higher contribution of Scope 3 compared to Scope 1 and Scope 2. CF of finished calf leather was calculated as 63.16 kg CO_2eq per m^2, which reported as 28.4 kg CO_2eq per kg of finished leather. Results indicated the substantial environmental impacts during the tannery process related to electricity production and solid waste landfilling.

Chen et al. (2019) quantified and analysed the CF of leather production process. Two impact categories (IPCC 2013 GWP 100 years and GHG Protocol) were applied for the assessments. Results showed that to process 1000 kg of raw hides, tanneries in Chile, China, India, Italy, and Spain emitted 882, 1180, 1608, 1198, and 755 kg of CO_2eq, respectively. The CF ranged from 3.41 to 6.30 kg of CO_2eq per kg of finished leather. Using conversion factor of 4.63 suggested by PEFCR (De Rosa-Giglio et al., 2018), the CF was calculated per m^2 of finished leather (**Table 2**). Energy consumption was the main contributor to total GHG emissions and followed by the consumption of acrylic resin, and chromium tanning.

Joseph and Nithya (2009) assessed environmental impacts of leather production in India. The system boundary covered the slaughtering and leather production processes. The FU was defined as 100 m^2 finished leather used for making shoe uppers. The results revealed that production of 100 m^2 leather leads to 15,190 kg CO_2eq (equal to 15.19 kg CO_2eq per m^2 leather). It was revealed that tanning and

finishing of leather have the highest environmental impacts. Fossil fuels as the source of energy contributed most to the total GHG emissions of leather production.
Chen et al. (2014) carried out a research to quantify CF of the finished bovine leather in Taiwan using LCA in a cradle to gate system boundary. The environmental impacts were reported in a unit of 1 m^2 finished aniline leather for four different thicknesses (1.5 ± 0.1 mm, 1.7 ± 0.1 mm, 1.9 ± 0.1 mm, and all thicknesses). The results were 64.8, 74.5, 79.6 and 73 kg CO_2eq per m^2 of different thickness (1.5 ± 0.1 mm, 1.7 ± 0.1 mm, 1.9 ± 0.1 mm and of all thicknesses), respectively. The breakdown of the total GHG emission is shown in Table 3.

Table 3 *Summary of CFP of the aniline leather (Chen et al., 2014).*

Aniline	**Unit**	**All thicknesses**	**1.5±0.1mm**	**1.7±0.1mm**	**1.9±0.1mm**
Raw material extraction	kg CO_2eq per m^2	56.8	48.8	58.3	63.3
Manufacturing	kg CO_2eq per m^2	16.2	16.0	16.1	16.4
Distribution	kg CO_2eq per m^2	0.01	0.005	0.01	0.01
Total	kg CO_2eq per m^2	73.0	64.8	74.5	79.6

Tasca and Puccini (2019) performed a LCA to calculate the environmental impacts of retanning, fatliquoring and dyeing processes during production of 1 kg of crust leather. Results showed the total GHG emissions of 2.64 kg CO_2eq per kg tanned leather. The emissions of retanning, fatliquoring and dyeing processes was calculated as 1.19, 0.74 and 0.71 kg CO_2eq per kg tanned leather, respectively. Electricity was the major contributor to the total GHG emissions. It was concluded that replacing fossil fuels with cleaner alternatives would strongly enhance the environmental performance of the leather production system. Also, the high amount of wastewater and its treatment was found to have high negative impacts on marine eutrophication. This issue can be reduced by reduction, reusing, recycling and recovering of solid waste and tannery effluents.
Laurenti et al. (2017) studied the GHG emissions of leather making processes for 12 tanners in different countries (for instance in Spain, Taiwan, Australia, Argentina, China, Mexico and Brazil) to compare the GHG emissions of chromium- and vegetable-tanned leather processes. The system boundary was limited to the production of leather and a limited number of inputs. Upstream processes such as animal farming, slaughtering, chemical production and water extraction, and after production processes, were not included in the system boundary. GHG emissions associated with the production and application of energy inputs (electricity/fuel) were considered in the system boundary. The downstream processes such as solid waste and wastewater treatment were not included in the calculations. FU was defined as 1 m^2 of finished leather with a thickness of 1.2-1.4 mm. Most of the tanners applied a chromium tanning technology while three applied a vegetable tanning technology. Obtained results for the companies (in Spain, Taiwan, Australia, and Argentina) that processed the raw hide to produce the finished leather, showed that CF of finished leather varied from 2.35 to 12 kg CO_2eq per m^2 of finished leather. Based on the findings no significant differences between the CF of chromium and vegetable leather processes was reported.
In a study conducted by Rivela et al. (2004), a representative leather tannery industry (chromium tanning) in Chile was evaluated from an environmental point of view. The system boundary was from cradle to gate and the FU was chosen as 1 tonne of wet salted hides per year used in the production of shoes. System boundary covered beamhouse, tan yard, retanning processes, and wood furnace as well as energy and chemicals supply. The control and reduction of chromium and ammonia emissions were the critical points for reduction of environmental performance of leather production.
Bacardit et al. (2015) evaluated a new sustainable continuous system for processing bovine leather in Spain and compared it with the conventional system in terms of GHG emissions. Results showed that the new process results in reductions of 30.6% in water use, 50.2% in chemical use and 16.4% in process time. LCA for the tanning processes showed the lower GHG emissions for new systems (23% less than the conventional system). Since the amount of GHG emissions per kg product was not provided by this study it was not possible to compare it with other countries.
Reviewing the results obtained from LCA studies carried out for leather production showed the importance of leather production in terms of environmental impacts. Nowadays, new technologies are being introduced to reduce the environmental impacts of leather. LCA as an important approach can help the leather industry to have a wider view of environmental issues and guide new technologies and innovations to more sustainable production.

The carried-out literature review showed a high variation in the CF of leather. There are different reasons for this high variation, such as application of final product (i.e., different quality), tannery method (chrome or vegetable), animal origin, different range of thickness, etc. Generally, there are four markets (end-user) for tanned leather including i) leather for automotive interiors and furniture upholstery, ii) leather for upper footwear and leather goods (e.g., bags, belts, wallets, …), iii) leather for garment and gloves, iv) sole leather. Depending on the use of finished leather they have different characteristics. **Table 4** provides detailed information regarding target markets, origin of leather and the type of processing applied to each product. Given the high variation on quality of finished leather applying conversion factors to convert the reported values to the same FU leads to a high uncertainty on the final results. To solve this issue, applying a standard or guideline for environmental assessment of leather production is strongly suggested. Recently, PEFCR provided a guideline for environmental assessment of leather industry. This guideline makes it possible to compare environmental impacts of various types of leather products. Using the PEFCR guideline, the LCA studies should provide more detailed information regarding the conducted assessment. More information regarding the guideline can be found in De Rosa-Giglio et al. (2018).

Table 4 *Characteristic of various kind of leather (De Rosa-Giglio et al., 2018).*

End use	Chrome-Tanned	Vegetable-Tanned	Free of Chrome	Animal Origin
Automotive and upholstery	63%	0%	37%	Bovine (100%)
Footwear and leather goods	75%	22%	3%	Bovine (66%), Calf (12%), Caprine (11%), Ovine (11%)
Garments and Gloves	100%	0%	0%	Calf (20%), Caprine (16%), Ovine (64%)
Sole leather	0%	100%	0%	Bovine (100%)

Besides the methodological differences in reporting the environmental results, there is a high variation in activities carried out in leather processing units. It is hardly possible to find two tanneries following the same finishing procedure with similar finishing formulation even when the same raw material is used, and the same finished leather is produced. Some of the studies were more or less comparable and we selected and presented them in **Table 5** to provide more insight about CF of leather production in Europe. The system boundary was limited to slaughtering and/or tannering steps. Therefore, the studies in which it was not possible to exclude emissions associated with the fattening step, were not mentioned in **Table 5**. Among the other studies, Laurenti et al. (2017) reported a very low CF compared to others. Since the aim of that study was comparing chromium and vegetable tanning, the system boundary was limited to a few numbers of inputs. Therefore, a lower CF was reported. Joseph and Nithya (2009) reported a high CF (152 kg CO_2eq per m^2 finished leather) in India which can be explained by the high environmental impacts due to applying conventional processing in the production process. Therefore, these two studies were excluded from the final comparison. As it is shown, CF of leather ranges between 7.75 and 53.7 kg CO_2eq per m^2 finished leather. The average CF was 24.6 kg CO_2eq per m^2 finished leather. The highest CF was reported in Turkey (Kılıç et al., 2018) where the emissions associated with the waste treatments were considered in the environmental assessment. Also, a long list of chemicals and inputs were considered in the life cycle inventory of that study which can be the reason of higher reported GHG emissions. By skipping the waste treatment, the CF was 45.77 kg CO_2eq per m^2 finished leather. Another higher CF was reported by Milà i Canals et al. (2002) in which compared to other studies, older technology was applied in the leather production. The lowest CF was reported by Notarnicola et al. (2011) for Italy and Spain.

Table 5 *The selected study for final comparison.*

Reference	Country	System boundary	CF (kg CO2eq per m2 finished leather)
Milà i Canals et al. (2002)	Spain	Slaughtering + Tannering	53.7
Notarnicola et al. (2011)	Italy	Slaughtering + Tannering	8.97
	Spain	Slaughtering + Tannering	7.75
Kılıç et al. (2018)	Turkey	Tannering	45.77
Chen et al. (2019)	Chile	Tannering	18.43
	China	Tannering	24.68
	India	Tannering	33.61
	Italy	Tannering	25.05
	Spain	Tannering	15.79
Tasca and Puccini (2019)	Italy	Tannering	12.22

To sum it up, as it has been mentioned, various technologies and approaches are being used in leather production in Europe which makes comparison of production systems complicated. Given the wide range of leather products with different qualities would result in an uncertain comparison. Moreover, application of different approaches for reporting the results will add to the complexity. Therefore, application of PEFCR as a comprehensive guideline can be an important solution.

4 Conclusion

A literature scan was carried out to evaluate environmental impacts of different beef production systems and leather production in Europe. More than 60 scientific publications were reviewed and papers which met the defined criteria were selected for deeper evaluations. For the beef literature review, 21 studies were selected which applied LCA for environmental assessments. Based on the literature scan it was found that the two main important sources of GHG emissions in beef production are feed production and enteric fermentation. Manure management and post-farm processing were the other sources of emissions in beef farming. CH_4 contributed most to the total emissions and CO_2 and N_2O had the lower contributions. Because the CF of beef products highly depends on different production systems (e.g., origin of calves, organic or non-organic system, and diet composition) we classified the reviewed studies based on these three parameters. Results showed the higher GHG emissions per kg carcass for suckler-based systems compared to the dairy-based system. The GHG emissions of organic farms was slightly, but not significantly, lower than the non-organic farms due to fewer GHG emissions associated with the production of animal feeds (including grass/forage). Comparison of a concentrate-based diet with the roughage-based diet showed that the cattle fed concentrate-based diet had lower GHG emissions, mainly due to higher daily weight gain. Reviewing beef studies showed the high potential for mitigating GHG emissions in beef systems. Increasing the production efficiency can be considered as the most important factor to reduce of GHG emissions in beef production. To this aim, adopting the ration based on the animal need (applying different feeding groups), reducing overfeeding by providing more fibre-rich roughages (in case the dairy × beef crossbred cattle is growing in herd with a higher feed efficiency) and reducing the number of unproductive animals can be helpful. Detailed evaluations showed that using a production system with lower CF (dairy-, organic- and concentrate-based beef systems) can mitigate GHG emissions. Besides the main mitigation strategies, modifying the dietary composition (e.g., use of feed additives, use of dietary supplements, reduction of N excretion by optimisation of N content of diet) leads to the lower CH_4 emissions.

A literature scan of leather production in Europe showed that most studies focused on an environmental assessment of leather production in Italy, Spain and Turkey. A high variation was seen in the LCA results because of methodological differences (e.g., system boundary, FU) and differences in use of final product, tannery method (chrome or vegetable), animal origin, different range of thickness, etc. Because few studies were found in Europe, we also added studies conducted outside Europe. Reviewing the results obtained from LCA studies showed the importance of leather production in terms of environmental impacts. Supplying energy and chemicals contributed most to the total GHG emissions of leather production. Conventional production systems had higher environmental impacts than the production systems with new technologies. It was illustrated that applying new technologies has substantial impact on the reduction of leather CF. The average CF was 24.6 kg CO_2eq per m^2 finished leather (ranged between 7.75 and 63.16 kg CO_2eq per m^2 finished leather). Besides the technologies and approaches to reduce the environmental impact of leather, applying a standard approach such as PEFCR for environmental assessments of leather product can be considered as an important solution.

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