

Environmental Sustainability in Beef Production and Life Cycle Assessment as a Tool for Analysis

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Abstract

The sustainability of meat production systems has been highlighted by the impact on the environment and the conservation of natural resources. The aim of this manuscript is to provide a specific review of the environmental sustainability of beef production in a life cycle assessment (LCA) context. Questions about the main environmental impacts caused by beef production were discussed. The phases of the LCA were detailed as well as the main functional units, boundaries of the systems and categories of impacts used in recent studies. LCA is a fast, easy and intuitive method that correlates human activities and their environmental performance in different sectors, such as beef production.

Author Keywords. Life Cycle Assessment, Circular Economy, Environmental Management, Environmental Assessment, Beef Production.

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1. Introduction

Food production requires large amounts of material and energy resources and is responsible for the emission of various wastes, which cause a number of negative effects on the environment. In the present day society, environmental impacts come from two main issues: the decrease in the supply of fossil fuels and the limited availability of renewable resources; and the production of wastes with subsequent disposal into the environment without proper treatment. Both can be considered as an effect of the technological development of human society ([Brown and Ulgiati 2002](#)).

Meat production is one of the most important economic sub-sectors of the agri-food sector. The largest producers of this industry are the United States, Brazil, European Union (EU) and China, respectively, representing almost the total annual production of 60 million tons of carcass weight per year ([USDA 2016](#)).

EU has a cattle population of about 87 million head and a total annual production of about 7.6 million tons of meat ([Eurostat 2017b](#)). In quantitative terms, the cattle production to the EU is 8.1% of total agricultural production and 18.8% of livestock

([Marquer, Rabade, and Forti 2015](#)). Within the EU member states, France, Germany, the United Kingdom and Italy account for more than half of EU beef production (55.9%) ([Eurostat 2017a](#)).

Meat is one of the foods that generates more pressure on the environment within the food sector ([Garnett 2011](#)). Faced with an increase in meat consumption in the world of around 50% in the last 40 years, meat production and agricultural systems in general play a relevant role in the environmental sustainability of the agri-food sector ([Alexandratos and Bruinsma 2012](#)). Thus, studies that focus on the determination of environmental impacts in the livestock sector are essential for the development of more sustainable practices ([O'Brien et al. 2016](#)).

Life cycle assessment (LCA) is a structured tool with the objective of analyzing the potential environmental impacts throughout the life cycle of a product or service, that is through the stages of production and product use, to the management of waste produced. It also allows guide the environmentally conscious product design, based on the interpretation of the life cycle.

In accordance to [ISO \(2006a\)](#), the LCA of a product, process or service is one of the tools for assessing inputs, outputs and their respective potential environmental impacts throughout their life cycle (Cradle to Gate Approach) considering the raw materials used, the processes of production, transportation, use, end-of-life treatment, recycling and, lastly, final disposal. Consumption of mass and energy resources (inputs) and emissions of substances (output) are the main causes of environmental impacts ([Santagata, Ripa, and Ulgiati 2017](#)). Moreover, LCA results are expressed as indicators for several environmental categories, i.e., the results are translated into global warming potential, acidification potential, eutrophication potential, land use and occupation, resource depletion, among others ([Pennington et al. 2004](#)).

The aim of this paper is to provide a specific review of the environmental sustainability of beef production in a life cycle assessment context. The importance of using this assessment tool to align sustainable development and food production is also discussed.

2. Stages of the Life Cycle of Beef Production

In the basic structure of the industry involving beef production, three phases of its production chain can be distinguished: (i) animal production; (ii) slaughtering and processing of meat; and (iii) the commercialization.

Animal production in beef value chain is important because of the interaction between the breeders and their production stages (rearing and fattening). This stage refers to the main products and services that producers need to raise cattle, including food, veterinary services and animals (genetics) ([Lowe et al. 2009](#)). Breeders can be grouped into individual producers, producer groups and cooperatives.

When the animal reaches the ideal weight and age it is slaughtered and undergoes specific processing, some of which may be used for the production of processed meat products. Many of these operations also involve additional processes related to the manufacture of more elaborate meat products, for example, meats for frozen meals.

Finally, marketing is done through wholesalers or direct sales to retailers, where supermarkets, restaurants and food service operators sell the food to the final consumer. The market is included throughout the beef value chain, interacting between the various stages and influencing imports and exports.

3. Life Cycle Assessment (LCA)

3.1. Stages of Life Cycle Assessment

LCA shows in detail the inputs and outputs taking into account the coevolution of economic, environmental and social systems due to its process-based approach. Thus, the LCA has important characteristics for decision making, allowing farmers and producers to commercialize their products in a socially and environmentally friendly way to consumers (Land & Water Australia 2009).

LCA can be divided into four main steps: (1) goal and scope definition, (2) inventory analysis, (3) impact assessment and (4) interpretation of results (Figure 1). ISO (2006a) and ISO (2006b) documents describe and standardize the methodologies related to LCA and environmental management.

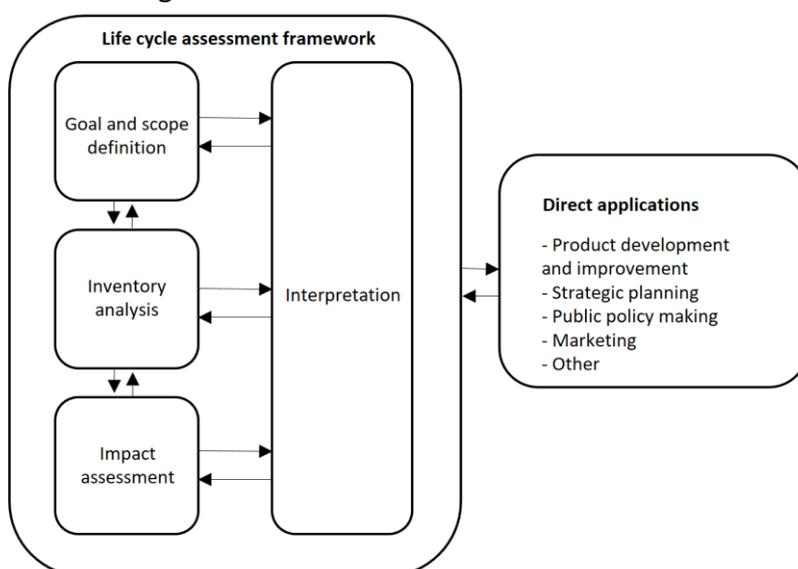


Figure 1: Overview of stages of a life cycle assessment (ISO 2006a)

3.2. Goal and scope definition

The initial phase of the LCA is to determine the goal and scope of the study to be carried out. This is an important phase, where the user will determine the limits and context of the system. The level of detail and the target audience is also required at this stage.

In addition to defining the boundary of the study, the type of target audience for whom the results are presented, this stage also determines the main categories of environmental impact.

In summary, at this stage of LCA the following procedures should be defined: (i) objective of the study related to a product or service; (ii) target audience to whom the study is directed; (iii) system boundary and limitations in data collection; (iv) functional unit and allocation procedure; (v) environmental impact assessment and impact category.

The functional unit provides a reference to relate the data entering and leaving the system. This unit may vary according to the need of the study. It should take into account a global functional unit, for comparing the results of an evaluation with those of other studies (ISO 2006b).

After identifying all the components of a study, each of them can be seen as an individual system, where it will receive inputs (e.g. energy and raw materials), generate outputs (e.g. waste, emissions and water discharges) and a final product required by the system. In addition to the system impacts as a whole, it should take into account the

environmental discharges associated with the production, use, transport and final disposal of products.

Process systems are mainly based on the sum of the inputs and outputs of all the components involved, exemplified by inputs of energy and raw materials and outputs of waste and emissions. The system model becomes correct if it does not violate the laws of thermodynamics and mass conservation in which the quantities of output resources will be the same quantities counted at the input of the system.

[Table 1](#) shows the main functional units, the boundaries of the systems, the associated impacts and the respective locations for the LCA of beef production.

This table showed that most of the studies on LCA of beef production take into account the category of impact of global warming potential, also described as climate change. This can be explained due to the focus that recent studies have given to global warming and concern about rising temperatures on Earth. In addition, it was possible to observe a good distribution of LCA studies in beef production in different countries. Thus, different systems can be compared and more input and output information can be collected.

3.3. Life cycle inventory analysis (LCI)

Life cycle inventory (LCI) analysis is the second step in LCA. In this phase the values of inputs and outputs within and through the system boundary are identified and quantified. According to the [European Commission, Joint Research Centre - Institute for Environment and Sustainability \(2010\)](#), this procedure includes the use of basic life-cycle data (e.g. data on the production of electricity, purchased materials, or downstream processes such as recycling). Validation of these data is indispensable at this stage. After analyzing the data, the results are used in the Life Cycle Impact Assessment (LCIA).

Data collection is difficult to execute for reasons ranging from the lack of known data, passing by the need of estimating them to the quality of the available data ([Willers and Rodrigues 2014](#)). Often some companies may omit or change some important data because of secrecy or even fear of actions related to legal compliance. Therefore, care should be taken in the collection and analysis of data at this stage of LCA.

The collection of data for inclusion in the inventory should follow the guidelines of the purpose and scope of the study. In addition, the data used must be strictly delimited within the boundary of the system. The data that are collected, both by in situ analysis and by questionnaires are called primary data.

| Location | Functional unit | System boundaries | Impact categories | Reference |
|----------|--|-------------------------|--|--|
| USA | kg edible beef | cradle-to-gate approach | Water emissions, cumulative energy demand, land use, acidification potential, photochemical ozone creation potential, global warming potential, ozone depletion potential, abiotic depletion potential, consumptive water use, and solid waste. | Asem-Hiablie et al. (2019) |
| Portugal | kg of beef carcass | cradle-to-gate approach | Global warming potential, acidification potential, eutrophication potential, photochemical ozone creation potential | Presumido et al. (2018) |
| Italy | kg of cooked beef | farm to fork gate | Global warming potential | Vitali et al. (2018) |
| Italy | kg of live weight | cradle-to-gate approach | Land occupation, global warming, water depletion, acidification, eutrophication | Bragaglio et al. (2018) |
| Japan | kg of cold carcass weight of beef steers | cradle-to-gate approach | Global warming, acidification, and eutrophication, energy consumption | Tsutsumi et al. (2018) |
| Brazil | kg of live weight | cradle-to-gate approach | Global warming potential, fossil energy use, land occupation | Kamali et al. (2016) |
| Mexico | kg of boneless and fatless beef | cradle-to-gate approach | Climate change, human toxicity, terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, agricultural land occupation, water depletion, fossil depletion, photochemical oxidant formation, freshwater ecotoxicity, marine ecotoxicity | Huerta, Güereca, and Lozano (2016) |
| Brazil | kg of beef carcass | cradle-to-gate approach | Global warming potential, land occupation | Cardoso et al. (2016) |
| Thailand | kg of live weight | cradle-to-gate approach | Climate change, energy consumption, acidification, eutrophication | Ogino et al. (2016) |
| EU | kg beef meat | cradle to farm gate | Global warming, acidification, eutrophication, land use, non-renewable energy use | Nguyen, Hermansen, and Mogensen (2010) |

Table 1: LCA studies on the production of beef, with their respective functional units, system boundaries and impacts categories

3.4. Life cycle impact assessment (LCIA)

The Life Cycle Impact Assessment (LCIA) includes the results obtained in the LCI phase to select the impact category and calculate the potential environmental impacts. The categories of environmental impact most studied in beef production are shown in [Table 2](#).

| Category of Impact | Unity | Substances | Conversion factors |
|--------------------|------------------------|-------------------------------|--------------------|
| Acidification | kg SO ₂ -eq | SO ₂ | 1.00 |
| | | NH ₃ | 1.88 |
| | | NO _x | 0.70 |
| Global warming | kg CO ₂ -eq | CO ₂ | 1.00 |
| | | CH ₄ | 28.00 |
| | | N ₂ O | 310.00 |
| | | NO _x | 1.35 |
| | | P ₂ O ₅ | 14.09 |
| | | NH ₃ | 3.64 |
| Eutrophication | kg NO ₃ -eq | NO ₃ | 1.00 |
| | | PO ₃₋₄ | 10.45 |
| | | NH ₄ ⁺ | 3.60 |
| | | CQO | 0.22 |
| Land use | m ² | - | 1.00 |

Table 2: Impact categories with related units, contributing substances and characterization factors for the CML 2001 model ([Mogensen et al. 2012](#))

Impact assessment methods are used to facilitate the translation of inventory data into environmentally relevant results. These methods use previously defined factors that contain environmental information about the many substances and resources. The methods are characterized by their measurement principles, characterization, standardization and specific weighting factors.

Each impact category is expressed in the form of a numerical indicator, since this indicator seeks to represent the total environmental load or the significance that the use of a given resource impacts a given environment. For the conversion of the inventory data, it is preferred to use equivalence factors based on scientific knowledge and applicable to all conditions. Thus, the number obtained is a value of the category of environmental impact that becomes an environmental index through the characterization factor.

The CML 2001 model ([Guinée et al. 2001](#)) is one of the most used methods for converting the values obtained into environmentally applied results. To avoid uncertainties, this method restricts the model in the initial stages of the cause-effect chain.

Acidification is caused by the release of acid gases or influence on the degree of acidification, mainly from the burning of fossil fuels. For the production of bovine animals, the main element contributing to acidification is ammonia (NH₃), emitted from the handling of waste ([Mogensen et al. 2012](#)).

Global warming has been a widely studied environmental impact category in recent years. The main cause of this impact is the release of greenhouse gases by burning fossil materials. The most important contributors to global warming are nitrous oxide (N₂O), methane (CH₄) and carbon dioxide (CO₂) ([Wei et al. 2016](#)).

A large number of sources related to nitrogen (N) and phosphorus (P) emissions in farms and waste treatment processes causes eutrophication. In areas with high bovine density, these problems are evident due to nutrient leaching ([ten Hoeve et al. 2016](#)).

In relation to land use, the production of food and feed for animals occupies a land that could have been used for other purposes, for example, maintaining biodiversity. The quality of the ecosystem is related to biodiversity in the agricultural landscape. It can be mentioned that the

production of soybeans for pig feed contributes approximately half of the total land consumption for the production of pig meat. Thus, soy production causes the reduction of local biodiversity (Bosire et al. 2016).

The LCIA phase has to be carefully planned to achieve the objective and the initial scope of the LCA. This phase should be coordinated with other stages of the LCA to minimize the possibilities of omissions and uncertainties of the data.

3.5. Interpretation of LCA results (ILCR)

Finally, in the interpretation phase, the results are grouped and discussed. The most important points of this phase are the conclusions and recommendations relevant for supporting decision-making, always in agreement with the definition of the objective and scope of the work.

The ILCR phase begins by identifying the key issues, for example, the key processes and resources/emissions that quantitatively contribute most to the magnitude of the impacts. The interpretation includes comprehensiveness, sensitivity and consistency of the checks and also addresses the uncertainty and precision of the results (European Commission, Joint Research Centre - Institute for Environment and Sustainability 2010).

The ILCR occurs in all phases of a LCA. This is because, in comparing two alternatives for the same product, if an alternative shows a greater consumption of material and resources, a purely LCI-based interpretation can be conclusive. However, a study may also aim at comparing all impact categories, especially when there are links between product alternatives, or whether it is desirable to prioritize areas of concern within a LCA. For example, CO₂ emissions throughout the life cycle can result in a higher indicator of climate change than in another, but the alternative to minimize this impact involves more pesticides and has a greater potential contribution to toxicological effects (Rebitzer et al. 2004).

3.6. Advantages and limitations

In the food area, LCA has been used as an environmental management tool in several industries, such as milk production (Salvador et al. 2016; Pirlo and Lolli 2019), pork production (Wiedemann, McGahan, and Murphy 2018; McAuliffe et al. 2017), beef production (Presumido et al. 2018; Asem-Hiablíe et al. 2019) and other agricultural products (Borsato et al. 2019; Guarino et al. 2019).

Despite the great advantages of using the LCA, it has some limiting points. An example of those limitations is that the user often needs to simplify some of the data collected make possible the successful application of the LCA. Unfortunately, this can significantly affect the final results (Turconi, Boldrin, and Astrup 2013). In general, two approaches are used: process chain analysis and input-output analysis. The first uses engineering data and information collected directly in the actuating systems. This procedure requires more time, but generally leads to more accurate results (Finnveden et al. 2009). On the other hand, the input-output analysis system considers monetary data, taking into account the aggregate flows between the sectors (Turconi, Boldrin, and Astrup 2013). Compared with the process chain analysis, the input-output analysis produces less dependent and more complete results, but it can present less accurate results than those found in the installations (Joshi 1999).

It must be taken into account that any simplification of the collected data can lead to an erroneous result and minimization of the environmental impacts found. In an attempt to minimize errors, databases are being created to increase and improve the quality of information available to society.

According to [Andersson, Ohlsson, and Olsson \(1998\)](#), LCA presents several challenges for the food sector. The main difficulty found for this sector is the lack of information on the different processes involved. The LCA in this sector requires a thorough analysis with regard to acquisition of raw materials, transportation, industrial processing, storage, distribution and treatment of the waste produced. Multidisciplinary knowledge is essential for analyzing all the parameters involved.

The challenges are still great for the implementation of LCA, but this methodology can be an analysis used for the environmental impact assessment of the whole human production and consumption systems, contributing to encourage changes in behaviors, attitudes to minimize or eliminate most of danger arising from those environmental impacts.

4. Environmental Sustainability in Beef Production

A number of trends in the food industry have become environmental issues and improving process efficiency a constant concern in the value chain management structure of this industry. First, there was a need to invest more in the food sector, due to the increase in population and consequently the increased need for processed foods. On the other hand, there are increasingly demanding customers seeking better quality and more environmentally sustainable food ([Fritzson and Berntsson 2006](#)).

The sustainability of meat production systems has been highlighted by the impact of bovine production on the environment and the conservation of resources. Sustainable production involves the conservation of natural resources and the development of new technologies in order to achieve the continuous satisfaction of the human needs of present and future generations. In other words, sustainable meat production is defined as an “ecologically correct and economically viable form of production” ([Appleby 2008](#)). Sustainability in meat production involves aspects such as animal health, environmental protection, increased production and concern with food quality.

The main inputs and outputs of a beef production system that influence the environmental performance of this sector are shown in [Figure 2](#).

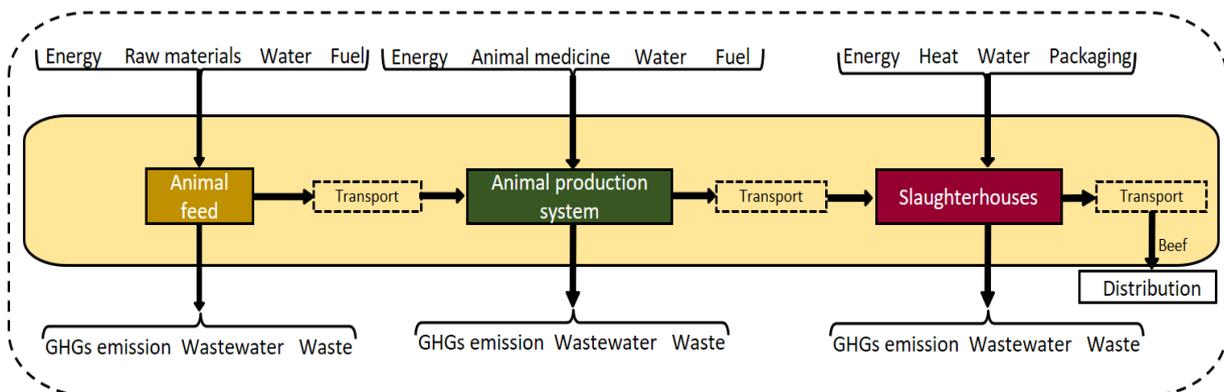


Figure 2: Main inputs and outputs of a beef production system, including animal feed, animal production and slaughterhouse

[Table 3](#) shows some studies on environmental impact caused by beef production. All studies evaluated environmental sustainability based on the LCA methodology. The categories of impacts most used to evaluate the production of beef are global warming potential, acidification potential, eutrophication potential, land use and water depletion. The high variability in some of the impact categories may be associated with the specific production characteristics of each country, as well as the uncertainties associated with the inputs and/or outputs of each system.

| Impact category | Quantity | Unit | Reference |
|--------------------------|-------------|--|--|
| Global warming potential | 22.2 | kg CO ₂ -eq kg ⁻¹ | Leip et al. (2010) |
| | 17.5 | | Peters et al. (2010) |
| | 23.0 | | Lupo et al. (2013) |
| | 23.4 | | Ruviaro et al. (2015) |
| | 25.4 | | Mogensen et al. (2015) |
| | 23.1 | | Ogino et al. (2016) |
| | 14.0 | | Presumido et al. (2018) |
| | 22.3 | | |
| Acidification potential | 101-210 | g SO ₂ -eq kg ⁻¹ | Nguyen, Hermansen, and Mogensen (2010) |
| | 170 | | Nguyen et al. (2012) |
| | 165 | | Lupo et al. (2013) |
| | 168 | | Presumido et al. (2018) |
| Eutrophication potential | 116-146 | g PO ₄ ⁻³ -eq kg ⁻¹ | Cederberg and Darelius (2000) |
| | 87-159 | | Nguyen, Hermansen, and Mogensen (2010) |
| | 104-142 | | Pelletier, Pirog, and Rasmussen (2010) |
| | 35.1-40.9 | | Lupo et al. (2013) |
| | 123-154 | | Presumido et al. (2018) |
| Land use | 111.9-274 | m ² year ⁻¹ | Huerta, Güereca, and Lozano (2016) |
| | 18.7-27.1 | | Berton et al. (2017) |
| | 32.6-194.4 | m ² a eq CB ⁻¹ | Bragaglio et al. (2018) |
| | 47.4 | | Asem-Hiablíe et al. (2019) |
| Water depletion | 2.47 | m ³ | Rotz et al. (2015) |
| | 0.084-0.111 | | Tichenor et al. (2017) |
| | 1.97-3.54 | | Bragaglio et al. (2018) |
| | 2.56 | | Asem-Hiablíe et al. (2019) |

Table 3: Impact categories used to evaluate the environmental sustainability of beef production and its main studies

Beef production is known to be a more environmentally damaging activity compared to pork and poultry production (Eshel et al. 2014). According to some studies, livestock farming accounts for approximately 18% of global greenhouse gas (GHG) (de Vries and de Boer 2010; González-García et al. 2015). The major contributors are carbon dioxide, which is largely the result of burning fossil fuels; nitrous oxide emitted by manure, urine and through the application of nitrogen fertilizers; and methane that is generated from the digestion of ruminants and waste manure.

In this sense, studies on LCA in the beef production showed that the methane generated from the intestinal tract of the animals can contribute around 60% for the GHG (Presumido et al. 2018). In an attempt to minimize the percentages of emission, some techniques have been used to intensify the production of pastures and reduce the fattening time of animals until slaughter (White et al. 2014) and consequently reduce GHG emissions.

In addition, beef production involves a wide range of by-products, which if mismanaged can be injurious to the environment. In view of this, these by-products can be used for a variety of purposes, for example for animal feed, and for the production of heat and electricity through biogas. The main purpose of using by-products is to reduce the use of resources in order to avoid the costs of treating this material and add value to the waste. For example, residual animal fat or beef tallow are considered to be a promising alternative raw material for the production of biodiesel.

Another important impact that comes from meat production is the consumption of water. The meat processing industry uses 24% of the total fresh water consumed and up to 29% of the consumption of the agricultural sector worldwide (Bustillo-Lecompte and Mehrvar 2015). And as a consequence of the great consumption of water, the wastewater from the beef

production system also appears as a relevant environmental problem. The meat industry produces large volumes of waste due to animal production and slaughterhouses. According to [Huerta, Güereca, and Lozano \(2016\)](#), residual water from cattle manure is the largest contributor to the categories of environmental impacts related to freshwater eutrophication (99.5% - 99.6%), marine eutrophication (65.4% - 81.6%) and terrestrial acidification (98.7% - 98.9%). In addition, according to the study published by the [European Commission \(2005\)](#), the average water consumption is around 1.62 - 9.00 m³ per ton of cattle carcass.

It also highlights the use of energy for meat processing, depending on its rational use, energy can also be an impacting factor of meat production. The main energy consumption of meat processing facilities is heating water for cleaning, steam production, operation of electrical equipment and refrigeration. In the production of beef, the energy consumed (electric and fuel) is between 90 and 1094 kWh per ton of cattle carcass ([European Commission 2005](#)).

LCA of beef production allows to investigate data inventories and environmental impact assessment and consequently permit to identify which of the beef production system stages are potentially the most impactful to the environment. Moreover, it is possible to identify the main differences between the various production systems and slaughterhouses that can lead to larger amounts of pollution. After identification of the impacts and their location, some improvement opportunities can be proposed to improve production efficiency and reduce the level of pollution released into the environment.

5. Conclusions

Meat production is impacting the environment in many ways, resulting in significant impacts on many environmental systems such as air, soil, water, biodiversity and climate change. Beef production is part of a large food industry, which is common in many countries where meat is an important part of the diet of their populations. All emissions require significant treatments for safe and environmentally sustainable disposal. Moreover, increasing the efficiency of animal production is an important route to reduce environmental impacts as well as production costs.

There are several positive points for the use of LCA as a tool for analyzing the environmental performance of the most diverse human activities, such as beef production. LCA has been widely used to assess the environmental performance of meat production, identifying the main environmental impacts associated to the sector.

In addition, this review showed the main functional units, system boundaries and categories of impacts most used to evaluate environmental sustainability in beef production.

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