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Life Cycle Assessment of a finishing farm and potential mitigation scenarios

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Abstract

European meat production is a resource intensive and energy demanding field that has a significant environmental impact. However, the scope of existing scientific literature on beef production is limited regarding the cattle finishing stage, which is a fundamental puzzle-piece in the grander scheme of meat production. This thesis presents a Life Cycle Assessment (LCA) of a beef finishing farm using as a case study the Cascina Camia di Testa Bruno, to identify environmental hotspots and propose plausible mitigation strategies.

A cradle-to-farm-gate system was adopted, considering processes up to the point where livestock are fattened, but excluding slaughter and distribution. The total body weight gain (BWG) of cattle was selected as the functional unit to better represent the specialized farm activity. Its environmental performance was analyzed by using standardized LCA methods, with data obtained from the Agribalyse and Ecoinvent databases. ReCiPe Midpoint (H) and Cumulative Energy Demand (CED) were employed as impact assessment methods to quantify environmental burdens.

This study identifies feed production, logistics and off-farm cattle management as the primary contributors to the potential environmental impact. The study proposes sustainable strategies, like transitioning to electric vehicles, expanding photovoltaic (PV) installations, improving transportation efficiency, and optimizing feed composition to reduce emissions.

1. Introduction

1.1 Context

The European Union is the third major largest producer of meat, with Italy between the leading European countries in beef production. Even though meat consumption is projected to decrease in future years with the promise of a more sustainable lifestyle, this field remains a resource-intensive and energetically demanding field, with a significant demand of feed and water. It makes it a large contributor to climate change emissions. For the Italian case, the activity of cattle fattening is concentrated in the North, given the favorable temperate climate and the presence of large stock farms. The objective is to increase the total weight gain (BWG) of cattle by feeding them a highly concentrated diet, like maize silage, soybean meal and wheat straw.

1.2 Objective

The thesis investigates a specific beef production system commonly found in Northern Italy, which a resource and energy intensive field. High amounts of energy is required for feed production, where fossil fuels are used for machinery equipment, fertilizers and transportation, and for cattle growth, ranging from the rearing process to manure management. The objective is to find environmental and energetic hotspots in the overall process, proposing and applying plausible mitigation scenarios to act upon, striving for a more sustainable farming activity. It could represent a positive puzzle-piece of a grander scheme of sustainable practices in this highly demanding and impacting field. To evaluate the environmental impact and energy demand of cattle growth the Life Cycle Assessment (LCA) tool was employed thanks to the OpenLCA version 2.1.1 software and employing the two databases "Agribalyse" version 3.1.1 and "Ecoinvent, allocation, cut-off by classification" version 3.8. To quantify the emissions and energy consumption two impact assessment methods were used: the ReCiPe Midpoint (H) v1.13 and Cumulative Energy Demand (CED). This research was conducted in collaboration with ABC Servizi, a consulting company based in Racconigi (CN), taking as case study the fattening farm Cascina Camia di Testa Bruno.

1.3 Structure

The thesis will be structured as follows:

- Chapter 2 presents an overview of European meat production, an early definition of what a Life Cycle Assessment (LCA) is and an analysis of the body of literature regarding the finishing phase.
- Chapter 3 introduces the Cascina Camia case study, deepens the concept and components of a Life Cycle Assessment in the context of Cascina Camia, and presents the results of the potential environmental impact.
- Chapter 4 discusses potential mitigation scenarios, like replacing fossil fuel-powered vehicles with electric ones, expanding the photovoltaic system, upgrading the transportation logistics and modifying the cattle diet.

- Chapter 5 integrates the most fitting mitigation scenarios among the ones proposed in Chapter 4, examining the synergies between different solutions and potential trade-offs.
- Chapter 6 summarizes the key findings of the thesis, underlining the main environmental and energy hotspots along with the impact of proposed mitigation strategies. It also mentions the importance of sustainable beef production, and directions for future research.

2. Research background

2.1 The context of European meat production

In the agricultural field the European Union (EU) plays a significant role, being a major producer, consumer, and trader of meat. In 2020 there were more than 76 million cattle in EU and beef production reached 6.8 million tons, making it the third largest producer after the USA and Brazil. Three European member states alone produced half of the EU's beef: France with 21,2%, Germany with 17,8% and Italy with 11,1% [1]. Meat production, specifically from cattle, represents a considerable contribution to global greenhouse gas emissions, accounting for approximately 65% of the sector's total emissions, with about 4,6 Gt of CO_2 equivalent released each year. By 2013 the global livestock sector represented an important contributor to climate change, producing about 7.1 Gt of CO_2 equivalent emissions each year, which accounts for about 14.5% of all anthropogenic greenhouse gas (GHG) emissions [2] . About 45% of the total is because feed production and 39% caused by enteric fermentation from ruminants, with an underlining importance given to the livestock supply chain, which burdens even further the overall emission of the sector.

A positive trend is expected in future years, with a decline in meat production in the EU mostly due to the increasing domestic and environmental costs and stricter environmental and animal welfare regulations [3]. In fact, in the last years, consumers have become more sensitive to environmental sustainability, with heated protests, debates and stronger environmental consciousness, impacting demand and as consequence production practices. Consumption is growing at a slower rate than in the past, with an expected annual average increase of less than 1% [4]. Because of this change in consumer preferences, along with less intensive systems, beef consumption is also expected to decline in the European Union [3].

Nevertheless, reducing beef production in Europe without addressing the growing global demand might not be effective. The ever-growing global population requires a satisfying increase in food production [5], a challenge particularly relevant for developing countries that include more animal products in their diet [4]. So, if on the one hand there's a European shift toward organic and non-genetically modified livestock production, on the other hand there's a fundamental dietary transition in developing countries, with the risk of simply offsetting the origin of meat-related emissions.

Returning to production, about 4,3% of all European farms in 2020 were categorized as cattle-rearing and fattening, also called finishing [6]. The finishing stage is resource intensive and demands significant inputs of feed and water for efficient cattle growth. In fact, it is designed to increase the body weight gain (BWG) of cattle before being sent to slaughter, by feeding them a concentrate diet usually composed of maize silage, maize grain, soybean meal and wheat straw. The most usual weight gain is up to 1.4 kg per day.

To conclude, beef production is a high resource and energy demanding, and it is imperative to analytically quantify with verifiable data the potential environmental impact. Among the wide range of available tools, Life Cycle Assessments (LCAs) guarantee a way to successfully quantify these impacts and identify important areas for improvement. The next chapter will dive deeper into the definition of Life Cycle Assessment.

2.2 The Life Cycle Assessment

The Life Cycle Assessment (LCA) is a standardized method [7] used to evaluate the potential environmental impacts of a product or service throughout its entire life cycle. This analysis can encompass the whole product's life cycle, from the extraction of raw materials to the final waste disposal (called cradle-to-gate), considering potential impacts like resource depletion and the effects on both human health and ecosystems. The LCA methodology follows ISO 14040 series standards, which provide a framework for correctly conducting LCA studies; the main standard, ISO 14040, outlines the principles and framework, while additional standards like ISO 14041-42-43 provide methods for completing different LCA phases.

Understanding how it works in practice if one wants to develop a holistic *forma mentis* that can be applied across various studying fields. Working at first hand on case studies through a LCA software offers valuable skills like fast problem-solving, critical thinking and open mindedness. It provides a whole understanding of a product or service’s environmental performance, informing decision-makers or other stakeholders like policymakers, to take information-based decisions for a more sustainable consumption and production of a product or service. For example, LCAs can help in informing consumers which product among the many is the most sustainable, gaining valuable marketing and competitiveness values and expanding its reach to more conscious customers. These studies can also help research to compare different models, broadening the scope of improvement possibilities. Moreover, it is a tool commonly used to determine if a product or a service is eligible or not for sustainability certifications, unlocking financial opportunities to those that have shown to aim at green practices.

Such comprehensive tool offers an objective and technical approach to wickedly complex problems, of complex and interconnected ever-changing systems.

In this case the thesis contributes to understanding which environmental hotspots can be improved upon, quantifying emissions, resource use, and other environmental burdens resulting from production processes. Plus, it can contribute to the ever-growing scientific literature by giving specific data insights tailored around specific real-life scenarios.

2.3 Literature analysis

After defining in broad strokes what a Life Cycle Assessment is, a research was performed on the topic of beef production, which gave numerous and growing results, which have significantly increased since 2003 [8]. The majority focus on the entire production cycle (cradle-to-gate), with a limited number focusing specifically on the finishing phase [9].

Regarding European countries: a study analyzed mixed production systems in Spain [8], one on intensive fattening units in Northern Italy [10], one was conducted in France focusing on the changes in the environmental impact of three different bull-fattening systems by varying the feeding composition [11], and one studied three different beef production systems, which include Italian fattening farms [12]. A summary of these studies can be appreciated in Table 1 and their potential mitigation scenarios in Table 2.

A study [9] from the sources found that LCAs that only considered the fattening stage tended to show an overall reduction in greenhouse gas emissions when comparing improved management practices to conventional ones. However, the sources acknowledge this trend was not statistically significant.

It’s also mentioned that the length of the fattening period can influence environmental outcomes, as longer finishing times on pasture are often associated with higher enteric methane emissions compared to shorter, concentrate-based feeding in feedlots.

A major concern is the emission of greenhouse gases due to the release of methane (CH_4) from enteric fermentation, which depends on the diet composition. For example, a higher concentrated diet would result in an increase in cattle growth rate and lower emissions per unit of weight gained, but the production of such feed is very energy-demanding and contributes to other environmental issues, like higher acidification due to fertilizers [11] [8]. Rather than a concentrate-based diet, a forage-based one could be chosen, since grassland for grazing would require a lower energy demand and land occupation.

Focusing on the high-concentrated diets, which can be composed of cereals and by-products, do guarantee a fast growth rate and fattening, but if they are effective for the body weight gain, problems arise on themes like sustainable resource use and nutrition efficiency. The high demand for cereals, which are the predominant ingredient in this type of diet, shouldn’t be underestimated since cultivation is highly resource-intensive, requiring an important amount of water and land for growing. Literature regarding this topic has shown mixed results. For example, one study [13] found that the average daily gains in young bulls did not differ much from they were fed a high-concentrate diet or a high-forage low-starch (HFLS) diet. It has been shown that a well-formulated diet based on forage can support a reasonable growth rate while lowering the dependence on concentrates. Another study [14] with Agnus cattle underlined that increasing the amount of concentrates did not significantly improve the daily weight gain, probably due to the lower digestibility of nutrients and the energy demanded. High-concentrate diets tend to reduce the total feed intake because of their high energy density, but it doesn’t equate to better feed conversion. For example, bulls on HGS consumed more dry matter and showed higher feed conversion ratio than bulls fed on high-concentrate diet, in spite of similar average daily gains. It shows a trade-off in optimizing feed efficiency between the energy density and the volume of intake feed. Plus, high-concentrate diets can have adverse effects on nutrient digestibility, since it has been reported that an increase in such diet is associated with a reduction in the digestibility of dry matter, crude protein and fiber. It can be due to reduced rumen retention time, thus limiting the time needed for microbial digestion. From a sustainable point of view, an HFLS diet, which includes forage and agro-industrial by-products, could offer a better solution in lowering external inputs and promoting circular food systems, but further research is needed on the methane emissions caused by such feed composition.

Another contributor to the environmental impact is ammonia (NH_3) from manure, which plays a significant role in acidification and eutrophication. Factors like feed intake and animal growth influence the amount of nitrogen excreted in manure [15]. And so, the chosen manure management, like solid manure or slurry, system strictly affects the amount of emissions released.

Off-farm activities like transportation of feed and animals are also taken into consideration, since the supply chain of food and cattle, along with the transportation system, strongly contribute to the emissions and energy consumption [15] [11].

Nevertheless, other on-farm activities should not be disregarded. A research on milk production in Emilia-Romagna found that diesel consumption from operating machines represented almost half of the total impact, with the animal feed being 15%.

An environmental impact assessment on intensive dairy cattle farms for milk production in Emilia-Romagna [16] found that the local consumption of fossil fuels is the most impactful. Diesel consumption from the farm operating machines (about 49%), production of packaging film (27%) and animal feed (15%) of the total impact.

Regarding the energy consumption, the integrated French-Italian production system had a significant Cumulative Energy Demand (CED) due to the energy-intensive production and import of feed from other European countries, since Italy lacks the necessary nutrients for a fattening diet. It unfortunately leads to the homegrown process to be twice as impactful [15] [17].

These results show how wickedly complex a finishing process is, balancing between an efficient diet that maximizes the animal growth rate, which depends on the length of the fattening period and the feedstuff, and the emissions caused by the production of this same feedstuff and its digestion. In fact, an excess of nutrients is counterproductive, since it would lead to higher nutrient excretion in manure and contribute to eutrophication.

Some studies do offer a vast range of mitigation strategies to overcome the environmental effects and energy consumption during the fattening stage, and some are categorized as traditional while others as innovative. The traditional strategies have a historical record in terms of practices, which can be adjusting the feed ratio between the forage and concentrate, reasoning on the type of animal, costs and forage availability [18]; incorporating locally available by-products or alternative feed to reduce prevent long transportation distances; and adjusting the feed duration based on the growth rates, market and feed availability [12] [11]. While more innovative strategies take advantage of new scientifically based approaches, like adopting oils and lipids in the diet to lower methane production [2]. A summary of some mitigation solutions is shown in Table 2.

Renewable energy resources are an encouraged solution to mitigate the environmental footprint. The use of anaerobic digestor is widely applied for biogas and digestate production, giving emphasis to a sustainable circular economy that minimizes and incorporates waste in its system. Plus, studies have shown that the synergetic combination of anaerobic digestion and rooftop photovoltaics can reduce a farm's global warming potential by 12% and reduce its fossil fuel-based use by 35% [19].

In conclusion, few LCA studies, as mentioned before, among the many focus on the finishing phase, specifically in the context of beef production in Italy. Great importance is given to beef production, fundamental for cattle growth, but the limited system boundaries don't allow for a more detailed analysis of the off-farm logistics. A more detailed look should be given to the Northern Italy activity, especially considering that the combination of anaerobic digestion and photovoltaic systems is extensively widespread, and not many finishing phase related studies do acknowledge the potential effect of these two resources. Plus, interesting mitigation scenarios are mentioned but are not implemented in their corresponding simulations, lacking the quantitative results, like emission savings, to better discuss their performance. It would be beneficial to conduct a farm-specific LCA that specifically focuses on the finishing phase, collecting on the field primary data. It would be interesting to discuss the qualitative and quantitative trade-offs that would come from a dietary change, starting from the feed production to the manure management emissions, and to implement new efficiency improvements regarding the supply chain. A new study would further expand the limited LCA literature body on the finishing farms, specifically in Northern Italy, where the activity is more concentrated, that integrates circular economy approaches. New sustainable practices could create a long-term domino effect across farmers and customers, and a valuable scientifically based and informative puzzle-piece in the context of meat production.

Source	Country	Focus	System Boundary	FU	Databases	Software	Allocation Method	Impact Method	Impact Categories										
									CC	**Fw-Eu**	**M-Eu**	**SOD**	**POF-Ecosys**	**POF-HH**	**GWP**	**AP**	**EP**	**CED**	**LO**
Tinitana-Bayas et al. (2024) **[8]**	Spain	Mixed beef production in Spain	Cradle-to-slaughterhouse gate. Includes feed production, transportation, and on-farm energy use for four systems, one of which is fattening	1 kg beef carcass	Managed LCA Content 2023.1, ecoinvent v3.8, MAPA (2019b)	LCA for Experts 10.7	Economic allocation is used to attribute impacts between the co-products of calves and cull cows.	ReCiPe 2016 v10 (hierarchist)	✓	✓	✓	✓	✓	✓					
Gallo et al. (2020) **[15]**	France, Italy	Integrated France-Italy beef production system	Cradle-to-farm gate. Includes herd management, on-farm and off-farm feed production, and materials used for on-farm activites. Specifically covers both French suckler cow-calf and Italian fattening phases, including transport.	1 kg of body weight (BW) sold	Charolais Network database (INRA)		The allocation problem was addressed using a mass allocation method as the primary approach.								✓	✓	✓	✓	✓
Berton et al. (2017) **[10]**	Italy	Intensive beef fattening sector	Arrival of calves to sale to slaughterhouse, farm-gate. Includes on-farm feed production and use, off-farm feed production and transport, materials used, and herd management. It doesn't include stock calves production and transport and slaughterhouse activites.	1 kg of body weight gained (BWG)	Ecoinvent, Agri-footprint	SimaPro									✓	✓	✓	✓	✓
Nguyen et al. (2012) **[11]**	France	Analysing the environmental impacts of three different bull-fattening systems in France	Cradle-to-farm gate, including production and delivery of feedstuff components, production and delivery of inputs for feed production, upstream processes, manure management and use for feed production. Building construction and maintenance, veterinary medicines, animal transport, slaughter of the animals are excluded.	1 kg of body weight gain (BWG), ha of land occupied	Not specified											✓	✓	✓	✓

Table 1 – Summary of LCAs on beef fattening systems

CC (Climate Change) measured in kg CO2 eq. (kilograms of carbon dioxide equivalent); Fw-Eu (Freshwater Eutrophication) measured in kg P eq. (kilograms of phosphorus equivalent); M-Eu (Marine Eutrophication) measured in kg N eq. (kilograms of nitrogen equivalent); SOD (Stratospheric Ozone Depletion) measured in kg CFC-11 eq. (kilograms of CFC-11 equivalent); POF-Ecosys (Photochemical Ozone Formation on Ecosystems) measured in kg NOx eq. (kilograms of nitrogen oxides equivalent); POF-HH (Photochemical Ozone Formation on Human Health) measured in kg NOx eq. (kilograms of nitrogen oxides equivalent); GWP (Global Warming Potential) measured in kg CO2 eq. (kilograms of carbon dioxide equivalent); AP (Acidification Potential) measured in kg SO2 eq. (kilograms of sulfur dioxide equivalent); EP (Eutrophication Potential) measured in kg PO4 eq. (kilograms of phosphate equivalent); CED (Cumulative Energy Demand) measured in MJ (megajoules); LO (Land Occupation) measured in m^2/year (square meters per year).

	Mitigation Action Scenarios
Tinitana-Bayas et al. (2024) **[8]**	• Dietary control: ○ Opting for cattle breeds that would require less feed maintaining the same body weight gain, so to lower GHG emissions and land use. ○ Lower protein and phosphorous content in the diet to have lower emissions from manure. ○ Promote the use of local by-products to have less impactful logistics. ○ Choose a diet that reduces methane during digestion. • Improved management of manure: ○ Use anaerobic digestion to break down manure and slurry and produce biogas. ○ More efficient manure application.
Gallo et al. (2020) **[15]**	• Efficient use of resources: ○ Use locally available sources and by-products to lower energy consumption and the impact of the supply chain. The study suggests a synergic cooperation between Italian farms and local crop producers. ○ Increasing on-farm feed production for stronger self-reliance and reduce the impact of logistics. • Improved diet or use of feed additives to increase the body weight gain of livestock keeping constant the amount of feed. • Crop rotation to lower emissions from fertilizers. • Improved management of manure: ○ Use anaerobic digestion to break down manure and slurry and produce biogas. ○ More efficient manure application.
Berton et al. (2017) **[10]**	• Diet improvement: ○ To lower the excess of nitrogen excretion it is suggested a tailored diet around the actual livestock needs. • Improved agriculture techniques: ○ Optimize the use of fertilizers. ○ Crop rotation to lower emissions from fertilizers. • More self-reliance on local cereal production to lower the emissions caused by logistics.
Nguyen et al. (2012) **[11]**	• Diet improvement: ○ To reduce land occupation and cumulative energy demand it is suggested to pass from concentrate-heavy diets to maize silage-based diet. • Improved storage for manure to avoid ammonia volatilization.

Table 2 - Mitigation Action Scenario based on studies

3. The case study: Cascina Camia di Testa Bruno

Considering the literature gap previously identified, regarding the potential environmental impact of the finishing phase, the following chapter will examine a specific case study in Northern Italy to better address the issue. In fact, with the application of a Life Cycle Assessment not only is it possible to quantify potential environmental burdens and energy-consuming operations, but also to analytically explore and evaluate tailored improvements.

The Cascina Camia farm is in Racconigi in the province of Cuneo, managed by the sole owner, Bruno Testa, with the support of family members, and a team of agricultural workers and administrative staff. It specializes in beef fattening and raises both male and female Limousine cattle, a breed known for its high-quality meat and carcass yield. In the reference year 2023, Cascina Camia raised 4.100 Limousine cattle in free-stall housing with permanent bedding, utilizing 47 hectares of agricultural land. The Limousine breed, named after its origin area, which the Limousin region of France, is widely regarded as a top choice for beef production globally.

Since 2011, Cascina Camia has expanded into renewable energy production by employing photovoltaic (PV) systems, which operates with three rooftop photovoltaic panels and two ground-based systems, and a biogas plant. The farm's energy production and consumption are as follows:

- A 42,04-kW rooftop PV system for self-consumption through onsite exchange.
- A 149,04-kW rooftop PV system that supports both self-consumption and energy sales.
- A 604,8-kW ground PV system with tracking panels for both self-consumption and energy sale.
- A 3.000 kW ground PV system dedicated entirely to energy sale.
- A biogas plant that self-consumes about 12% of the energy produced, with the remainder sold to the energy grid.

Figure 1 - Cascina Camia [51]

To begin with, when 50 calves from France arrive at the farm they are placed in arrival boxes, typically with an average age of 9 to 12 months. The next day, they undergo vaccinations and veterinary check-ups and within a week, they are moved to breeding boxes. Over the following six months, the calves are fed a balanced diet of cereals, legumes, vegetables, straw, and supplements, until they reach the desired weight and are sent to the slaughterhouse. A more detailed look at the diet can be appreciated in Table 3.

Considering the reference year 2023, the farm received 4.100 heads of cattle, weighing a total of 1.640.000 kg. As these animals are raised and fattened, they ultimately reach an output weight of 2.870.000 kg, reaching a total body weight gained (BWG) of 1.230.000 kg and 300 kg of weight gained per head.

Category	Ingredients	Description
Cereals (37,0%)	Spelt	Most of the feed energetic content comes from cereals, which contain carbohydrates fundamental for weight gain. Corn and barley are easy to digest and rich in starch, and bran adds fibrous quality to the diet, spelt is moderate in protein content and carbohydrates.
	Corn	
	Barley	
	Bran	
Legumes (24,4%)	Soybeans	Primary source of protein.
	Carob	Containing fiber and natural sugars.
Vegetables (10,7%)	Beet pulp	Containing digestible fiber.
Supplements (3,9%)	Urea	Source of protein that helps to break down fiber.
	Bicarbonates	Mineral supplements.
	Salt	
	Clinoptilolite	Natural minerals help cattle digestion and reduce toxins.
Roughage (24,0%)	Straw	Healthy fiber-rich feed that helps rumen chewing.

Table 3 - Cattle diet

To support the cattle's nutritional needs, Camia Farm utilizes a variety of feed sources. As can be seen the primary component is cereals, which account for 2.871.365 kg of the feed supply, including grains like spelt, corn, bran, and barley. Additionally, legumes such as soy and carob contribute 1.890.540 kg, providing essential protein. The farm also incorporates 833.051 kg of vegetable feed, primarily from sugar beets, to enhance the diet further. Plus, a small percentage of corn, barley and wheat is self-produced on-site.

In addition to the main feed components, the farm relies on 1.866.525 kg of straw for food and 494.495 kg for bedding, ensuring the welfare of the cattle. Moreover, 300.920 kg of feed supplements, that include vitamins, salts, and bicarbonates, ensure the optimal cattle health and growth during the fattening process.

Figure 2 - Anaerobic digestor

The vehicles used for worker displacements are gasoline and diesel-based, varying in size and type depending on the employee's role and travel needs.

The following tables show the equipment used in the farm and the assets, along with the functioning of the biogas, which can be more appreciated in Figure 3.

Fuel Type	Equipment
Gasoline	BCS Cultivator to prepare soil for crops
	Hedge Trimmer
	Chainsaw
	Brush Cutter
	Lawn Tractor
Diesel	Sweeper
	Agricultural Machinery to move large volumes of feed, bedding and manure
	Agricultural Dryer to dry harvested crops

Table 4 - Equipment

Asset Type	Vehicle Description	Description
Agricultural	Mixing wagon	Responsible for mixing and distributing feed to cattle
	Tractor	Used for transporting feed, supplies and equipment around the farm
	Slurry tanker	Used for handling and spreading slurry (liquid manure), which is processed for biogas
	Storage facility	For storing imported raw materials such as feed and bedding
Industrial	Wheel loader	Used for loading and moving heavy materials such as silage, feed, or manure
Goods Transport	Volvo truck	Vehicle for transporting calves to the slaughterhouse

Table 5 – Assets

Category	Description	Details
Input	Slurry	Liquid manure from livestock
	Manure	Solid manure, mixed with slurry to produce biogas
Process	Biogas Production	Anaerobic digestion of slurry and manure
Output	Digestate	Residual material after digestion, used as fertilizer for locally cultivated crops.
	Biogas	Methane-rich gas produced during digestion
Conversion	Electricity	Biogas is converted into electricity through a combined heat and power (CHP) unit
	Heat	Heat generated from the biogas combustion in the CHP process
Usage	Self-consumed Electricity	A portion of the generated electricity is used to power itself
	Excess Electricity	Surplus electricity sold to the grid
	Heat Utilization	Heat used in the farm infrastructure

Table 6 - Biogas

The Cascina Camia farm is supported by diverse supply chain that ranging from various regions in France and Italy for livestock and feed. Livestock are mainly sourced from France, specifically from Nouvelle- Aquitaine, Auvergne-Rhône-Alpes, Occitanie, and Bourgogne-Franche-Comté regions. Transport distances in these areas reach about 640 km and great volumes of cattle transportation. This dependence on multiple locations puts a burden on the logistics of the farm, especially from Nouvelle-Aquitaine, a region significantly accountable for overall transportation needs. Transport for feed and supplements coming from Piedmont is, on the other hand, shorter, requiring travel distances ranging from just 7,4 km to 46 km. This local sourcing strategy means fresh supplies can be delivered at a lower transport cost. Additionally, the farm has established a capacity of over 2 million kg in feed coming from Italian suppliers: for example, 46.800 kg of nutritional supplements come from Emilia-Romagna and 572.270 kg of feed from Marche.

Furthermore, the farm has a small agricultural area where they cultivate crops. The farm utilizes 47 hectares of agricultural land where about 15% of corn, barley, and wheat is self-produced on-site to contribute to the cattle's diet. It integrates a circular philosophy by using digestate from its biogas plant as fertilizer. Specifically, the farm produces 11.680 m^3 of liquid digestate and 4.745 t of solid digestate through the anaerobic digestion of manure and slurry.

On the waste management side, paper waste amounts to 1.000 kg and falls under urban waste disposal, while 2.000 kg of plastic is processed through specialized recycling; 12.500 kg of wood is completely reused; metal waste reaches a total of 1.500 kg and phytosanitary and medicinal products amount to 90 kg. To conclude, for the office items a comprehensive list was created, ranging from paper reams to printer inks.

A simplified diagram of Cascina Camia farm processes and emissions can be appreciated in Figure 3. On the left side there are the inputs: the cattle and food supply can be seen, together with transportation, which includes the displacement from home to work, and for customer and supplier services. In the central section there are the farm operations: the mixing wagon is used to mix feed and raw materials are stored in a storage facility, while the tractor is used for transporting feed, supplies and equipment. It also highlights the closed-loop system, where the manure and slurry are fed to the biogas production plant to produce biogas, which is used for producing heat and electricity, and digestate as by-product, used for on-farm crop production. On the right side there are the outputs: the fattened calves that are about to be transported for slaughter, waste and the emissions caused by the overall process: for example, manure management that causes the release of methane (CH_4) and nitrous oxide (N_2O), and CO_2 from feed production, transport and also off-farm activities.

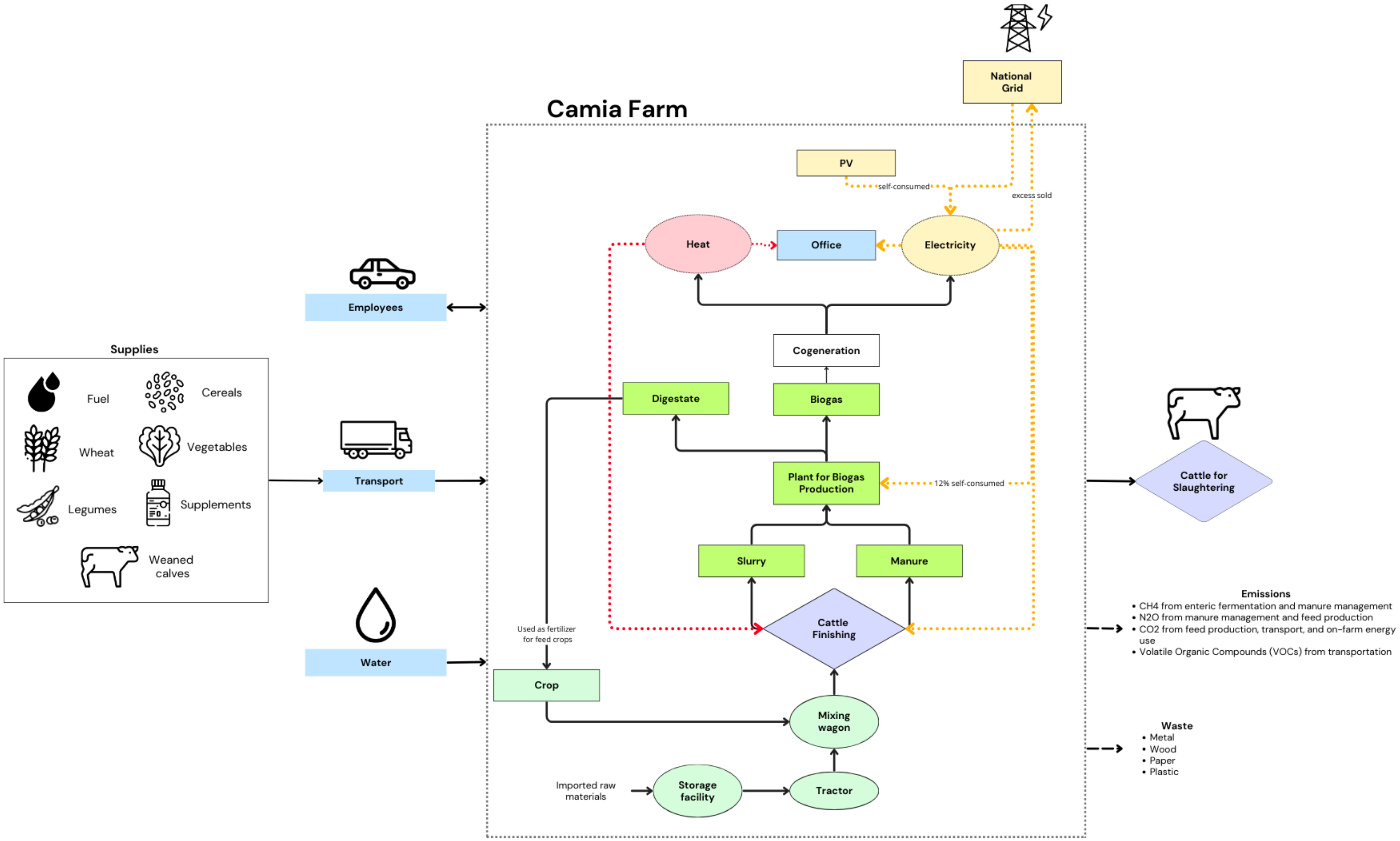

Figure 3 - Diagram of Cascina Camia farm processes and emissions

3.1 The LCA applied to Cascina Camia

The objective of the thesis is to assess the potential environmental performance and energy consumption of a finishing farm located in Northern Italy through the standardized Life Cycle Assessment (LCA) methodology. After identifying the most relevant environmental and energetic hotspots, different mitigation strategies are evaluated and applied. This study provides an understanding of the sustainability of finishing farms, filling a gap in existing LCA literature, which is broader in scope and often overlooks this specific activity.

According to ISO 14040 standards, the whole system was analyzed with respect to the appropriate functional unit, ensuring consistency and comparability of the results. The functional unit of the total Body Weight Gain (BWG), measured in kilograms, was chosen. It directly reflects the primary objective of the farm and is commonly used in LCAs on beef fattening processes, giving a more accurate picture of the farm's productivity.

The system boundary for this LCA follows a cradle-to-farm-gate approach, starting from the production of raw materials and covering on-farm processes for the reference year 2023. The boundary ends when the final product (which is fattened calves in this case) is ready to leave the farm, excluding stages like transportation to the slaughterhouse and any subsequent off-farm activities, such as slaughter, processing, and distribution.

For the study the following assumptions were made:

- For simplicity a constant number of calves entering and leaving the farm during the year was assumed to be constant.
- Carcass disposal was excluded from the system.
- Livestock rearing was included in the perimeter, but not the slaughter stage and transport to the latter as it is outside the scope of this specific farm.
- Waste transport was considered an off-farm activity.
- The use and disposal of phytosanitary products and other special wastes were not included because the databases used lacked specific data.
- Pesticides and cleaning products were excluded.
- The total water consumption during the reference period includes water used for livestock (drinking troughs, cleaning, etc.), irrigation, and office operations.
- In the context of evaluating the fattening unit’s operations, the contribution of office items is assumed to be minimal when compared to the overall environmental footprint and energy consumption, concentrating only on production processes of these materials, excluding stages such as transportation and distribution

3.2 Data collection

The data collection stage involves the collection and quantification of data on the inputs and outputs associated with the system’s entire life cycle. The collected data will be used to quantify the environmental impact of the farm company's operations.

This phase is divided into two main systems: the foreground system and the background system. The foreground system includes processes and activities that are typically within the control or direct influence of the organization. This system relies on primary data collected through direct measurements, company records, and detailed supplier information. This data is specific and accurate, tailored to aspects specific to the organization. Moreover, practical changes can be made to update the model. In fact, the collection of this primary data provides a more accurate and realistic reproduction of the company's actual performance, and it also ensures specificity of improvements. On the other hand, the background system includes general processes and activities not directly controlled by the organization. These may include the production of raw materials, energy generation, and transportation. Data for the background system is usually obtained from life cycle databases and industry averages, providing a more generalized view.

At first, a preliminary meeting was held, which concerned the farm’s overall operations and internal dynamics. This was followed by interviews with the staff, where essential qualitative information was obtained while establishing a relationship based on trust and collaboration. Afterwards, regular communication was maintained through emails, phone calls, and constant meetings, which helped to better define the farm’s system boundaries and to keep up to date with the situation. To ease the data collection process, an Excel file with a checklist was shared, which helped to provide a comprehensive overview. This data collection phase was guided by the internationally standardized protocol UNI EN ISO 14064 [20], making sure of the compliance and reliability of the information gathered. Additionally, details regarding the quantity of feed were received via email, allowing for the completion of the necessary quantitative analysis for an overall evaluation of the company’s situation. The name of cattle and food suppliers was disclosed but will be omitted in this thesis for privacy reasons.

The checklist was designed to collect data from the company, and it was organized into four main categories according to the UNI EN ISO 14064, each focusing on specific aspects of the farm's operations to quantify emissions and resource consumption:

- Category 1- Direct GHG emissions and removals: company's assets, expenses related to natural gas and fuel, as well as the amount of biogas produced from animal waste.
- Category 2 - Indirect GHG emissions from imported energy: it was asked about the amount of electricity purchased in the reference year.
- Category 3 - Indirect GHG emissions from transportation: transportation details on both suppliers and employees.
- Category 4 - Indirect GHG emissions from products used by the organization: the annual quantity of waste by type of disposal, details of packaging waste, and the annual quantity of purchased goods expressed in weight and pieces.

ISO 14064 focuses on GHG emissions, allowing us to gain important information on the system’s inner workings, but it was more importantly useful to build an all-encompassing system for evaluating other potential environmental impacts other than GHG emissions.

In conclusion, the data used in this research is predominantly foreground data, which was helpful to develop a detailed and farm-specific model. Background data was also used from databases and literature where information was unavailable, allowing for a better comparison with other LCA studies.

3.3 Life Cycle Inventory

The OpenLCA software (version 2.1.1) is a professional open-source tool designed for collecting and analyzing the potential environmental performance of products and services. It allows users to model and assess complex life cycles in a transparent and systematic way, following the standardized ISO

14040 and ISO 14044 procedures. The software offers its results in both graphical and numerical formats, identifying the potential environmental hotspots in different life cycle stages.

This study resembles an Attributional LCA (aLCA), which involves taking a detailed snapshot of the system as it currently operates, focusing on the direct environmental impacts of its life cycle stages. The primary objective is to understand and improve the existing environmental performance, identifying the areas of improvement.

One of the key stages in Life Cycle Assessment (LCA) is the Life Cycle Inventory (LCI), which involves the detailed compilation and quantification of inputs and outputs associated with a product system. For this phase, the OpenLCA software had as its resource an extensive amount of databases that store environmental information about various materials, processes, and products. The two databases utilized for calculating environmental impacts were:

- Agribalyse v3.1.1, a comprehensive LCI database from France, particularly relevant for the agricultural sector, focusing on agricultural and food production and consumption.
- Ecoinvent v3.8, a global LCI database containing over 20,000 datasets across various sectors, widely used for environmental impact analysis and sustainability assessments.

Another key stage is choosing the most fitting system model. It is fundamental to define the rules for calculating the Life Cycle Inventories and to show environmental impacts are distributed throughout the life cycle. The widely used “Cut-off” system model was chosen. It works on the Polluter Pays Principle, meaning that the producer of waste is the primary responsible for its treatment, and the Cut-off point is at the end of the activity that produced recyclable material [21].

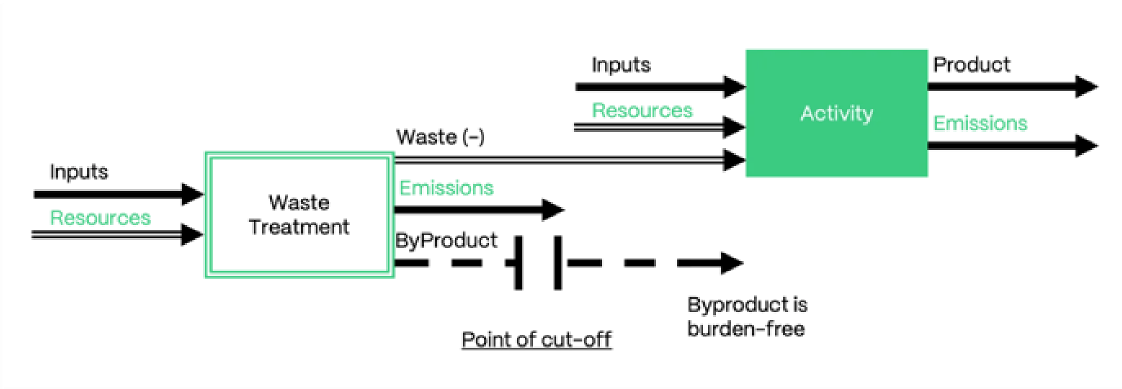

Figure 4 - Handling of waste by the Cut-off method [21]

Since priority is given to primary (foreground) data, and to avoid "double counting" of energy and material flows, "Unit" data aggregation was selected from databases instead of "System" data aggregation. The "System" (S) type of data aggregation is like a black box that contains predefined and non-modifiable internal processes, whereas the "Unit" (U) type is more transparent, allowing for easier management of process and internal material flows. For example, for straw production (Straw, stand-alone production, S) transportation to the consumer (in this case the Camia farm) was intrinsic to the "System". By choosing a "Unit" system, the transportation, which had a predefined generic value, was removed and later added in the appropriate category using the company's primary transportation data.

In Table 7 it is possible to the LCI of the analyzed farm. The emissions were calculated as shown in the subchapter A2. Equations and a more detailed look to the processes can be appreciated in A1. Life cycle Inventory of Camia, both present in the Appendix chapter.

The following table shows the LCI of the Camia system, modulated according to the chosen functional unit of body weight gain (BWG), measured in kilograms. The process Cattle Supply refers to the purchased cattle that is then transported to the farm, where different amounts of cattle were attributed to their transportation, and the same approach was followed for the process Food Supply. For the logistic transportation Euro 5 standard freight lorries were chosen after a discussion with the company. The process Company Assets includes machinery, modes of transport and other equipment used for on-farm activities. The covered distances by vehicles were given by the company after compiling the survey, along with the amount of transported feed, cattle and fuel. The process Fuels includes all the fossil-based fuels combusted in agricultural machinery, making sure that is data is coherent with the databases in order to avoid double counting.

	Process	**Amount**	**Unit**
Input	Cattle Supply	8,13E-07	Item/kg BWG
	Company Assets	8,13E-07	
	Food Supply	8,13E-07	
	Fuels	8,13E-07	
	On-farm Cereals (corn, barley and wheat)	8,13E-07	
	Electricity from Anaerobic Digestion, medium voltage	1,88E-02	kWh/kg BWG
	Electricity, low voltage {RoW}| electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted | Cut-off, S	2,52E-02	
	Electricity, medium voltage	1,43E-01	
	Heat from Anaerobic Digestion	5,34E-02	
	Fuel transport - transport, freight, light commercial vehicle	1,30E-03	t*km/kg BWG
	Water, completely softened	8,13E+00	kg/kg BWG
Output	Manure, liquid, cattle	6,53E-02	kg/kg BWG
	Slurry, from cattle, stocked in concrete pit (fertilizer) - RER	9,50E+00	
	Disposal, ferrous metals {FR} U - FR	1,22E-03	
	Disposal, paper {FR} U - FR	8,13E-04	
	Disposal, plastic, recycling {FR} U - FR	1,63E-03	
	Hazardous waste, for incineration	7,32E-05	
	CH4 emissions from enteric fermentation - Enteric emissions, other farmed animals	1,23E+00	
	CH_4 from Manure Management - Methane, non-fossil	1,37E-03	
	Indirect N_2O from Leaching - Nitrogen oxides	6,65E-05	
	Indirect N_2O from Volatilization - Nitrogen oxides, IT	1,06E-04	
	Direct N_2O from Manure Management-Nitrogen oxides, IT	9,62E-04	

Table 7 - LCI of Cascina Camia

3.4 Life Cycle Impact Assessment

The ReCiPe Midpoint (H) v1.13 method was developed by a group of Dutch universities and organizations in 2008 to expand on the CML (Institute of Environmental Sciences Leiden) methodology. Specifically, the Hierarchist (H) midpoint method was selected over the other ReCiPe methods due to its emphasis on scientific consensus to interpret results.

The impact categories chosen from this methodology were:

- Agricultural Land Occupation (ALOP) to assess land use for farming.
- Climate Change (GWP100), to calculate greenhouse gas emissions over a 100-year period.
- Fossil Depletion Potential (FDP) to evaluate the consumption of non-renewable fossil resources.
- Freshwater Eutrophication Potential (FEP) to measure nutrient pollution in freshwater.
- Metal Depletion Potential (MDP) to assess the scarcity of metal and mineral resources.
- Particulate Matter Formation Potential (PMFP) to quantify the formation of air pollutants harmful to human health.
- Photochemical Oxidant Formation Potential (POFP) to track the formation of ground-level ozone (smog).
- Terrestrial Acidification Potential (TAP100) to measure the impact of acidifying emissions on soil and water ecosystems.

Furthermore, the Cumulative Energy Demand v1.12 method was used to capture the total energy used throughout the system, including both renewable and non-renewable sources, and "fossil" category was chosen to quantify the amount of fossil-fuel energy consumed. Some impact categories were specifically chosen to facilitate a more comprehensive discussion in relation to the potential mitigation scenarios presented in the next section.

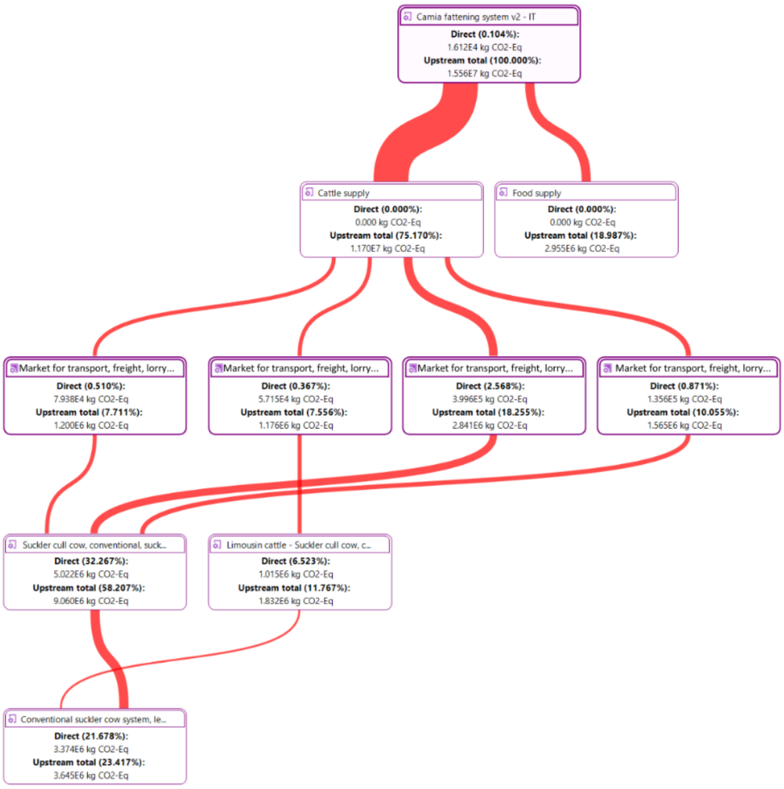

Figure 5 - Sankey Diagram of Camia farm with GWP as Impact Category

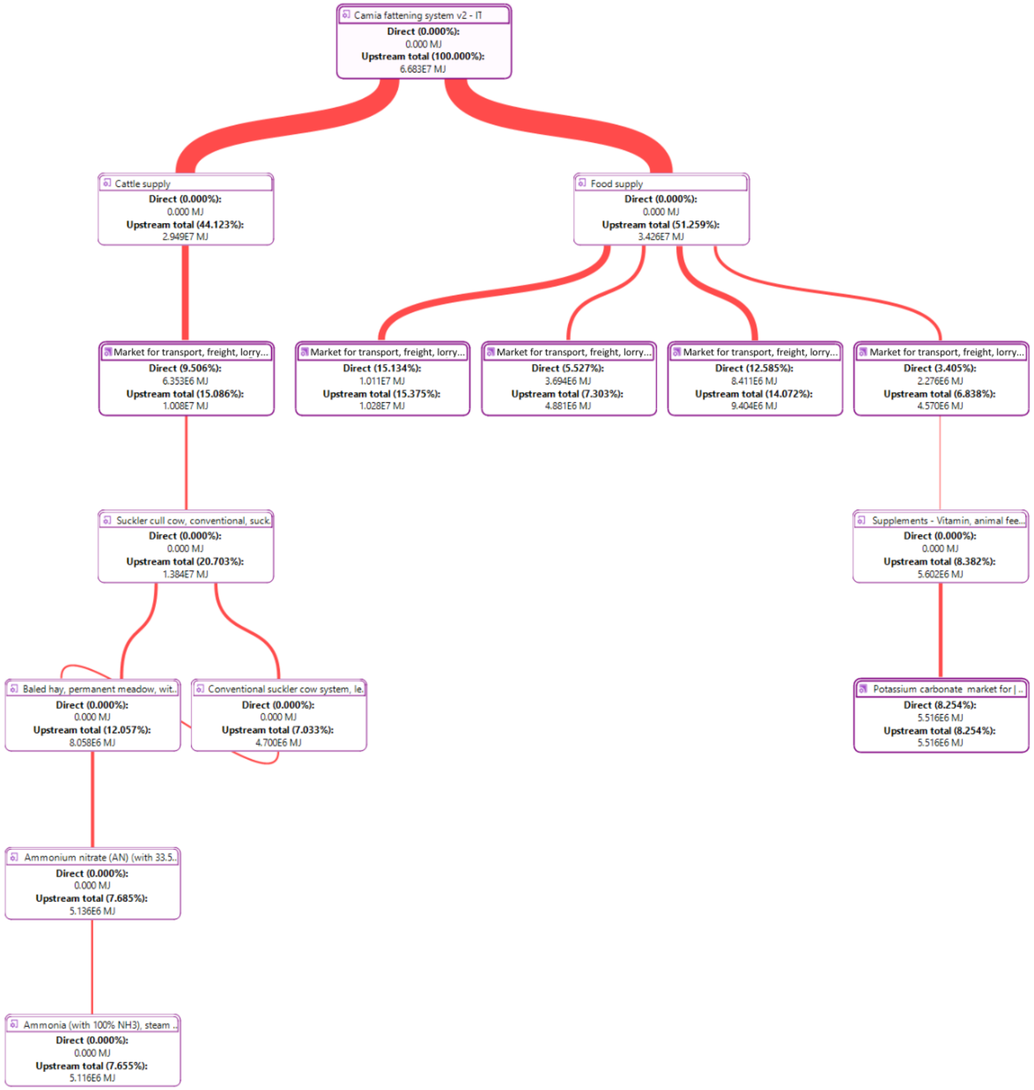

Figure 6 - Sankey Diagram of Camia farm with fossil energy from CED as Impact Category

Method	Impact Category		Unit	Result
Cumulative Energy Demand	Non-renewable	Fossil	MJ	66.822.100
	Renewable	Wind Solar Geothermal	MJ	572.524
ReCiPe Midpoint (H) V1.13	Agricultural Land Occupation (ALOP)		m2a	42.405.900
	Climate Change (GWP100)		kg CO2 eq	15.560.000
	Fossil Depletion Potential (FDP)		kg oil eq	1.588.440
	Freshwater Eutrophication Potential (FEP)		kg P eq	828,14
	Metal Depletion Potential (MDP)		kg Fe eq	164.604
	Particulate Matter Formation Potential (PMFP)		kg MP10 eq	26.313,5
	Photochemical Oxidant Formation Potential (POFP)		kg NMVOC eq	32.845,3
	Terrestrial Acidification Potential (TAP100)		kg SO2 eq	156.472

Table 8 - Results of the LCIA

For all the impact categories chosen the most relevant processes for the Camia farm are the food supply chain and the off-farm raising of Limousine cattle, with company assets contributing a smaller percentage. The food supply chain encompasses processes like production and transport of cattle feed. It has a significant environmental impact because:

- The production of feed crops, more specifically cereals, requires a substantial amount of land, contributing to the Agricultural Land Occupation (ALOP) impact category.
- The growth of feed crops is energy-intensive, and the supply chain requires an important consumption of non-renewable fuels, justifying the contribution of fossil energy consumption and the release of emissions.
- The use of mineral fertilizers for feed crop production contributes to freshwater eutrophication (FEP).

Plus, raising Limousine cattle also holds a significant impact since:

- Raising cattle requires resources like water and energy, which contributes to the overall environmental footprint of the farm.
- Ruminants produce methane during digestion, which is a highly impactful greenhouse gas, contributing significantly to Climate Change (GWP100).
- Manure storage and processing release methane and ammonia, which contribute to also acidification and eutrophication potential.

The company assets, which include both agricultural and industrial equipment, as well as company vehicles, make a low contribution to the overall system, but are still worth mentioning. In fact, the use of on-farm machinery powered by diesel and gasoline for soil preparation, feed transport, and manure management leads to fossil fuel consumption, contributing to the Fossil Depletion Potential (FDP).

Going into more detail, Table 9 shows the main emissions from the Camia farm, specifically focusing on methane, ammonia, carbon dioxide, nitrogen oxides, and volatile organic compounds (VOCs), which are primarily attributed to the Limousine cattle and the food supply chain.

The Limousine cattle are responsible for the majority of the methane, ammonia, and carbon dioxide emissions, largely due to enteric fermentation, which produces methane, and the management of manure, which releases ammonia The food supply is the dominant source of nitrogen oxides and contributes a considerable amount of carbon dioxide emissions, both from the transport activities and from the cultivation of feed crops and subsequent processes.

Emissions	Contribution	Category	Result (kg)
Methane - Emission to air/unspecified	Methane is a major greenhouse gas, contributing to the farm's climate change impact.	Limousin cattle	55,47
Ammonia - Emission to air/low population density	Ammonia contributes to acidification and eutrophication, impacting air and water quality.	Limousin cattle	123.573,25
		Food supply	3.637,41
Carbon dioxide, fossil - Emission to air/low population density	Carbon dioxide is a major greenhouse gas, contributing to the climate change impact.	Limousin cattle	979.216,62
		Food supply	1.395.640,25
Nitrogen oxides - Emission to air/unspecified	Nitrogen oxides contribute to the formation of smog and acid rain.	Limousin cattle	1.085,97
		Food supply	10.435,03
VOC, volatile organic compounds, unspecified origin - Emission to air/low population density	VOCs contribute to the formation of smog.	Food supply	1,95

Table 9 - Emissions from the most relevant processes

The results of the LCIA were then compared to the other three LCA studies mentioned in Table 1, after scaling the functional unit (for this calculation for the total weight gained of 2870000kg) for a fair comparison, which can be viewed in Table 11. The final body weight (BW) represents the kilograms of the live animal at the end of the fattening phase, the body weight gained (BWG) represents the kilograms gained during the fattening period and the carcass weight represents the kilograms after the slaughter and processing, where the value 0.57 represents the carcass yield [15].

Mitigation Action Scenarios	**Cumulative Energy Demand**	**ReCiPe Midpoint (H) V1.13**							
	Non-renewable, fossil	**ALOP**	**GWP100**	**FDP**	**FEP**	**MDP**	**PMFP**	**POFP**	**TAP100**
Adoption of Electric Vehicles (EVs)	✓		✓	✓		✓			
Expansion of the photovoltaic system	✓		✓	✓		✓			
Supply chain transportation upgraded to EURO6	✓		✓				✓	✓	✓
Improvement in upstream fuel consumption in agriculture	✓		✓	✓	✓				
Improvement in upstream fertilizers used in agriculture	✓		✓	✓	✓				
New cereal-based diet	✓	✓	✓	✓					✓

Table 10 - Summary of Impact Categories used for each action mitigation scenario

Functional Unit	**Scaling Factor (1/kg)**
1 kg final body weight (BW)	$\frac{1}{2870000}$
1 kg carcass weight	$\frac{1}{2870000 \cdot 0.57}$
1 kg body weight gained (BWG)	$\frac{1}{2870000 - 1640000}$

Table 11 - Scaling factors used according to the functional unit

It must the reminded that Table 10 includes information from three different studies that use differing system boundaries. In fact, some studies use a cradle-to-slaughterhouse gate approach, while the Camia case study uses a cradle-to-farm gate approach, ending before the fattened animal leaves the farm, and the diet differs. Regarding the Global Warming Potential (GWP100), the Camia case study's value is similar to the ones of the mixed beef production system in Spain [8] and the integrated France-Italy beef production system [15], while it is much higher than the cereal-based intensive beef fattening sector in Italy [10], which can be due to the fact the it excludes the production and transport of calves. For the Agricultural Land Occupation (ALOP) the Camia farm has a higher value when compared to the other studies [10] [15], which could be due to the production of diet-related feed crops that require a significant amount of land. The integrated French-Italian system has a lower fuel depletion potential (FDP) than the Camia farm, which could be due to the intensive cereal-based system of the Camia farm and its diverse supply chain. The Spanish system has a similar freshwater and marine eutrophication potential (FEP and MEP) to the Camia farm system, and as consequence a similar impact on water bodies, due to the high quantities of manure and reliance on fertilizer-intensive production of feed. The Terrestrial Acidification Potential (TAP100) of the Camia farm doesn't differ much from sources [10] [15], but more than double of the Spanish system, which studies a mix of grazing and landless operations, which are more geographically disperse and need fewer external inputs like fertilizers and feed crops.

Functional Unit	Source	ALOP (m^2/year)	GWP100 (kg CO_2 eq.)	FDP (MJ)	FEP (kg P eq.)	MEP (kg N eq.)	ODPinf	TAP100 (kg SO_2 eq.)
1 kg carcass weight	Tinitana-Bayas et al. (2024) [8]		2.09E+01		1.09E-03	1.03E-02	2.50E-04	8.62E-02
	Camia farm		2.22E+01		1.18E-03	6.50E-02	9.87E-07	2.23E-01
1 kg final weight (BW)	Gallo et al. (2020) [15]	1.87E+01	1.30E+01	3.60E+01	5.70E-02			1.93E-01
	Camia farm	3.45E+01	1.27E+01	5.43E+01	6.73E-04			1.27E-01
1 kg body weight gained (BWG)	Berton et al. (2017) [10]	8.90E+00	7.9-9.0	6.20E+01	6.50E-02			0.141-0.197
	Camia farm	8.04E+01	2.95E+01	1.27E+02	1.57E-03			2.97E-01

Table 12 - Camia results compared with other LCA studies on beef fattening

4. Discussion of potential mitigation scenarios

This chapter focuses on potential mitigation scenarios aimed at reducing the environmental impact and energy consumption of the finishing farm, based on the results presented in the previous chapter. Each scenario focuses on specific areas of intervention, like energy use, feed composition and transportation efficiency. The principal proposed solutions discussed with respect to the impact categories previously chosen in the LCIA in order to address the most relevant environmental and energetic burdens.

In general, off-farm processes like weaned calves raising and logistics have a significant environmental impact on the overall system, and can't be superficially disregarded, even if the leeway is limited compared to other farm activities. So, a more holistic approach was adopted. The solutions provided have been subdivided into their respective categories according to the framework outlined by UNI EN ISO 14064. This allows for a better distinction between actions that can be implemented within the farm and those that depend on off-farm activities.

4.1 Category 1

The following measures are implemented for sustainability and to reduce the farm's environmental impact:

- Adoption of hybrid or electric vehicles: transitioning the company's fleet to hybrid or fully electric vehicles would significantly reduce GHG emissions by reducing fossil-based fuel.
- Electric vehicles could be rented for occasional transportation or business travel, and this can minimize the carbon footprint without the need to purchase additional vehicles.
- Installation of electric vehicle charging stations can ease the transition to electric mobility.
- Implement monitoring systems to optimize fuel usage and reduce consumption through more efficient routing.
- Ensure proper maintenance of vehicles to decrease fuel consumption and minimize emissions.
- Upgrade outdated agricultural and industrial machinery with modern, high-efficiency models.

These actions collectively can promote a cleaner, more energy-efficient transport system, contributing to the organization's overall efforts to reduce its environmental impact.

The LCIA highlighted the farm's reliance on fossil fuels for transportation and agricultural machinery, and the adoption of EVs addresses this issue by reducing energy consumption and GHG emissions.

One of these changes was applied in the LCA model, and it regards the displacement of workers. The process "Transport, passenger car, electric {GLO}| market for | Cut-off, S" was used to represent electric vehicles in this analysis. This dataset represents the global consumption mix of electric passenger transport, including production, imports, and transport-related losses.

Evaluating the environmental benefits of using electric vehicles for transport, the most relevant impact categories to choose from are:

- Non-renewable energy, fossil (from the Cumulative Energy Demand category): electric vehicles eliminate direct fossil fuel consumption for transportation, reducing dependence on non-renewable energy sources.
- Global Warming Potential: PV panels generate electricity without direct CO_2 emissions, reducing the use of fossil fuels and decreasing GHG emissions.

- Fossil Depletion Potential
- Metal Depletion Potential: batteries of electric vehicles require significant amounts of critical minerals such as lithium, cobalt, and nickel, increasing demand for these raw materials and rare earth materials.

Method	**Impact Category**	**Unit**	**Base**	**50% EVs**	**Change**	**100% EVs**	**Change**
Cumulative Energy Demand	Non-renewable, fossil	MJ	138.939	105.417	-32%	71.895,7	- 93%
ReCiPe Midpoint (H) V1.13	Global warming potential	kg CO2 eq	9.447,93	7.579,47	-25%	5.711	-65%
	Metal depletion potential	kg Fe eq	777,19	1.392,89	+44%	2.008,58	+61%
	Fossil depletion potential	kg oil eq	3.238,10	2.502,62	-29%	1.767,13	- 83%

Table 13 - Change in percentage of impact categories after using electric vehicles

With a full switch to EVs, non-renewable fossil energy demand drops by 93%, and fossil resource depletion decreases by 83%, showing a major step toward reducing reliance on fossil fuels. Additionally, global warming potential sees a substantial reduction, with emissions decreasing by 25% at 50% EV penetration and 65% with full adoption, reinforcing the climate benefits of electrification.

However, metal depletion potential increases by 44% at 50% EV penetration and 61% with full adoption, reflecting the higher demand for materials like lithium, cobalt, and nickel used in EV batteries. This highlights the need for responsible sourcing, improved recycling technologies, and advancements in battery efficiency to mitigate the environmental impact of increased metal extraction.

4.2 Category 2

To meet the energy demand and reduce grid electricity imports, increasing the photovoltaic installation area based on available irradiation data. In the reference year 2023 about 176.324 kWh of electricity is taken from the national grid, which is distributed between the office and the rest of the company. With a specific photovoltaic power output of 1,457.7 kWh/kW$_p$ and global tilted irradiation at the optimal angle of 1,762.1 kWh/m^2 [22], an additional 100 m^2 of PV panels would generate sufficient electricity to cover the required energy. This expansion would increase the company's self-reliance from external energy sources.

Process	Amount	Unit	Database
Electricity, low voltage {IT}| electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted | Cut-off	30963,32	kWh	Ecoinvent v3
Photovoltaic module, building-integrated, for slanted-roof installation {GLO}| market for | Cut-off	100	m^2	
Electricity, low voltage {IT}| electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted | Cut-off	176.324	kWh	

Table 14 - Detail of PV installation

Evaluating the environmental benefits of installing more photovoltaic panels, the most relevant impact categories to choose from are:

- Non-renewable energy, fossil (from the Cumulative Energy Demand category): PV systems replace energy derived from fossil fuels, lowering overall non-renewable energy consumption
- Global Warming Potential: PV panels generate electricity without direct CO_2 emissions, reducing the use of fossil fuels and decreasing GHG emissions.
- Fossil Depletion Potential
- Metal Depletion Potential: on the other hand, PV panels require minerals like silicon, silver, and rare earth metals

Method	Impact Category	Unit	Base	After PV installation	Change
Cumulative Energy Demand	Non-renewable, fossil	MJ	1.298.622,6	485.677,28	-62,60%
ReCiPe Midpoint (H) V1.13	Global warming potential	kg CO2 eq	357.447,63	303.350,47	-15,13%
	Metal depletion potential	kg Fe eq	485,55	644,09	+32,65%
	Fossil depletion potential	kg Oil eq	28.487,58	10.654,66	-62,60%

Table 15 - Change in percentage of impact categories after PV installation for Category 2

It's evident that there was an increase of 32.65% in Metal Depletion, primarily due to the materials required to produce the PV panels like rare earth materials. It can be viewed though as a reasonable trade-off due to the evident long-term environmental benefits of expanding the farm's photovoltaic park. In fact, after the installation of the photovoltaic panels there is a significant reduction in Cumulative Energy Demand for non-renewable fossil resources, with a 62.6% drop. Plus, another positive environmental impact is the reduction of 15.13% of CO2 equivalent emissions and by 62.6% of non-renewable fossil fuels.

Alternatively, another option could be purchasing electricity from IGO-qualified plants (in compliance with Directive 2009/28/EC), ensuring that the energy consumed is sourced from certified, sustainable renewable systems, aligning with the goals for environmental sustainability.

4.3 Category 3

The Cascina Camia farm has limited influence over the transportation impacts associated with its suppliers. However, it can prioritize suppliers that utilize a fleet of hybrid vehicles or alternative fuel vehicles. Information regarding these suppliers can be compiled into a register of eco-sustainable suppliers, which would include details about their carbon footprint and energy consumption. This initiative not only encourages sustainable practices among suppliers but could make the farm's overall sustainability profile well-viewed among customers.

Additionally, collaboration with local suppliers or those in nearby areas is advisable for sourcing raised cattle and other livestock, which would help reduce transportation distances, and shortening these supply routes can significantly lower greenhouse gas emissions and transportation burdens.

Diving deeper on the supply chain, an analysis can be performed on the cattle and food supply, which hold a significant impact on the overall system. To briefly introduce the Euro emissions standards: the European Union established regulations to limit harmful pollutants emitted by vehicles. The Euro 5 standard introduced limits on particulate matter and nitrogen oxide emissions for diesel vehicles, and more significant reductions are required for the successive Euro 6 vehicles.

Therefore, the following impact categories were chosen to capture the changes after upgrading the vehicles:

- Global warming to account for the CO_2 and other GHGs emissions.
- Particulate matter formation to capture the effects of a stricter limit on the PM emissions.
- Photochemical oxidant formation to notice the reduced effects of ground-level ozone (like smog) due to the emission of NO_x and volatile organic compounds (VOCs).
- Terrestrial acidification due to the emissions of NO_x and SO_2 from vehicle exhaust gases.
- Non- renewable energy (fossil), to measure the energy consumption of fossil fuel due to vehicle operations.

Method	Impact Category	Unit	Euro 5	Euro 6	Change
Cumulative Energy Demand	Non-renewable, fossil	MJ	29.994.300	29.463.400	- 2 %
ReCiPe Midpoint (H) V1.13	Global warming	kg CO2 eq	1.886.900	1.850.030	- 2%
	Particulate matter formation	kg PM10 eq	3.193,20	2.439,18	- 31%
	Photochemical oxidant formation	kg NMVOC eq	7.794,95	4.512,16	-73%
	Terrestrial acidification	kg SO2 eq	5.881,22	4.041,16	-45,5%

Table 16 - Improvement of cattle supply transportation

It is evident that upgrading from Euro 5 to Euro 6 freight vehicles for cattle supply leads to noticeable environmental improvements. The transition results in a 2% reduction in non-renewable fossil energy use and global warming emissions, reflecting improved fuel efficiency and lower carbon dioxide output. Plus, particulate matter emissions decrease by 31% thanks to advanced filtration systems present in Euro 6 engines. The formation of photochemical oxidants drops by 73%, and terrestrial acidification also improves with a 45.5% reduction in acidifying emissions like sulfur dioxide and nitrogen oxides, benefiting soil and water quality.

Method	**Impact Category**	**Unit**	**Euro 5**	**Euro 6**	**Change**
Cumulative Energy Demand	Non-renewable, fossil	MJ	80.002.700	78,990.400	- 1,3 %
ReCiPe Midpoint (H) V1.13	Global warming	kg CO2 eq	6.900.610	6.830.240	- 1%
	Particulate matter formation	kg PM10 eq	10.109,6	8.662,22	- 16,7%
	Photochemical oxidant formation	kg NMVOC eq	25.164,3	18.862,4	- 33,4%
	Terrestrial acidification	kg SO2 eq	29.452,5	25.920.6	- 13,6%

Table 17 - Improvement of food supply transportation

In Table 17 a similar improvement can be noticed for the food supply, contributing to the overall reduction in air pollution and fossil fuel consumption.

4.4 Category 4

The farm also has a limited influence over the impacts associated to the imported livestock, but it can consider selecting a breed of cattle that exhibits a higher growth rate and better feed efficiency compared to the Limousine breed. For instance, the Charolais breed (originating from France or Veneto) reaches market weight more quickly while consuming less feed overall [23]. This not only contributes to better resource efficiency but also reduces greenhouse gas emissions associated with feed production and livestock rearing.

In addition, it is advisable to carefully monitor the actual feed consumption to optimize the precise quantity required for fattening the livestock. Implementing a system for tracking feed conversion ratios can help identify areas for improvement, ensuring that the cattle are receiving the appropriate nutrients without excess waste.

Moreover, the use of composted manure is encouraged for efficient carbon capture and sequestration. This practice not only enhances soil quality but also contributes to reducing the carbon footprint of the farming operations by recycling nutrients back into the ecosystem.

While the impact of purchased office supplies is minimal, adopting a “green” approach can still yield benefits:

- Raise awareness among staff about good energy-saving practices, such as turning off lights and equipment when not in use and encouraging the use of natural light.
- Prefer digital documents over paper and printed materials to reduce paper waste. Encouraging a paperless environment can significantly lower the company's ecological footprint.
- Choose eco-sustainable suppliers and use recycled materials for office supplies. This includes sourcing from companies that prioritize sustainable practices and materials, thereby supporting the circular economy.
- Implement the 3 R's principle: reduce, recycle, and reuse. Encourage staff to bring reusable containers and cutlery for meals, and to recycle paper and plastics through clearly labeled bins in the workplace.

By integrating these practices, the company can enhance its sustainability efforts across both livestock management and office operations.

4.5 A detailed look at the off-farm Limousin cattle rearing's impact

An analysis over the off-farm Limousine breed cattle rearing was performed since its environmental impact has a predominant effect on the whole system. The analysis originated from a dataset titled "Beef cattle, national average, at farm gate" which included a wide range of categories related to different cattle types, production systems, and feeding practices across France. This comprehensive dataset encompassed both suckler and dairy cattle, representing various management styles, feeding systems. Categories that were related to dairy production systems (for example, highland milk system, lowland milk system) were excluded because they are not related to beef production, and categories indicating cattle already in a fattening phase (such as suckler heifers and young dairy bulls) were also excluded, as they fell outside the scope of the thesis.

Regarding the livestock unit, according to a study [24] the Limousine breeding system in France has a stocking rate lower than 1.2 Livestock Units (LU) per hectare, and as consequence the process was chosen accordingly. It's important to clarify the LU measurement system: it is a standardized measure that in the agricultural world is used to quantify the impact of livestock on land. In farming systems classified as having more than 1.2 LU per hectare, there is a higher density of livestock per unit area. This means that a significant number of animals are concentrated on a relatively small piece of land. While on the other hand, farming systems classified as having less than 1.2 LU per hectare typically have a lower stocking density, with fewer animals spread over more land.

Within the category of "*Suckler cull cow, conventional, suckler cow system, less than 1.2 LU per ha, at farm gate,*" the most impactful process is the raising of new-born calves. For their growth the impact of baled hay, water and electricity consumption are significant. Agricultural practices contribute significantly to the environmental impact of this farming system, with the use of fossil fuel-based agricultural machinery and an important quantity of fertilizers.

Regarding the machinery, according to an experimental study [25] fuel consumption in diesel-based agricultural tractors can decrease by 3-4%, and this change was applied to all the subcategories. In the overall process diesel-powered tractors are used for baling straw with a round baler, for producing soft wheat grain, and to manage the suckler cattle building. The two main inputs for diesel "*Diesel combustion, in tractor {FR} U*" and "*Diesel, market for Europe without Switzerland, Cut-off, S*" were changed accordingly.

Unfortunately, making these changes leads to small improvements (even considering a hypothetical decrease by 10%), as shown in the following table, where the total input of Limousine breed cattle is considered.

Method	Impact Category	Unit	Base	- 4% in fuel consumption	- 10% in fuel consumption
Cumulative Energy Demand	Non-renewable, fossil	MJ	38.792.300	38.696.400	38.552.500
ReCiPe Midpoint (H) V1.13	Global warming	kg CO2 eq	25.402.100	25.395.600	25.385.800
	Freshwater eutrophication	kg P eq	897,947	897,875	897,767
	Fossil depletion	kg oil-Eq	961.560	959.363	956.064

Table 18 - Improvement in fuel consumption

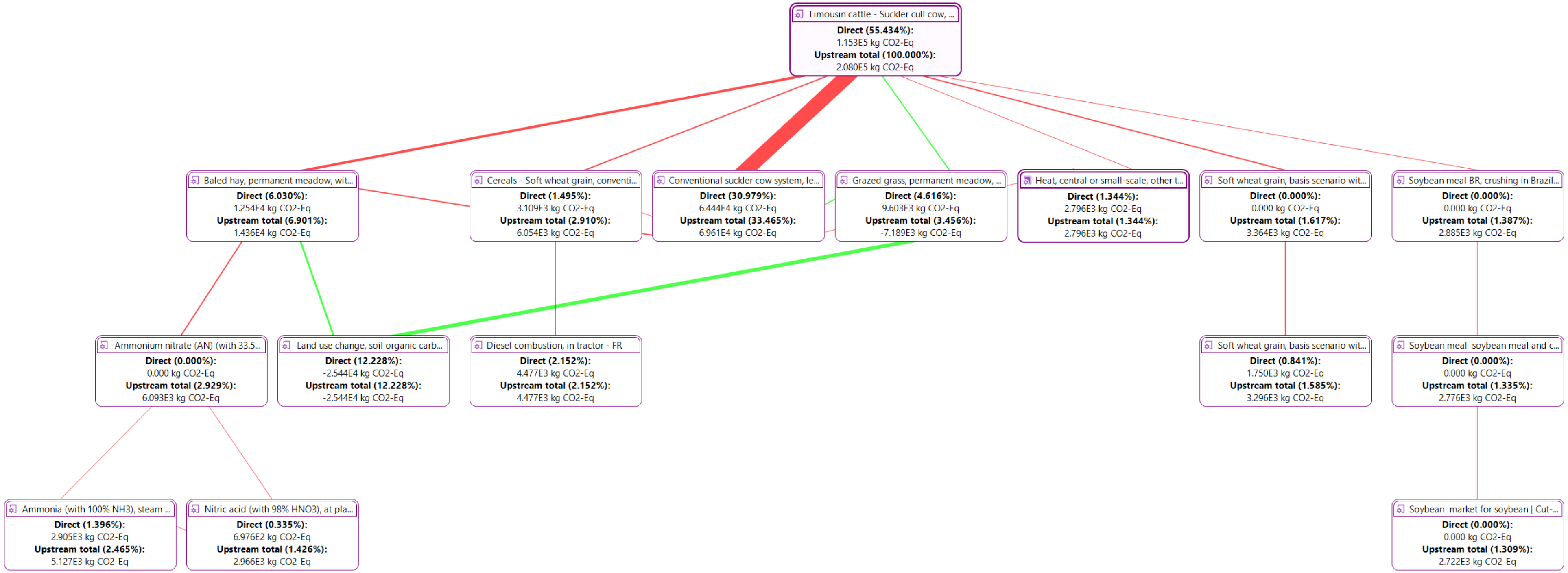

Figure 7 - Sankey Diagram with GWP as Impact Category

Shifting instead the focus to fertilizers, mineral fertilizers such as P_2O_5, ammonium nitrate (33.5% N), and K_2O are applied during the following processes:

- "Soft wheat grain, conventional, national average, animal feed, at farm gate, production", which includes soil cultivation, sowing, fertilization, pest control, irrigation, and harvesting. It also includes machinery, farm infrastructure, input materials (seeds, fertilizers, fuel, water), and direct emissions from fuel combustion and field activities.
- "Baled hay, permanent meadow, without clover, Auvergne, at farm", which covers all inputs and processes involved in maintaining a meadow, including soil cultivation, sowing, fertilization, weed and pest control, irrigation, and harvesting. It also accounts for farm machinery, storage areas, input materials like seeds, fertilizers, fuel, and water, as well as direct emissions from fuel combustion and field activities.
- "Soft wheat grain, basis scenario without lever, at farm gate", which includes soil cultivation, sowing, fertilization, weed and pest control, irrigation, harvesting, and transport to the farm.

Recent studies [26] have shown that employing site-specific management practices can lead to the reduction of nitrogen fertilizer usage by 10–20%, while also cutting down phosphorus and potassium inputs by 15–20%. These changes were applied to the fertilizers accordingly.

Method	**Impact Category**	**Unit**	**Base**	**- 15% fertilizers**	**- 20% fertilizers**
Cumulative Energy Demand	Non-renewable, fossil	MJ	38.792.300	37.119.300	36.561.700
ReCiPe Midpoint (H) V1.13	Global warming	kg CO2 eq	25.402.100	25.298.300	25.263.600
	Freshwater eutrophication	kg P eq	897.947	878.364	871.836
	Fossil depletion	kg oil-Eq	961.560	914.830	899.253

Table 19 - Improvements in fertilizers

Although the percentage change for global warming is small, noticeable improvements are observed in freshwater eutrophication and fossil depletion, with reductions of up to 3% and 7%, respectively. Plus, there is a 7% decrease in energy derived from fossil fuels.

4.6 A detailed look at the cattle diet's environmental impact

As seen before, the food supply chain had an impact on the overall system, and besides the related transportation activities, the cereal-based diet itself also had a significant impact. The initial diet formulation consisted of a mix of spelt, grain maize, barley, and soft wheat. However, this composition was re-evaluated and replaced with a new mix of cereals with higher energy density to improve efficiency and reduce greenhouse gas emissions while ensuring that the energy intake remained constant. The original diet had a total mass of 2.871.365 kg, supplying the required energy for cattle fattening, and given the need to optimize environmental performance without compromising animal growth, it was crucial to maintain the same total energy content in the revised diet.

Cereal Type	Total weight (kg)	Gross Energy (MJ/kg)	Source
Spelt	143.015	15	[27]
Organic grain maize	1.127.980	15,2	[28]
Organic barley	230.220	15	[29]
Soft wheat grain	1.370.150	14,2	[28]

Table 20 - Energy content of the cereal-based diet

Cereal Type	Total weight (kg)	Gross Energy (MJ/kg)	Source
Corn gluten feed	750,000	18	[29]
Durum wheat	750,000	18	
Sorghum grain	621,365	17	
Wheat bran	750,000	18	

Table 21 - New cereal-based diet

Keeping almost constant the total weight alternative cereals were selected based on their higher energy density and potential to reduce methane emissions per unit of feed consumed. The new formulation included: corn gluten feed, durum wheat, sorghum grain and wheat brain, with their gross energy content, as shown in Table 21. This reformulated diet slightly reduced total weight while maintaining the same total energy output. The energy level was kept constant to ensure that cattle continued to gain weight efficiently, as energy is the primary driver of growth and feed conversion efficiency in beef production.

Method	Impact Category	Unit	Base	New cereal-based diet	Change
Cumulative Energy Demand	Non-renewable, fossil	MJ	5.277.810	6.335.280	16,70%
ReCiPe Midpoint (H) V1.13	Global Warming Potential	kg CO2 eq	1.180.160	1.096.180	-7,66%
	Freshwater Eutrophication Potential	kg P eq	101,13	83,39	-21,27%
	Agricultural Land Occupation Potential	m2a	4.939.310	3.263.350	-51,36%
	Terrestrial Acidification Potential	kg SO2 eq	12.187,4	10.047,9	-21,29%

Table 22 - Change of the LCI with the new cereal-based diet

As can be seen in the table, the introduction of the new cereal-based diet results in a 16.70% increase in non-renewable fossil energy consumption, caused by using high-pressure natural gas in ammonia production, which is necessary to produce ammonium nitrate, a key fertilizer used in durum wheat cultivation and, to a lesser extent, in sorghum grain production. However, this higher energy demand holds space for environmental benefits across several other impact categories.

For example, the new diet has led to a 7.66% reduction in Global Warming Potential indicating lower greenhouse gas emissions associated with feed production. Plus, the new diet has led to a 21.27% decrease in Freshwater Eutrophication Potential, reflecting lower runoff into water, likely due to lower fertilizer application. A particularly notable benefit is the 51.36% reduction in Agricultural Land Occupation, which is a direct consequence of the new cereals' higher energy density. Furthermore, Terrestrial Acidification Potential has dropped by 21.29%, likely due to changes in fertilizer use that result in fewer acidifying emissions during crop cultivation.

Even though the changes were beneficial in the supply chain, it must be reminded that a change in diet composition directly affects cattle growth, and as consequence the whole Camia farm system. In fact, the following emissions significantly contribute to the release of greenhouse gases: enteric fermentation, with the release of methane, and manure management, which generates both methane and nitrous oxide (N_2O).

By implementing precise calculations for these emissions, we can better understand how dietary modifications affect overall environmental performance. The following sections present the methodological approach used to estimate these emissions. The calculations were based on the guidelines of “Global Roundtable for Sustainable Beef (GRSB) Carbon Footprint Guideline” [30], which provides a standardized framework for evaluating greenhouse gas emissions across the beef supply chain.

Base diet		**Total weight (kg)**	**Gross Energy (MJ/kg)**	**Source**
Cereals	Spelt	143.015	15	[27]
	Organic grain maize	1.127.980	15,2	[28]
	Organic barley	230.220	15	[29]
	Soft wheat grain	1.370.150	14,2	[28]
Legumes	Soybean	1.890.540	20	[29]
Vegetables	Sugar beet pulp	833.051	16	[29]
Straw	Straw	1.866.525	17	[29]
	Total Gross Energy		129.542.232 MJ	

Table 23 - Total gross energy of the base diet

New proposed cereal-based diet		**Total weight (kg)**	**Gross Energy (MJ/kg)**	**Source**
New cereal-based diet	Corn gluten feed	750,000	18	[29]
	Durum wheat	750,000	18	
	Sorghum grain	621,365	17	
	Wheat bran	750,000	18	
Legumes	Soybean	1.890.540	20	
Vegetables	Sugar beet pulp	833.051	16	
Straw	Straw	1.866.525	17	
	Total Gross Energy		137.714.826 MJ	

Table 24 - Total gross energy of the new proposed cereal-based diet

As can be seen in Table 25, the gross energy intake for the two diets (composed of cereals, legumes and vegetables) was set at 0,2164 MJ/head/day and 0,2300 MJ/head/day respectively, reflecting the energy density of the diets. The methane emissions from enteric fermentation were calculated and these were found to be 0,000923 kg/head/year for the first diet and 0,000981 kg/head/year for the second diet. When scaled to the total animal population, the total methane emissions increased from 1.513 kg/year to 1.608

kg/year, representing a 5,93% increase in enteric fermentation methane emissions for the higher-energy diet.

Parameter	Base Diet	New Diet	Unit
GE_T	0.2164	0.2300	MJ/head/day
$EF_{met,ent,T}$	9.23E-04	9.81E-04	kg/head/year
$CH_{4\,\text{ent},T}$	1513.07	1608.53	kg/year
Change		+5.93	%

Table 25 - Methane emission from enteric fermentation results

Parameter	Base Diet	New Diet	Unit
VS_T	0,0112	0,0119	kg/head/year
$CH_{4\,\text{man},T}$	1.686,46	1.793,35	kg/year
Change		5.96	%

Table 26 - Methane emissions from manure management results

As can be seen in Table 26, when scaled to the total population, the methane emissions from manure increased from 1.686 kg/year to 1.793 kg/year, a 5,96% increase. Moreover, calculating N_2O emissions from manure management is crucial because N_2O is a greenhouse gas that contributes to the global warming potential. Plus, excessive nitrogen in manure can lead to environmental issues like eutrophication and soil acidification. It is calculated with the equation (5) from the Appendix.

Base diet		Total weight (kg)	Dry matter (%)	Crude protein (%)	CP_T	Source
Cereals	Spelt	143.015	85	15,03	21,56	[31]
	Organic grain maize	1.127.980	86,3	9,4		[32]
	Organic barley	230.220	88	4		[33]
	Soft wheat grain	1.370.150	89	13		
Legumes	Soybean	1.890.540	90	55		
Vegetables	Sugar beet pulp	833.051	20	13		
Straw	Straw	1.866.525	88	4		

Table 27 - Crude protein content in the base diet

New proposed cereal-based diet		Total weight (kg)	Dry matter (%)	Crude protein (%)	CP_T	Source
New cereal-based diet	Corn gluten feed	750.000	90	26	25,35	[33]
	Durum wheat	750.000	87,9	16,5		[34]
	Sorghum grain	621.365	28	8		[33]
	Wheat bran	750.000	89	18		
Legumes	Soybean	1.890.540	20	55		
Vegetables	Sugar beet pulp	833.051	88	13		
Straw	Straw	1.866.525		4		

Table 28 - Crude protein content in the new cereal-based diet

Parameter	Base Diet	New Diet	Unit
CP_T	21.56	26.33	kg/day/head
$N_{intake,T}$	1.34E-4	1.88E-4	kg/day/head
$N_{ext,T}$	0.0477	0.0668	kg/day/head
$N2O_{dir,T}$	391.88	548.56	kg/day/head
Change		+ 29%	

Table 29 - Direct emission of N2O from manure results

As can be seen in Table 29, by comparing the two diets it’s possible to highlight the significant increase in direct nitrous oxide (N_2O) emissions from manure management. The base diet produced 391.88 kg/day/head of N_2O emissions, while the new diet resulted in 548.56 kg/day/head, marking a 29% increase.

The two factors responsible for this increase in emissions are the crude protein content and the nitrogen excretion. First, the new diet has a higher crude protein content (26.33%) compared to the base diet (25,35%). Since crude protein is directly related to nitrogen intake, the increase in dietary protein led to higher nitrogen consumption by the animals. Second, the higher nitrogen intake resulted in greater nitrogen excretion, as not all the nitrogen consumed can be efficiently utilized for growth. This surplus nitrogen in the excreta contributes to increased N_2O emissions during manure decomposition and management.

Parameter	Base Diet	New Diet	Unit
$N_2O_{ind,leach}$	81.84	102.29	kg/year
Change		+ 20%	

Table 30 - Indirect N_2O emissions from leaching of manure results

As can be noticed in Table 30, the increase in the annual N excretion per animal due to the new diet causes an increase by 20% of the indirect N_2O emissions from leaching of manure.

Parameter	Base Diet	New Diet	Unit
$N_2O_{ind,leach}$	130.19	162.74	kg/year
Change		+ 20%	

Table 31 - Total indirect nitrous oxide emission from volatilization results

As can be noticed in Table 31, the increase in annual N excretion per animal due to the new diet causes an increase by 20% of the indirect nitrous oxide emission from volatilization. The change in diet leads to a reduction by 6% in manure and slurry quantity by doing a proportion calculation as shown in the equations (15) [35] and (16) from the appendix, which results in 75.753 kg and 11.018,64 m^3 respectively.

As discussed earlier in the thesis, the high-forage, low-starch (HFLS) diet is considered an alternative to the cereal-based one. It reduces dependence on energy-intensive cereal production and may also lower nitrogen excretion by enhancing rumen digestion efficiency through a higher fiber content. Additionally, it can still support reasonable growth rate without an excessive use of concentrate, integrating forage and agro-industrial by-products for a higher resource efficiency. So, to assess the potential benefits of this diet a new analysis was performed and by quantifying the change in the impact categories and emissions check if there's an overall improvement. Firstly, the feed energy content was kept constant, along with the total kilograms, reducing the high-starch ingredients and increasing forage. In the new HFLS diet, because of the high starch content, organic maize was removed and the amount of soft wheat grain and organic barley reduced. The new diet increased the forage content, incorporating alfalfa hay, grass silage and bran. More details can be seen in Table 32. The total amount of starch amounts to 54.605.000 kg and forage 4.250.000 kg, while the original diet had a total amount of starch of 187.037.787,4 kg and forage 1.866.525 kg.

Ingredient	New Diet (kg)	Dry matter (%)	Crude Protein (%)	Starch (% of DM)	Gross Energy (MJ/kg)
Organic barley	300,000	88	4	52,3	18
Soft wheat grain	250.000	89	13	60	14,2
Straw	1.000.000	88	4	0,8	17
Sugar beet pulp	900.000	20	13	0,9	16
Soybean	700.000	90	55	5,1	22
Alfalfa hay	1.800.000	92,2	52,2	0,9	20,2
Grass silage	1.450.000	90	14,6	1,1	16,8
Wheat bran	800.000	86,9	15,3	19,4	16,4

Table 32 - HFLS diet

Calculated as before, Table 33 shows the emissions comparison between the base diet and the HFLS diet. Methane emissions remain stable between the two diets, while nitrous oxide emissions are higher in the HFLS diet, due to increased nitrogen excretion. HFLS diets include a forage-rich mix with lower protein content, but in this case the crude protein intake is higher compared to the high-concentrate diet, leading to a less balanced nitrogen use by cattle and more nitrogen being excreted.

Emission Type	High-Concentrate Diet (kg/year)	HFLS Diet (kg/year)
CH_4 Emissions from Enteric Fermentation	1.513,07	1.513,63
CH_4 from Manure Management	1.686,46	1.687,09
Direct N_2O from Manure Management	1.183,58	1.512,85
Indirect N_2O from Leaching	81,84	104,60
Indirect N_2O from Volatilization	130,19	166,41

Table 33 - Comparison emissions by HFLS diet

As consequence, the ingredient quantities were adjusted to have a lower total crude protein intake, with a total gross energy close to the original base diet, and then the crude protein was prioritized over the gross energy in order to decrease the nitrogen excretion. These changes were performed to maintain a diet that is coherent with a HFLS mix composition. More details can be seen on the following table.

Ingredient	First Attempt (kg)	Total Gross Energy (MJ)	Crude protein (kg)	Second Attempt (kg)	Total Gross Energy (MJ)	Crude protein (kg)
Organic barley	267.791	118.887.173,40	1.610.003,484	260.215	116.809.936,6	1.582.068,3
Soft wheat grain	220.088			213.932		
Straw	1.032.887			1.015.432		
Sugar beet pulp	937.155			925.841		
Soybean	562.293			552.318		
Alfalfa hay	1.494.276			1.468.287		
Grass silage	1.494.354			1.468.365		
Wheat bran	654.156			642.287		
Total	6.663.000			6.546.677		

Table 34 - Look at the two attempts

Choosing the data from the second attempt the new emissions can be calculated and are shown in the following table.

Emission Type	HFLS diet (kg/year)	Change (%)
CH4 emissions from enteric fermentation	1360.63	-11.204%
CH_4 from Manure Management	1515.89	-11.253%
Direct N_2O from Manure Management	1276.59	7.29%
Indirect N_2O from Leaching	88.27	7.29%
Indirect N_2O from Volatilization	140.42	-15.89%

Table 35 - New emissions with the adjusted HFLS diet

Compared to the previous calculation the emissions CH_4 from enteric fermentation and manure management are lower by 11% compared to the base diet, while before the values were almost constant, since by prioritizing the minimization of crude protein intake the gross energy intake per head per day is much lower. On the other hand, direct N_2O emissions from manure management and indirect N_2O emissions from leaching of manure remain higher compared to the base diet, but it’s much lower than the first calculation done previously passing from a 22% increase to a 7%. Indirect N_2O emissions from volatilization of NH_3 and NO_x also experienced an increase of 7%, which remains lower than the previous calculation. More details can be seen on the following table.

Emission Type	Base diet (kg/year)	HFLS diet (kg/year)	Change (%)
CH4 emissions from enteric fermentation	1.513,07	1.364,36	-10,9%
CH_4 from Manure Management	1.686,46	1.515,89	-11,25%
Direct N_2O from Manure Management	1.183,58	1.276,59	7,29%
Indirect N_2O from Leaching	81,84	88,27	7,29%
Indirect N_2O from Volatilization	130,19	140,42	7,29%

Table 36 - New emissions with adjusted HFLS diet

To have a satisfactory low N_2O emissions the crude protein intakes were decreased by 8%, leading to these final HLSF feed mixture. This causes an important decrease of 25% of the total amount of feed intake needed, but also an important fall in the total gross energy intake.

Ingredient	First Attempt (kg)	Total Gross Energy (MJ)	Crude protein (kg)
Organic barley	236.795,65	106.297.042,3	1.439.682,14
Soft wheat grain	194.678,12		
Straw	924.043,12		
Sugar beet pulp	842.515,31		
Soybean	502.609,38		
Alfalfa hay	1.336.141,17		
Grass silage	1.336.212,15		
Wheat bran	584.481,17		

Table 37 - Final HFLS diet composition

This new diet composition has a lower total dry matter intake of 634.410,72kg, while originally it amounted to 803.689,97kg. The following equation (1) was used to calculate the total weight gain, where the feed conversion ratio (FCR) is the ratio of dry matter intake to live-weight gain, the value for the limousine cattle was taken from literature, which is equal to 7.5 kg/kg [23].

$$Total\ weight\ gain\ (kg) = \frac{Total\ feed\ intake\ (kg)}{FCR} \qquad (1)$$

It results in an increase by 7% of the total weight gain of cattle at the end of the finishing process, which is higher than the expected value from suppliers, while the cereal-based diet proposed in the thesis is lower less than the 2% of the demanded value, which can be adjusted with the on-farm cultivation of feed. The trade-off is a positive trend for all emissions, where CH_4 from enteric fermentation and manure management are much lower by about 22% and N_2O emissions by about 2%, reflecting the advantages of choosing a HFLS diet, as can be appreciated in the following table.

Emission Type	**Base diet (kg/year)**	**HFLS diet (kg/year)**	**Change (%)**
CH4 emissions from enteric fermentation	1.513,07	1.241,56	-21,87%
CH_4 from Manure Management	1.686,46	1.382,76	-21,96%
Direct N_2O from Manure Management	1.183,58	1.164,88	-1,61%
Indirect N_2O from Leaching	81,84	80,54	-1,61%
Indirect N_2O from Volatilization	130,19	128,14	-1,61%

Table 38 - Final emissions by the HFLS diet

With these results the LCIA was performed to assess the potential environmental impact of this new diet production, which can be seen in the following table. An HFLS-based diet has a higher content of forage (alfalfa hay, grass silage and straw), which requires a significant amount for processes like harvesting and drying, causing a higher energy demand. Plus, forage crops require more manure and organic fertilizers which lead to a higher freshwater eutrophication and terrestrial acidification potential, and the lower need of extensive croplands leads to a decrease in the agricultural land occupation.

Method	**Impact Category**	**Unit**	**New HFLS diet**	**Change**
Cumulative Energy Demand	Non-renewable, fossil	MJ	22.046.500	3%
ReCiPe Midpoint (H) V1.13	Global Warming Potential	kg CO2 eq	2.521.090	-34%
	Freshwater Eutrophication Potential	kg P eq	841,77	14%
	Agricultural Land Occupation Potential	m2a	13.600.800	-64%
	Terrestrial Acidification Potential	kg SO2 eq	26.119,3	14%

Table 39 - Change of the LCI with the new HFLS-based diet

5. Integrated mitigation strategies

The results of the new dietary mix shown in the previous chapter have a domino effect on the overall farm system, causing a decrease in output from the digester onwards, In fact, regarding the biogas production, a lower quantity of slurry and manure means less organic material available for anaerobic digestion, leading to a reduction in the total amount of methane generated, which means less fuel for cogeneration, both for heat and electricity. The heat deficit of about 69,642 kWh can be recovered by installing a heat pump; and the surplus electricity that was previously sold to the grid and to maintain virtuous self-sufficiency and additional expansion of the photovoltaic mark would be needed, with a roof installation of additional 85,5m^2 of modules.

Plus, the digestate volume, used as organic fertilizer for on-farm activities, will not be the same for crops. If not compensated with other fertilizers this could reduce crop yields over time. Since the impact of the on-farm activities on the overall carbon footprint is small, no updates were applied on the LCA system.

Since all outputs from the digester depend on the quantity of slurry and manure, a reduction in these inputs will cause proportional decreases in biogas, digestate, energy generation, and fertilizer availability, possibly requiring adjustments in farm management to maintain energy and crop production levels.

After considering these cascading effects, starting from a new-cereal based diet, the changes were considered and implemented in the LCA software, Moreover, mitigation scenarios were also applied, which are, in cascading order:

- Using more efficient by 20% of fertilizers used during the off-farm cattle rearing phase.
- Choosing a cattle supply chain with freight vehicles that have upgraded from Euro 5 to Euro 6.
- The expansion of the photovoltaic system to thrive for a stronger self-reliance.
- The adoption of electric vehicles (EVs) by at least 50%.

Finally, the results are shown in Table 40, which shows the LCIA of both Camia systems. The impact on climate change is small but shows a positive trend, and it’s noticeable that the consumption of fossil energy has notably decreased, showing that measures for higher efficiency worked, like more efficient vehicles and the adoption of photovoltaic systems. In fact, the use of renewable energy resources has experienced a rise, showing a shift toward more sustainable practices. But a small change in metal depletion potential can be noticed, probably due to the production of photovoltaics and batteries for electric vehicles, which require rare earth materials and metals. Thanks to the improved transport system, with cleaner vehicles and better fuel efficiency, there’s a reduction in particulate matter formation and smog-forming emissions.

Table 40 shows the comparison between the emission flows of the two systems. The overall trend is positive, except for the ammonia emission in the new food supply caused by the shift in a new cereal diet that required more N-based fertilizers.

Method	Impact Category		Unit	Original	Improved system with the cereal-based diet	Change
Cumulative Energy Demand	Non-renewable	Fossil	MJ	66.822.100	62.927.500	-6,19%
	Renewable	Wind Solar Geothermal	MJ	572.524	874.571	+34,54%
ReCiPe Midpoint (H) V1,13	Agricultural Land Occupation (ALOP)		m2a	42.405.900	3.983.0400	-6,47%
	Climate Change (GWP100)		kg CO2 eq	15.560.000	15.167.400	-2,59%
	Fossil Depletion Potential (FDP)		kg oil eq	1.588.440	1.500.900	-5,83%
	Freshwater Eutrophication Potential (FEP)		kg P eq	828,14	811,18	-2,09%
	Metal Depletion Potential (MDP)		kg Fe eq	164.604	164.362	-0,15%
	Particulate Matter Formation Potential (PMFP)		kg MP10 eq	26.313,5	25.086,4	-4,89%
	Photochemical Oxidant Formation Potential (POFP)		kg NMVOC eq	32.845,3	27.657,6	-18,76%
	Terrestrial Acidification Potential (TAP100)		kg SO2 eq	156.472	153.992	-1,61%

Table 40 - LCIA comparison with the improved cereal-based diet system

The same approach was used for the improved HFLS-based diet system (Table 41), leading to a lower production of manure and slurry by about 26%, asking as consequence for more reliance on the photovoltaic system and heat pump. The same mitigation scenarios as before were applied. The following table shows the LCIA result, which presents a positive trend, with a reduction of fossil fuel dependency, resource depletion and GHG emissions. Table 42 shows which of the two LCIA had better values, and the HFLS-based diet showed a more positive trend regarding potential environmental impacts and energy hotspots.

Method	Impact Category		Unit	Original	Improved system with the HFLS-based diet	Change
Cumulative Energy Demand	Non-renewable	Fossil	MJ	66.822.100	50.611.300	-32,0%
	Renewable	Wind Solar Geothermal	MJ	572.524	811.577	+29,46%
ReCiPe Midpoint (H) V1,13	Agricultural Land Occupation (ALOP)		m2a	42.405.900	40.505.800	-4,69%
	Climate Change (GWP100)		kg CO2 eq	15.560.000	14.069.300	-10,6%
	Fossil Depletion Potential (FDP)		kg oil eq	1.588.440	1.200.110	-32,36%
	Freshwater Eutrophication Potential (FEP)		kg P eq	828,14	738,75	-12,1%
	Metal Depletion Potential (MDP)		kg Fe eq	164.604	132.258	-24.46%
	Particulate Matter Formation Potential (PMFP)		kg MP10 eq	26.313,5	24.656	-6,72%
	Photochemical Oxidant Formation Potential (POFP)		kg NMVOC eq	32.845,3	25.328,9	-29,68%
	Terrestrial Acidification Potential (TAP100)		kg SO2 eq	156.472	154.250	-1,44%

Table 41 - LCIA comparison with the improved HFLS-based diet system

Impact Category	Cereal-based Diet	HFLS-based Diet
Agricultural land occupation (ALOP)	✓	
Climate change (GWP100)		✓
Fossil depletion (FDP)		✓
Freshwater eutrophication (FEP)		✓
Metal depletion (MDP)		✓
Particulate matter formation (PMFP)		✓
Photochemical oxidant formation (POFP)		✓
Terrestrial acidification (TAP100)	✓	
Non-renewable fossil energy		✓
Renewable energy (wind, solar, geo)	✓	

Table 42 - Summary of the two systems based on the diet

6. Conclusion

For this thesis a Life Cycle Assessment was conducted on a finishing farm in Northern Italy, more specifically taking as case study the Cascina Camia farm, evaluating its environmental impact and to act upon the identified hotspots some potential mitigation scenarios were identified and applied. The most impacting processes were related the diet composition, from the feed production to the manure management, off-farm livestock management and the food supply chain, contributing to greenhouse gas emissions, resource depletion and eutrophication.

The diet mix played a significant role in showcasing an alternative, less impactful scenario, since a new HFLS-based diet showed a positive shift with about 10% reduction in the Global Warming Potential and 5% decrease in Agricultural Land Occupation. The new feed composition had a lower energetic content and lower dry matter content, with a rippling effect on the overall system, from the nitrogen excretion to the total production of manure, from the biogas production to the amount of digestate used in on-farm activities. Optimizing the feed source has a significant effect on the environmental burden, remembering that cattle growth rate and health have the priority given the farm's objective.

Moreover, the use of electricity from the anaerobic digester and the expansion of the photovoltaic park were proven effective in lowering the farm's dependency on fossil fuels, which was also mitigating by implementing a more efficient on-farm and off-farm transportation system. In fact, by using electric vehicles and transitioning freight transport up to the Euro 6 standard the particulate matter formation and photochemical production experienced a reduction. It shows that a more sustainable supply chain can have a beneficial ripple effect on the anthroposphere.

Despite these perks, enteric fermentation and manure management still represent a challenging field, since there are intrinsic processes in cattle production, and further studies are necessary to substantially reduce the impact beyond dietary changes.

From a broader perspective, this thesis contributes to the growing body of literature on sustainable agriculture, but with a limited number of studies specifically on the finishing phase, by providing primary and region-specific data into its environmental impact.

In conclusion, this study demonstrates that while beef finishing farms are associated with important environmental impacts, effective mitigation strategies can lead to significant improvements. Through a synergic combination of an optimized diet, the use of renewable energy resources and a more sustainable supply chain, it is possible to strive for a more sustainable beef production system.

Appendix

A1. Life cycle Inventory of Camia

	Process	Amount	Unit	Database
Agricultural purpose	CARRO MISCELATORE ROTOMIX (1) - Machine operation, diesel, >= 74,57 kW, high load factor {GLO}| market for | CUT-OFF, S	370	h	Ecoinvent v3.8
	CARRO MISCELATORE ROTOMIX (2) - Machine operation, diesel, >= 74,57 kW, high load factor {GLO}| market for | CUT-OFF, S	1.000	h	
	TRATTRICE MERLO F50TD - Machine operation, diesel, >= 74,57 kW, low load factor {GLO}| market for | CUT-OFF, S	550	h	
	TRATTRICE MERLO F28TD - Machine operation, diesel, >= 74,57 kW, low load factor {GLO}| market for | CUT-OFF, S	365	h	
	TRATTRICE FIAT 880 - Machine operation, diesel, >= 18,64 kW and < 74,57 kW, low load factor {GLO}| market for | CUT-OFF, S	365	h	
	TRATTRICE MASSEY FERGUSON K145221A911A - Machine operation, diesel, >= 74,57 kW, low load factor {GLO}| market for | CUT-OFF, S	150	h	
	TRATTRICE MASSEY FERGUSON MF 8S,265 - Machine operation, diesel, >= 74,57 kW, low load factor {GLO}| market for | CUT-OFF, S	885	h	
	TRATTRICE MASSEY FERGUSON MF 5S,125 - Machine operation, diesel, >= 74,57 kW, low load factor {GLO}| market for | CUT-OFF, S	550	h	
	TRATTRICE MASSEY FERGUSON MF 7718 S/MF7S 180 - Machine operation, diesel, >= 74,57 kW, low load factor {GLO}| market for | CUT-OFF, S	500	h	
Industrial purpose	PALA GOMMATA CARICATRICE CNH ITALIA - Machine operation, diesel, >= 74,57 kW, low load factor {GLO}| market for | CUT-OFF, S	185	h	
	PALA GOMMATA CARICATRICE FIAT HITACHI - Machine operation, diesel, >= 18,64 kW and < 74,57 kW, low load factor {GLO}| market for | CUT-OFF, S	365	h	
Company cars	PORSCHE CAYENNE HYBRID - SUV-Transport, passenger car, medium size, diesel, EURO 5 {GLO}| market for | Conseq, S	4.000	km	
	FT CINQUECENTO - UTILITARIA - Transport, passenger car, small size, petrol, EURO 5 {GLO}| market for | CUT-OFF, S	2.500	km	
	PICK UP MITSUBISHI - Transport, passenger car, large size, diesel, EURO 5 {GLO}| market for | CUT-OFF, S	9800	km	
	LAND ROVER - FUORISTRADA - Transport, passenger car, large size, diesel, EURO 5 {GLO}| market for | CUT-OFF, S	9.800	km	

Table 43 – LCI of Company Assets

Process	Amount	Unit	Database
MOTOCOLTIVATORE BCS - Diesel, burned in agricultural machinery {GLO}| diesel, burned in agricultural machinery | CUT-OFF, S	10	l	Ecoinvent v3.8
TAGLIASIEPI - Diesel, burned in agricultural machinery {GLO}| diesel, burned in agricultural machinery | CUT-OFF, S	20	l	
MOTOSEGA - Diesel, burned in agricultural machinery {GLO}| diesel, burned in agricultural machinery | CUT-OFF, S	20	l	
TRATTORE TAGLIAERBA - Diesel, burned in agricultural machinery {GLO}| diesel, burned in agricultural machinery | CUT-OFF, S	70	l	
DECESPUGLIATORE - Diesel, burned in agricultural machinery {GLO}| diesel, burned in agricultural machinery | CUT-OFF, S	25,00	l	
SPAZZATRICE DULEVO - Petrol, unleaded {RER}| market for | CUT-OFF, S	150	l	
ESSICATORE PRODOTTI AGRICOLI - Petrol, unleaded {RER}| market for | CUT-OFF, S	13.000	l	

Table 44 - LCI of Fuels

	Process	Amount	Unit	Database
Input	Electricity, low voltage {IT}| electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted | CUT-OFF, S	30.963,32	kWh	Ecoinvent v3.8
	Ufficio - Electricity, medium voltage {IT}| market for | CUT-OFF, S	31.738	kWh	
	Azienda - Electricity, medium voltage {IT}| market for | CUT-OFF, S	144.586	kWh	
Output	Biogas - Electricity, high voltage {IT}| heat and power co-generation, biogas, gas engine | CUT-OFF, U	262.800	kWh	
	Biogas (self-consumed) - Electricity, high voltage {IT}| heat and power co-generation, biogas, gas engine | CUT-OFF, U	31.536	kWh	

Table 45 - LCI of Electricity

	Process	Amount	Unit	Database
Output	Digestate, from anaerobic digestion of manure and slurry mix (fertilizer) {RER} U	9.498.170	kg	Ecoinvent v3.8
	Biogas, from anaerobic digestion of manures mix {RER} U	1.953.480	m3	
Input	Slurry, from cattle, stocked in concrete pit (fertilizer) {RER} U	1.168E7	kg	
	Manure, from cattle, stocked in concrete surface or pit (amendment) {RER} U	80.300	kg	
	Anaerobic digestion plant, agriculture, with methane recovery {RoW}| construction | Cut-off, S - Copied from Ecoinvent U	0.065698	p	
	Agricultural digestate, stocked in silo (fertilizer) {RER} U	9.498.170	kg	
Emissions	Methane, biogenic	18.069,69	kg	
	Carbon dioxide, biogenic	17.092,95	kg	

Table 46 - LCI of Anaerobic Digestion

	Process	Amount	Unit	Databse
Food & implements supply	Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | CUT-OFF, S	2.030.330.822	tkm	Ecoinvent v3.8
	Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | CUT-OFF, S	7.503.853,5	tkm	
	Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | CUT-OFF, S	329.5314,9	tkm	
	Transport, freight, lorry 7,5-16 metric ton, euro5 {RER}| market for transport, freight, lorry 7,5-16 metric ton, EURO5 | CUT-OFF, S	74.805,12	tkm	
	Transport, freight, lorry 7,5-16 metric ton, euro5 {RER}| market for transport, freight, lorry 7,5-16 metric ton, EURO5 | CUT-OFF, S	58.968	tkm	
	Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | CUT-OFF, S	9.023.553,36	tkm	
	Transport, freight, lorry 3,5-7,5 metric ton, euro5 {RER}| market for transport, freight, lorry 3,5-7,5 metric ton, EURO5 | CUT-OFF, S	1.820,4	tkm	

Table 47 – LCI of suppliers

	Process	Amount	Unit	Database
Fuel supply	Transport, freight, light commercial vehicle {Europe without Switzerland}| market for transport, freight, light commercial vehicle | CUT-OFF, S	762,26	tkm	Ecoinvent v3.8
	Transport, freight, light commercial vehicle {Europe without Switzerland}| market for transport, freight, light commercial vehicle | CUT-OFF, S	839,16	tkm	
Cattle supply	Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | CUT-OFF, S	1.125.722,16	tkm	
	Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | CUT-OFF, S	1.922.618,88	tkm	
	Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | CUT-OFF, S	5.667.801,98	tkm	
	Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | CUT-OFF, S	9.303.489	tkm	
	Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | CUT-OFF, S	246.090.312	tkm	
	Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | CUT-OFF, S	708.230.016	tkm	
	Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | CUT-OFF, S	810.445.779	tkm	
	Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | CUT-OFF, S	1.1173.383	tkm	
	Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | CUT-OFF, S	13.288.509	tkm	
	Transport, freight, lorry > 16-32 metric ton, euro5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | CUT-OFF, S	25.871.976	tkm	
	Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | CUT-OFF, S	354.789.396	tkm	
	Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | CUT-OFF, S	20.274.164	tkm	
	Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | CUT-OFF, S	247.531,05	tkm	
	Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | CUT-OFF, S	40.401.972	tkm	
	Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | CUT-OFF, S	10.238.436	tkm	
	Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | CUT-OFF, S	71.040.645	tkm	
	Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | CUT-OFF, S	2.942.784	tkm	

Process	Amount	Unit	Database
SUV ibrido - Transport, passenger car {RER}| market for | CUT-OFF, S	36.720	Km	Ecoinvent v3.8
Utilitaria - Transport, passenger car, small size, petrol, EURO 5 {GLO}| market for | CUT-OFF, S	2.500	Km	
Utilitaria - Transport, passenger car, small size, diesel, EURO 5 {GLO}| market for | CUT-OFF, S	5.600	Km	
STATION WAGON - Transport, passenger car, medium size, petrol, EURO 5 {GLO}| market for | CUT-OFF, S	7.200	Km	
Utilitaria 4x4 - Transport, passenger car, small size, diesel, EURO 5 {GLO}| market for | CUT-OFF, S	7.500	km	

Table 48 - Life Cycle Inventory of workers

Process	Amount	Unit	Database
Carta - Waste paper, unsorted {Europe without Switzerland}| market for | CUT-OFF, S	1.000	kg	Ecoinvent v3.8
Plastica - Waste plastic, mixture {Europe without Switzerland}| market group for waste plastic, mixture | CUT-OFF, S	2.000	kg	
Legno - Waste wood, untreated {RER}| market group for waste wood, untreated | CUT-OFF, S	12.500	kg	
Metallo - Aluminium scrap, post-consumer {RER}| treatment of, by collecting, sorting, cleaning, pressing | CUT-OFF, S	1.500	kg	

Table 49 - LCI of Waste

	Process	Amount	Unit	Database
Cattle to be fattened [w/out transportation]	Beef cattle, national average, at farm gate {FR} U	1.640.000	kg	Agribalyse V3.1.1
Cereals	Spelt, organic, at farm gate {FR} S	143.015	kg	
	Grain maize, organic, animal feed, at farm gate {FR} S	1.127.980	kg	
	Barley, organic, animal feed, at farm gate {FR} S	230.220	kg	
	Soft wheat grain, conventional, national average, animal feed, at farm gate, production {FR} S	1.370.150	kg	
Legumes	Soybean, national average, animal feed, at farm gate {FR} S	1.890.540	kg	
Vegetables	Sugar beet pulp dehydrated, animal feed, at plant {FR} S	833.051	kg	
Straw	Alimentazione - Straw, stand-alone production {RER}| market for straw, stand-alone production | CUT-OFF, U	1.866.525	kg	
	Lettiera - Straw, stand-alone production {RER}| market for straw, stand-alone production | CUT-OFF, U	494.495	kg	
Supplements	Vitamin, animal feed, at retailer gate {FR} S	300.920	kg	
Water	Water, completely softened {RER}| market for water, completely softened | CUT-OFF, U	10.000.000	kg	Ecoinvent v3.8

Table 50 - LCI of livestock assets

	Process	Amount	Unit	Item(s)	Source	Database
Transparent envelopes	Extrusion, plastic film {GLO}| market for | CUT-OFF, S	5.40E-01	kg	5		Ecoinvent v3.8
Folders	Folding boxboard carton {RER}| market for folding boxboard carton | CUT-OFF, S	1.60E-01	kg	20		
Scissors	Acrylonitrile-butadiene-styrene copolymer {RER}| acrylonitrile-butadiene-styrene copolymer production | Cut-off, S	1.80E-02	kg	1	[36]	
	Steel, chromium steel 18/8 {RER}| steel production, electric, chromium steel 18/8 | CUT-OFF, S	2.20E-02	kg			
Printer ink	Toner module, laser printer, colour {GLO}| production | CUT-OFF, S	1.140	kg	6		
Pencil	Electricity, high voltage {IT}| market for | CUT-OFF, S	8.64E-02	kWh	20	[37]	
	Lead {GLO}| market for | CUT-OFF, S	1.92E-03	kg			
	Paraffin {GLO}| market for | CUT-OFF, S	1.15E-03	kg			
	Sawnwood, board, hardwood, dried (u=10%), planed {Europe without Switzerland} | market for sawnwood, board, hardwood, dried (u=10%), planed | CUT-OFF, S	6.07E-05	m3			
	Synthetic rubber {GLO}| market for | CUT-OFF, S	8.68E-04	kg			
	Water, decarbonised {RoW}| market for water, decarbonised | CUT-OFF, S	8.43E-03	l			
Pen	Benzyl alcohol {GLO}| market for | CUT-OFF, S	2.70E-04	kg	100	[38]	
	Brass {RoW}| market for brass | CUT-OFF, S	4.99E-04	kg			
	Electricity, high voltage {IT}| market for | CUT-OFF, S	7.00E-04	kWh			
	Polypropylene, granulate {GLO}| market for | CUT-OFF, S	6.93E-04	kg			
	Polystyrene, general purpose {GLO}| market for | CUT-OFF, S	3.88E-04	kg			
Post-it notes (pack of 10)	Paper, woodcontaining, lightweight coated {RER}| market for | CUT-OFF, S	4.16E-03	kg	2		
Staples	Containerboard, linerboard {RER}| market for containerboard, linerboard | CUT-OFF, S	6.50E-02	kg	20		
	Steel, low-alloyed	4.00E-01	kg			
Reams of paper	Paper, woodcontaining, lightweight coated {RER}| market for | CUT-OFF, S	2.50	kg	10		
Document binder	Folding boxboard carton {RER}| market for folding boxboard carton | CUT-OFF, S	6.20E-01	kg	10		
Adhesive tape roll	Polypropylene, granulate {GLO}| market for | CUT-OFF, S	1.36E-01	kg	5		
	Synthetic rubber {GLO}| market for | CUT-OFF, S	3.40E-02	kg			

Table 51 - Life Cycle Inventory of the office items

A2. Equations

The methane emission from enteric fermentation is calculated as follows:

$$CH_{4\,\mathrm{ent},T} = EF_{met,ent,T} \cdot AAP_t \qquad (2)$$

$$EF_{met,ent,T} = \frac{GE_T \cdot \frac{Y_{m,t} \cdot 356}{100}}{55{,}65} \qquad (3)$$

Where:

- $CH_{4\,\mathrm{ent},T}$ are the methane emissions from enteric fermentation (kg CH_4/year).
- $EF_{met,ent,T}$ is the emission factor for methane from enteric fermentation (kg CH_4/head/year). It depends on the gross energy content of feed and methane conversion efficiency.
- AAP_t is the average annual population (head) and it's provided by the Camia farm, with value equal to 1,640,000 heads.
- GE_T is the gross energy intake per head, per day (MJ/head/day), It depends on the diet fed to the livestock and it is calculated based on the energy content of the feed, More details can be seen in Table 23 and Table 24.
- $Y_{m,t}$ is the methane conversion factor (dimensionless). It depends on the diet and the specific feed methane-producing capacity, and it's given by default. The default IPCC value for beef cattle is 6,5%.
- 55,65 is the energy content of methane (MJ/kg CH_4),

The methane emission from manure management is calculated as follows:

$$CH_{\mathrm{man},T} = VS_T \cdot 365 \cdot AAP_t \cdot B_{0,T} \cdot \rho_{\mathrm{met}} \cdot \sum_S \mathrm{Frac}_{S,t} \cdot \frac{MCF_S}{100} \qquad (4)$$

Where:

- $CH_{4\,\mathrm{man},T}$ are the methane emissions from manure management (kg CH_4/year).
- VS_T are volatile solids produced per animal (kg VS/head/year), It is calculated based on the diet digestibility (DE_t), urinary energy (UE_t) and ash content (ASH_t).
- AAP_t is the average annual population (head) and it's provided by the Camia farm, with value equal to 1,640,000 heads.
- $B_{0,T}$ is the maximum methane producing capacity for manure (m^3 CH_4/kg VS) and it's a default value provided by the guideline,z The default IPCC value for cattle manure is 0,25m^3/kg.
- ρ_{met} is the density of methane (kg CH_4/m^3).
- $\mathrm{Frac}_{S,t}$ is the fraction of manure managed by the system S (dimensionless), The value depends on the manure management practices, The IPCC guidelines provide values often used as defaults in the absence of farm-specific data, and they correspond to 60% as the fraction stored as solid, and 40% as the fraction spread directly as fertilizer.

- MCF_S is the methane conversion factor for the system, and it depends on manure management and temperature (%), Default values are provided in the guidelines, and the default IPCC value for temperate climate and solid storage system is equal to 15%.

$$VS_T = \left[GE_T \cdot \left(1 - \frac{DE_T}{100}\right) \cdot (UE_T \cdot GE_T)\right] \cdot \frac{1 - ASH_T}{18{,}45} \tag{5}$$

Where:

- DE_t is the diet digestibility, expressed as a fraction of gross energy (%), It can be provided by the interested subject or estimated based on diet composition and feed quality. The IPCC Guidelines for National Greenhouse Gas Inventories suggest using 85% for digestibility when detailed feed composition data is unavailable.
- UE_t is the urinary energy, expressed as a fraction of gross energy (dimensionless), It is provided by the interested subject or taken from default values, The default value is equal to 2%.
- ASH_t is the ash content of feed, expressed as a fraction of gross energy (dimensionless), It can be provided by the interested subject or estimated based on the feed analysis. According to the IPCC guidelines 4% is the default value for ash content in the feed for livestock.
- $18{,}45$ is the energy content of volatile solids (MJ/kg) .

The nitrous oxide emission from manure management is calculated as follows:

$$N2O_{dir,T} = \sum \left[\left(AAP_T \cdot N_{ext,T} \cdot Frac_{S,T} + N_{cdg,s}\right) \cdot EF_{nit,T}\right] \cdot \frac{44}{88} \tag{6}$$

Where:

- $N2O_{dir,T}$ is the direct N_2O emissions from manure (kg N_2O/year).
- AAP_T is the average annual population (head) and it's provided by the Camia farm, with value equal to 1,640,000 heads.
- $N_{ext,T}$ is the annual N excretion per animal (kg N/head/year) and it is provided by the interested subject, It is calculated with **Errore. L'origine riferimento non è stata trovata.**.
- $Frac_{S,T}$ is the fraction of manure managed in the system (dimensionless),
- $N_{cdg,s}$ is the annual N input via co-digestate (kg/year).
- $EF_{nit,T}$ is the emission factor for direct N_2O emissions from manure management (kg N_2O-N/kg N), According to the IPCC guidelines the default value is 0,01 kg N_2O-N/kg N.

$$N_{ext,T} = N_{intake,T} \cdot \left(1 - N_{retention\,frac,T}\right) \cdot 365 \tag{7}$$

Where:

- $N_{intake,T}$ is the daily nitrogen intake per animal (kg N/head/day) and it is calculated with **Errore. L'origine riferimento non è stata trovata.**.

- $N_{retention\,frac,T}$ is the fraction of daily N retained by animal (dimensionless) and it is calculated with **Errore. L'origine riferimento non è stata trovata.**.

$$N_{intake,T} = \frac{GE_T}{18{,}45} \cdot \frac{CP_T/100}{6{,}25} \qquad (8)$$

Where:

- GE_T is the gross energy intake per animal (MJ/head/day).
- CP_T is the crude protein content in the overall diet (%), As shown by **Errore. L'origine riferimento non è stata trovata.** it is calculated as the weighted average of the crude protein content of each component, adjusted for the dry content, as seen in Table 27 and Table 28.

$$\mathrm{CP_T} = \frac{\sum CP_i \cdot \mathrm{DM_i} \cdot \mathrm{Feed\ intake_i}}{\sum DM_i \cdot Feed\ intake_i} \qquad (9)$$

Where:

- CP_i is the crude protein content of the specific feed i (% of dry matter).
- DM_i is the dry matter content of the specific feed i (%).
- $Feed\ intake_i$ is the quantity of the feed ingredient i (kg) .

$$N_{retention\,frac,T} = \frac{WG_T \cdot \frac{268 - \frac{7{,}03 \cdot NE_{g,T}}{WG_T}}{100}}{6{,}25} \qquad (10)$$

Where:

- WG_T is the animal weight gain (kg/day).
- $NE_{g,T}$ is the net energy for growth (MJ/day) and It is calculated with **Errore. L'origine riferimento non è stata trovata.**.

$$NE_{g,T} = 22{,}02 \cdot \left(\frac{BM_T}{C_T \cdot MW_T}\right)^{0{,}75} \cdot {WG_T}^{1{,}097} \qquad (11)$$

Where:

- BM_T is the average body weight (kg).
- MW_T is the expected mature weight of cattle (kg).
- WG_T is the average weight gain per day (kg/day).
- C_T is the coefficient for maintenance energy requirement, a scaling factor used to adjust net energy for growth calculations and according to the IPCC guidelines it is equal to 1,2.

The indirect N_2O emissions from leaching of manure is calculated as follows:

$$N_2O_{ind,leach} = N_{leach} \cdot EF_{leach} \cdot 44/28 \qquad (12)$$

Where:

- $N_2O_{ind,leach}$ is the total indirect nitrous oxide emission from leaching of manure (kg/year).
- N_{leach} is the total amount of manure lost due to leaching (kg/year) and it is calculated as shown with **Errore. L'origine riferimento non è stata trovata.**.
- EF_{leach} is the emission factor for N_2O emissions from nitrogen leaching and runoff, and its default value is set to 0,011.

$$N_2O_{leach,T} = \sum\left[\left(AAP_T \cdot N_{ext,T} \cdot Frac_{S,T} + N_{cdg,s}\right) \cdot Frac_{leach,S,T}\right] \qquad (13)$$

Where:

- AAP_T is the average annual population (head) and it's provided by the Camia farm, with value equal to 1,640,000 heads.
- $N_{ext,T}$ is the annual N excretion per animal (kg N/head/year) and it is provided by the interested subject, It is calculated with **Errore. L'origine riferimento non è stata trovata.**.
- $Frac_{S,T}$ is the fraction of manure managed in the system (dimensionless),
- $N_{cdg,s}$ is the annual N input via co-digestate (kg/year).
- $Frac_{leach,S,T}$ is the fraction of manure nitrogen lost through leaching and according to the IPCC guidelines the default value is equal to 0,02.

The total indirect nitrous oxide emission from volatilization of NH_3 and NO_x is calculated as follows:

$$N_2O_{ind,vol} = N_{vol} \cdot EF_{vol} \cdot 44/28 \qquad (14)$$

Where:

- $N_2O_{ind,vol}$ is the total indirect nitrous oxide emission from volatilization of NH_3 and NO_X (kg/year).
- N_{vol} is the total amount of manure lost due to volatilization (kg/year), and it is calculated with the **Errore. L'origine riferimento non è stata trovata. Errore. L'origine riferimento non è stata trovata.**.
- EF_{vol} is the emission factor for N_2O emissions from nitrogen leaching and runoff, and its default value is set to 0,010.

$$N_{vol,T} = \sum\left[\left(AAP_T \cdot N_{ext,T} \cdot Frac_{S,T} + N_{cdg,s}\right) \cdot Frac_{vol,S,T}\right] \qquad (15)$$

Where:

- AAP_T is the average annual population (head) and it's provided by the Camia farm, with value equal to 1,640,000 heads.

- $N_{ext,T}$ is the annual N excretion per animal (kg N/head/year) and it is provided by the interested subject, It is calculated with **Errore. L'origine riferimento non è stata trovata.**.
- $Frac_{S,T}$ is the fraction of manure managed in the system (dimensionless).
- $N_{cdg,s}$ is the annual N input via co-digestate (kg/year).
- $Frac_{vol,S,T}$ is the fraction of managed manure nitrogen that is volatilized from the manure management system, and according to the IPPC guidelines its default value is equal to 0,035.

The total amount of manure and slurry due to the new diet formulation are calculated as follows:

$$Manure_{new} = \left(\frac{DMI_{new}}{DMI_{base}}\right) \cdot Manure_{base} \qquad (16)$$

Where:

- $Manure_{new}$ is the total manure production with the new diet (kg/year).
- $Manure_{base}$ is the total manure production with the base diet (kg/year).
- DMI_{new} is the total dry matter intake with the base diet (kg/year).
- DMI_{base} is the total dry matter intake with the new diet (kg/year).

$$Slurry_{new} = \left(\frac{Manure_{new}}{Manure_{base}}\right) \cdot Slurry_{base} \qquad (17)$$

Where:

- $Slurry_{new}$ is the total amount of slurry production with the new diet (kg/year).
- $Slurry_{base}$ is the total amount of slurry production with the old diet (kg/year).

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