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Abstract

The environmental sustainability of livestock production is a well-researched topic. Although there are various ways to reduce the environmental impact of producing milk and meat from dairy cows, enteric methane emissions remain a significant and unavoidable factor. However, improvements in efficiency, greater attention to animal health and welfare, and renewable energy production initiatives can help farmers minimise their environmental footprint. In this context, technology and farm digitalisation can support farmers in managing their farms. This study aims to analyse the environmental performance of a dairy cattle farm in an intensive livestock area in northern Italy using Life Cycle Assessment (LCA). The farm has automatic milking and feeding systems, as well as renewable energy production plants (solar panels and anaerobic digestion), all of which can be monitored remotely. Through an external enterprise, a data collection platform was developed with inputs and outputs of the barn that automatically update daily. To each input/output, a value of carbon footprint was matched, resulting in a daily carbon footprint calculator of the farm, for the whole year 2024. The results of the LCA study show a remarkably low environmental impact, with a carbon footprint of 0.80 kg CO_2eq/kg fat- and protein-corrected milk (FPCM). Instead, the daily carbon footprint calculator consistently yielded lower estimates because of its simplified methodology. However, its purpose is not to replace comprehensive emission assessments but to provide a simple and easily generated indicator that helps increase farmers' awareness of the environmental impacts associated with their daily farming practices.

Key words: automatic data collection; automatic feeding; automatic milking; biomethane; carbon footprint daily counter; photovoltaic energy.

Introduction

The production of animal protein has become a significant environmental concern, particularly with regard to livestock (Espinosa-Marrón *et al*., 2022; Pulina *et al*., 2022). This production activity is often attributed a considerable negative environmental impact, primarily due to the enteric methane emissions of ruminants (Berton *et al*., 2024; Evangelista *et al*., 2024), and the storage and field distribution of manure, which leads to ammonia emissions into the air (Finzi *et al*., 2019), as well as nitrogen and phosphorus leaching and runoff (Bacenetti *et al*., 2016; Kupper *et al*., 2020). These emissions contribute to climate change, acidification and eutrophication. Methane (CH_4) is a potent greenhouse gas that has been extensively investigated by researchers in recent years (Manono, 2026), as efforts have been made to properly quantify its contribution from livestock activities to climate change (Spizzirri *et al*., 2024; Correddu *et al*., 2025) and to identify possible ways of reducing it from enteric fermentation (Melgar *et al*., 2021). Ammonia (NH_3) is a gas that contributes to soil acidification and particulate matter (PM) formation, and nitrogen and phosphorus released into soils and water systems cause water eutrophication. These compounds are widely emitted by livestock practices, and strategies to limit these emissions are well known (de Vries, 2021). Furthermore, the considerable use of resources such as energy and water on livestock farms could impact the depletion of fossil resources (Papadopoulos *et al*., 2025) making it necessary to focus on renewable sources. Lastly, concerns from consumers and society about animal welfare and living conditions are leading to the introduction of stricter rules on the traceability of animal products, requiring an additional commitment on farmers and on data availability (Gorton *et al*., 2023).

In this context, to support farmers in managing their livestock herds and responding to environmental and social requirements, an increasing number of tools and instruments have become available. These tools have been developed within the framework of Precision Livestock Farming (PLF), a field of study that uses sensors and tools to monitor farmed animals 24/7 in order to support farmers' decisionmaking processes (Berckmans, 2017). Automatic milking systems (AMS), for example, were the first of such tools to be distributed on the market around 30-40 years ago to support farmers in managing milking operations (Jacobs and Siegford, 2012). The consequences of these AMS and subsequent technological improvements have been to increase animal production, improve the milking routine and monitor milk quality, quantity and udder health. Although not all studies have consistent findings, AMS often results in reduced somatic cell count in the long term (Jacobs and Siegford, 2012). Moreover, it enables the identification of fertility status to support artificial fertilisation procedures (Dzermeikaite *et al*., 2023). Other introduced technologies include automatic feeding systems (AFS) that distribute feed to animals, and accelerometers (pedometers and collars) that monitor animal behaviour (Leliveld *et al*., 2024; Riaboff *et al*., 2022). These technologies contribute to improving knowledge of animal health, welfare, and management. It is known that through PLF, farmers can improve their knowledge of animal management, health, welfare and productivity, act promptly on the herd, lastly improving their overall efficiency (Berckmans, 2017). Consequently, the adoption of PLF and the digitalisation of farms has become a reality and has shown to be able to support the achievement of more environmentally sustainable livestock farms (Papadopoulos *et al*., 2025; Balaine *et al*., 2020; Lovarelli *et al*., 2024). However, the effective application of these techniques still poses challenges that need to be investigated (e.g. costs and data use) (Finger, 2023). The rapid achievement of a net zero emissions approach is fundamental from the perspective of current European policies. Hence, advanced and efficient management techniques are needed to maintain satisfactory production rates that meet the needs of the global population while guaranteeing productions with reduced environmental impacts (Espinosa-Marrón *et al*., 2022).

In this context, the aim of this study is to present the environmental sustainability results of a case study farm located in northern Italy that hosts dairy cattle and that is equipped with various PLF tools and a digitalised data collection system that supports the daily farm management. In particular, this digitalised platform summarises on a daily basis the main inputs and outputs of the livestock farm and enables the farmer to control what is used (i.e. amount of feed used by cows, amount of electricity consumed by the different users) and what is produced (i.e. amount and quality of milk produced, amount of renewable energy produced) on farm. A specific objective of this study is to understand if the availability of inputs and outputs data on a daily basis can inform better about the environmental impact of the farm. To do so, first a comprehensive Life Cycle Assessment (LCA) has been completed with a yearly base of data; then, the focus has been paid on the development of a Daily Carbon Footprint calculator, which has resulted in a daily indication of the carbon footprint of the farm. This daily carbon footprint calculator has been added to the digitalised platform, hence resulting in an automatic system that updates every day the carbon footprint of the farm based on the inputs used and outputs produced. In addition, since the installed technologies are powered almost entirely by renewable energy solutions, this assessment enables to raise considerations about the mitigation role of renewable energy production on farms. The innovation of this study is linked with the assessment of the benefits of having a digitalised platform on farm that provides information on farm performance on a daily basis, including a daily carbon footprint calculator.

Materials and Methods

Description of the case study farm

The housing system

The monitored farm is located in the province of Cremona, Lombardy region, in Northern Italy. Lombardy is a region highly specialised in dairy production where more than 26% of Italian cow farms are located (data from the Italian National Institute of Statistics – 2025; https://esploradati.istat.it/databrowser/#/en).

The farm has a recently built barn structure housing a herd of about 800 dairy Friesian Holstein cows. The barn has a rectangular layout and is oriented east-west. It comprises parallel buildings: one measuring 180 m long by 45 m wide for lactating cows; a second measuring 140 m long by 38 m wide for heifers and primiparous cows; and two smaller structures measuring 60 m long by 20 m wide and 30 m long by 10 m wide for calves. All buildings are open with a ridge opening to support natural ventilation, and the barns' lateral sides are completely open with sliding shading nets to protect the animals from adverse weather conditions. Furthermore, all sections of the barn, including those housing calves, have mechanical ventilation with vertical fans. The cows lie on bedding cubicles made of precast reinforced concrete and filled with the solid fraction of digestate produced on the farm through an anaerobic digester. Sprinklers are installed to help dissipate the heat generated by the cows while they are eating at the rack in the warm seasons. Drinking water is constantly available for all animals, and in winter it is heated using the heat produced by the combined heat and power engine. This heat is also used to warm the boxes housing calves, ensuring they are kept at an adequate temperature for their welfare during the winter.

Available precision livestock equipment

The farm has automatic systems to support the most intensive operations in the barn. With regard to feeding operations (Figure 1), two feeding robots (Trioliet BV Triomatic) were purchased for feeding the cows. These robots automatically prepare different diets for distinct groups of animals in the herd by mixing available feeds in a defined storage area. The robots move along an electric rail in the barn, going through it several times a day and night to automatically distribute feed (usually 6-8 times a day) and transfer the ration closer to the rack. This allows the cows to have access to fresh feed. The diet is defined by the farm nutritionist, who lists the feed types and quantities in the dedicated software. Additionally, new-born calves (on average aged between 1 and 15 days) are fed by an automatic feeding system consisting of an arm that moves through the boxes and distributes a defined amount of milk to the calves six times a day (CalfRail, Förster-Technik). After this period, calves (from about 15 days to complete weaning around 80 days) are housed in groups and fed through automatic calf feeders that distribute milk; starter feed is available at the rack until they are fully weaned. These automatic feeders record the milk consumption of each calf per day on the dedicated software. All these automatic feeding systems use only electricity as energy source, with an average energy consumption of 3-4% of the total energy consumption of the livestock farm.

In addition, 10 Lely Astronaut A5 milking robots are available for the automatic milking system (AMS). These robots allow cows to be milked with a free access solution. The dedicated software registers daily data on milk quantity, quality and frequency for each cow and for the herd. Each cow is equipped with neck collars (Lely Qwes series) that are used for the identification of animals in the AMS as well as for monitoring their behaviour. The electricity consumption dedicated to the AMS amounts to around 6-7% of the farm's total consumption.

Other equipment in the barn

Other systems complete the picture of the barn management solutions:

- slurry management in the barn: scrapers remove the slurry from the barn every hour and convey it to a closed under-floor slurry channel at the end of the barn. From there, the slurry is pumped directly and immediately to the anaerobic digestion plant, where it is digested. The purpose of the closed under-floor slurry channel is simply to enable the pumps to work immediately after the slurry is conveyed from the barn. Therefore, no open pit is present, and no pit storage is present. In addition, no slurry storage tank is required. Therefore, no emissions from slurry storage in open tanks are considered, but only those deriving from the anaerobic digestion plant. On the energetic point of view, this operation accounts for 11% of the farm's overall energy consumption, with 0.5% dedicated to the scrapers and 10.6% to pumping slurry to the AD plant. After digestion, the resulting digestate is pumped to a solid-liquid separation system. The liquid fraction is spread on fields as an organic fertiliser, while the solid fraction is used as animal bedding,
- barn ventilation: nowadays the mechanical ventilation system is fundamental, especially in areas such as Po Valley where summers are particularly hot and cows can suffer prolonged

heat stress (Polsky and von Keyserlingk, 2017). To guarantee milk productivity, animal welfare, and overall animal efficiency, vertical fans are installed throughout the barn, accounting for around 8% of the total electricity consumption. It should be noted that fans use the most electricity in summer, while their use is minimal in winter. For example, in winter, the electricity consumed by the fans is below 4%, whereas in summer it can account for up to 35% of the total electricity consumption,

- barn's lighting system: the barn is equipped with efficient LED bulbs that consume on average 2.4% of total electricity,
- refrigeration: the refrigeration system used to keep milk at 4°C between milking and delivery to the dairy uses about 8.1% of the barn's annual electricity.

Table 1 provides a summary of the energy user and annual electricity consumption, as well as the relative consumption. The data refers to the year 2024 and was collected automatically using the data collection platform.

Renewable energy production plants

In terms of renewable energy production, the farm has an anaerobic digestion (AD) plant that upgrades biogas into biomethane. The plant uses dairy cattle slurry pumped directly from the barn, as feed. It also uses a fraction of the triticale and sorghum silages produced on the farm, as well as tomato peels and sweetcorn cobs purchased from the local agri-food industry. Other inputs include maize stover, cow manure and poultry manure, which are purchased from local farms. The biogas produced is upgraded in several steps: first, it is cleaned in a desulphurisation tower and then upgraded through membranes that remove the carbon dioxide. The resulting biomethane is 99% pure and is entirely sold through pipelines as gas for local heating systems. The carbon dioxide separated from the biomethane during upgrading is released into the atmosphere rather than being valorised. This AD plant produces approximately 390 Sm^3/h of biomethane, with an average of 3,450,487 Sm^3 of biomethane per year. The digestate produced is mechanically separated using a centrifuge. The liquid fraction is stored in closed tanks and used as fertiliser in the fields, while the solid fraction is stored and used as bedding material in the cows' cubicles.

In addition, on the barn’s roof is installed a photovoltaic plant with total power output of 920 kW which consists of monocrystalline silicon panels. In 2024, 74% of the electricity produced was used on site, while a small amount was sold to the grid (equivalent to 323,604 kWh). To cope with peak electricity demand, the farm uses a combined heat and power engine (CHP) of 300 kW of electric power, which meets energy requirements when renewable energy production is insufficient. The CHP produces electricity using natural gas as fuel and is primarily used in the process of biomethane upgrading and plant functioning. The benefit of this solution is that it produces electricity and recovers heat through a heat exchanger, resulting in a combined cycle that increases the overall process efficiency. The recovered heat is valorised by recirculating warm water for internal use and for heating the digesters (e.g. warm the cows and calves' drinking water, the boxes where calves are reared and the biomethane plant).

Herd composition and milk productivity

The herd is composed of an average of 692 lactating Holstein Friesian cows, 127 dry cows, 180 heifers and 130 calves.

Their average milk production (based on quantity sold to the dairy) is 39.5 kg per cow per day, with a fat content of 3.91% and a protein content of 3.56%. The farm also sells all male calves, with a total live weight of 41,309 kg produced.

Regarding the feed rations, the animals are provided with the feed quantities reported in Table 2, using the aforementioned AFS. In particular, the following amounts of dry matter (DM) are fed daily: 26.7 kg/d per lactating cow, 14.8 kg/d per dry cow, and 11.2 kg/d per heifer.

Water is provided by the farm's well. Its daily consumption includes drinking water for the cows (approximately 100 litres per dry cow and heifer per day, and approximately 180 litres per lactating cow per day), water to be mixed with milk powder for calves, water for sprinklers and for cleaning AMS, floors and farm facilities. Overall, an average consumption of 95,500 m^3 per year has been recorded in 2024.

Field operations

The farm has 1,263 hectares of cultivated land, 400 of which are cultivated using double cropping systems. Almost 700 hectares are cultivated with winter crops, such as wheat, triticale and Italian ryegrass. These are sown in autumn and harvested in spring to produce silage. In spring, maize is sown to produce maize silage, partly as a single crop (almost 300 hectares) and partly in a double cropping system with winter crops (400 hectares). Lastly, sorghum is produced on a total area of around 300 hectares. These crops are used as animal feed and as biomass for the biomethane digester. The farm also has 100 hectares dedicated to producing agri-food products, such as sweetcorn, tomatoes and beans, which are cultivated, harvested and processed by the local agri-food industry under a dedicated contract.

In terms of field operations, minimum soil tillage practices are adopted and only the liquid fraction of digestate is used as fertiliser, which is injected directly into the soil. No mineral fertiliser is used. The soil texture is medium on half of the area, sandy on 20%, and clayey on 30%. Summer crops (maize and sorghum) are irrigated to guarantee their water requirements, with different techniques used for different fields, such as drip irrigation or sprinkler irrigation. The diesel consumption for each field operation was gathered through interviews with farmers, resulting in a total of 412,200 litres per year during the monitored period.

Table 3 reports the main inventory data for field cultivation practices. The aforementioned agri-food products (sweetcorn, tomatoes and beans) are excluded from this list and the subsequent analyses, as the agri-food industry is responsible for these practices and their use.

Life Cycle Assessment

In compliance with ISO Standards 14040-14044 (ISO 14040, 2006; ISO 14044, 2018), the LCA methodology was used to carry out the study on the environmental sustainability assessment. The methodological steps are reported in the following paragraphs.

Goal and scope, system boundary and allocation method

This study aims to quantify the environmental impact of an intensive livestock farm in the Po Valley in northern Italy in its current state. The farm is characterised by advanced technological systems at barn level and by a digitalised data collection system. In particular, barn management is automated through the use of automatic milking and feeding systems for livestock, and renewable energy is produced. Data from the different tools is conveyed on one single platform where the input and output data of the livestock farm are visible and updated automatically every day. This case study farm enables stakeholders and policymakers to assess the benefits of technological support, data collection and usage for sustainable livestock farming. Consequently, a second objective is to show the results of a daily carbon footprint calculator developed using the farm's digitalised data collection system. This calculator quantifies the carbon footprint per input and output, lastly resulting in a final daily value of carbon footprint. Its primary use could be to make farmers aware of their daily contribution to global warming.

In accordance with the PEFCR document (2025), the functional unit (FU) selected for this study was 1 kg of fat- and protein-corrected milk (FPCM). This was calculated using the IDF (2015) equation, considering a milk quality standard of 4% fat and 3.6% protein content.

The system boundary is shown in Figure 2 and extends from cradle to farm gate. All relevant stages of the production cycle aimed to produce milk until the farm gate are included. Instead, from the system boundary are excluded the crops cultivated, harvested and processed directly from the agri-food industry (and not from the farm) for food production (i.e. sweetcorn, tomatoes and beans) and the indirect land-use change. Renewable electricity produced on farm is partially used and partially sold to the grid in the national mix, while the produced biomethane is fully sold and considered as an output which avoids the extraction and use of methane of fossil origin. The temporal boundary is equal to one year, in particular year 2024. The attributional approach uses the biophysical allocation method suggested by PEFCR (2025), whereby the environmental impact is shared between milk and meat production. In particular, the impact allocated to milk accounts for 90.5%, while the remaining to meat.

Life Cycle Inventory

The methodological steps detailed in the Product Environmental Footprint Category Rules (PEFCR) for dairy products (PEFCR, 2025) were followed. In particular, in this document are listed inputs and outputs to be included in the life cycle inventory, the allocation method and the calculation method to be used for quantifying emissions from the system in order to conduct a robust and comparable study. All data relating to farm management, animals, feed, energy use and production was collected directly on the farm with the support of an external enterprise that developed the automated platform capable of collecting data from all the farm's dedicated software and tools. In practice, this platform collected daily data automatically from various software systems available on farm, gathering information on the number and category of animals, on the AMS productivity and AFS of cows and calves, on energy production and use, energy production from photovoltaic and biomethane plants, CHP energy production (electricity and heat), energy use from the mechanical ventilation system, the lighting system, the slurry removal from the barn and pumping it to the biomethane plant, and water usage. The final output of the data collection platform was a series of daily tables in .xlsx format. Additionally, other data was collected directly from the farmer, including the overall barn and equipment management, amount of feed produced on field and purchased, and field cultivation practices including cultivated crops, area cultivated, crop yield, cultivation practices (e.g. minimum tillage, liquid digestate distribution and irrigation techniques) and inputs used (e.g. seeds, water and diesel fuel).

A detailed list of the main inventory data can be found in Tables 1, 2 and 3. Table 4 reports the main inventory data at barn level.

The environmental impact assessment was based on primary data collected on the farm with regard to the foreground processes, while background processes (e.g. purchased feed and other inputs) were obtained from the Environmental Footprint database (EF v.3.1).

Animal and field emissions were quantified using different methods based on the emission source.

Tier 2 assessment, as suggested in the IPCC methodology (IPCC, 2019 Refinement to the 2006 Guidelines for National Greenhouse Gas Inventories, Volume 4: Agriculture, Forestry and Other Land Use), was used to model enteric CH_4 emissions. Following this methodology, the emission factor (EF) of enteric CH_4 was quantified considering the estimation of the gross energy intake (GE) (Eq. 10.16 from Chapter 10, IPCC 2019) based on the net energy needs for maintenance (Eq. 10.3 and coefficients from Table 10.4 for each animal category), activity (Eq. 10.4 and coefficients from Table 10.5), lactation (Eq. 10.8), pregnancy (Eq. 10.13 and coefficients from Table 10.7) and growth (Eq. 10.6) and data on body weight of the animals (BW equal to 630 kg for lactating cows, 680 kg for dry cows, 450 kg for heifers, 120 for calves 3-6 months), weight changes for the growing population (0.75 and 0.90 kg/d for heifers and calves 3-6 months), production parameters (milk yield 39.5 kg/cow; fat content 3.91%), and fraction of pregnant cows equal to 90%. Weight gain, BW and pregnant cows were obtained during the interview with the farmer. Feed digestibility (DE) was equal to 74% for lactating cows and 64% for dry cows and 61% for heifers and calves 3-6 months. The Ym factor was selected based on the diets characteristics and set equal to 6.0% for high-producing lactating cows (milk yield >8,500 kg/year per cow) with high feed digestibility (DE>70%) and high neutral detergent fibre (NDF>35%); to 6.3% for non-lactating cows (rations of >75% high quality forage and/or mixed rations) which is dry cows, heifers and calves of 3-6 months of age, and to 0% for pre-weaned calves under 3 months of age.

IPCC Refinement (2019) Tier 2 was used to model also CH_4 emissions from manure storage and application by considering that manure/slurry produced in the barn is removed with high frequency and sent directly through dedicated pipelines to the anaerobic digester. Volatile solid excretion rates were calculated using the Eq. 10.24, adopting the previously quantified values for GE and DE and the collected data on ash content in the diet. The CH_4 conversion factor (MCF) selected was from the category of anaerobic digestion management, low leakage, high-quality gastight storage, best complete industrial technology and warm temperature in moist conditions, and set equal to 1% (Table 10.17), while B_0 was set equal to 0.24 (Table 10.16). Direct (manure storage and application) and indirect dinitrogen oxide (N_2O) were quantified with Tier 1 method from IPCC Refinement (2019) using Equation 10.25 for direct N_2O and Equations 10.28 and 10.29 for indirect N_2O emissions (related with volatilisation and leaching of N). The tabulated emission factors related with the anaerobic digestion practice available in Table 10.22 were used. Lastly, NH_3 and nitrogen oxide (NO) emissions from manure storage and field spreading and PM emissions were modelled in accordance with the EMEP/EEA (2019) guidelines. Phosphate (PO_4^{3-}) emissions to water were calculated based on the amount of nutrient distributed on field during digestate spreading. No mineral fertiliser was spread on field, hence this aspect was not accounted for.

Impact assessment and uncertainty analysis

The LCA software adopted was Simapro 9.5.0.2 from which the recent Environmental Footprint EF 3.1 characterization method was used to quantify the environmental impact of the studied farm, focusing on the following 15 impact categories:

- Acidification (AC), mol H+ eq
- Climate change (CC), kg CO_2 eq
- Ecotoxicity freshwater - inorganics (FEX), CTUe
- Particulate matter (PM), disease inc.
- Eutrophication, marine (ME), kg N eq
- Eutrophication freshwater (FE), kg P eq
- Eutrophication terrestrial (TE), mol N eq
- Human toxicity cancer (HTc), CTUh
- Human toxicity non-cancer (HTnc), CTUh
- Land Use (LU), Pt
- Ozone depletion (OD), kg CFC11 eq
- Photochemical ozone formation (POF), kg NMVOC eq
- Resource use, fossils (FRU), MJ
- Resource use, minerals and metals (MMRU), kg Sb eq
- Water use (WU), m3 deprived.

An uncertainty analysis was completed to test the robustness of the environmental impact results. The sampling method used included the Monte Carlo technique with 1000 iterations and 95% confidence interval.

Daily counter for carbon footprint

The abovementioned digitalised data collection platform was used as the data source both for the LCA study and for the development of the daily counter for the carbon footprint. The platform is automatically updated every day with data from the various software and tools used on the farm and results in tables with the amounts of inputs used and outputs produced. The advantage of this platform is that it goes beyond the current limits of PLF for what concerns the lack of communication systems between different IoT solutions (Leliveld *et al*., 2024). In other words, the main problem with having different technologies on the farm is establishing consistent and open communication channels between them. In this case, such a problem was resolved with the development of the data collection platform, which collects data on:

- Herd dimension and composition (n.)
- Composition of the herd diet, per single feed and per animal category, expressed as amount of dry matter and as wet basis (kg/d)
- Milk production, expressed as quantity (L/d)
- Milk quality (fat and protein), expressed as %
- Electric consumption and thermal consumption per utility (kWh/d)
- Amount of biomass fed in the anaerobic digestion plant (t/d)
- Biomethane production (Sm^3/d)
- Electric energy production from the photovoltaic plant (kWh/d)

This data was used to create a simplified daily carbon footprint calculator with daily automated updates. To achieve this goal, an environmental impact or environmental benefit (as kg CO_2eq.) was attributed to each unit of input and output, lastly resulting in a quantification of the carbon footprint of the farm on a daily basis (as kg CO_2eq./kg FPCM). The carbon footprint of each unit of input and output was calculated using Simapro 9.5.0.2 software and then added to the data collection platform. The emission factors used for this assessment are reported in Table 5. The calculation steps for the carbon footprint counter are the following.

Once the carbon footprint value of each unit of input (Im) is multiplied by the amount of that input (In), all values of carbon footprint are summed, resulting the impacts on the system (IMP):

$$IMP = \sum In_{i} \cdot Im_{i} \quad \text{(Eq. 1)}$$

Where:

IMP = sum of impacts on Carbon Footprint (kg CO_2 eq)

In = the amount of the *i*-input in the system

Im = the Carbon Footprint of the *i*-input

Then, the sum of the avoided impacts on the system is calculated, taking into account the production of renewable energy. For example, the environmental impact associated with the production and use of solar panels is attributed to the production of energy from solar panels, as quantified in Eq. (1);

however, the impact that would be present if that amount of energy were produced using electricity from the national mix is quantified using Eq. (2), representing the avoided impact.

$$A\_IMP = \sum In_{i} \cdot Im_i \quad \text{(Eq. 2)}$$

Where:

A_IMP = sum of the avoided impacts on Carbon Footprint (kg CO_2 eq)

Then, with Eq. (3) is quantified the total Carbon Footprint of the farm, subtracting A_IMP from IMP.

$$T\_IMP = IMP - A\_IMP \quad \text{(Eq. 3)}$$

Where:

T_IMP = total impact on Carbon Footprint (kg CO_2 eq)

Lastly, the fat and protein corrected milk (FPCM) is calculated according to IDF (2015) using Eq. (4), which is based on daily milk production and milk quality.

$$FPCM = MY \cdot (0.2534 + 0.1226 \cdot F + 0.0776 \cdot P) \quad \text{(Eq. 4)}$$

Where:

FPCM = fat and protein corrected milk (kg)

MY = milk yield (kg/d)

F = fat content (%)

P = protein content (%)

The carbon footprint is calculated daily using Eq. (5), which includes the biophysical allocation between milk and meat production (IDF, 2015).

$$CF_d = \frac{T\_IMP}{FPCM} \cdot A \quad \text{(Eq. 5)}$$

Where:

CF_d = daily Carbon Footprint of the farm (kg CO_2 eq/kg FPCM)

A = allocation value between meat and milk (%)

Every day, the quantities of inputs used, and outputs produced on farm vary, and consequently the Carbon Footprint gets automatically updated.

Results and Discussion

Table 6 shows the results of the LCA study expressed as absolute values in relation to the FU of 1 kg of FPCM. Figure 3 shows the relative results, highlighting the hotspots of each impact category.

Overall, this farm's absolute environmental impact shows satisfactory results. Most of the environmental impact categories have values lower than other studies completed on the environmental impact of milk production in dairy cattle farms characterised by similar production characteristics and study assumptions (Lovarelli *et al*., 2024; Lovarelli *et al*., 2019). Compared to Lovarelli *et al*. (2019), which examined around 80 dairy cattle farms of Northern Italy, this study's environmental results are lower for CC, AC, FE, POF, RU-f and RU-mm. As far as AC and FE are concerned, the reduced volatilisation of ammonia linked with the lack of slurry storages and the efficient technique adopted for the field application of the liquid digestate are the main reasons for the low values. When focusing on POF, RU-f and RU-mm a relevant role is played by the production of renewable energy, which avoids the use of natural gas and non-renewable energy sources used to produce electricity from the national mix. Instead, the results of ME and TE impact categories are higher in this study than in the previous one. The other categories are not comparable due to different characterisation methods or because they were not analysed.

The main reason for the higher ME and TE impact is related to emissions released into the environment due to the digestate management; in particular, the field application of the liquid fraction of digestate via an umbilical system and a direct soil injection are efficient techniques that reduce the volatilisation of ammonia but can increase the runoff and leaching of nutrients, involving the emission of nitrate and nitrogen monoxide responsible for the ME and TE results.

Concerning the impact category of CC, the result of this study (0.80 kg CO_2eq/kg FPCM) is valuable and primarily linked with milk production and the efficient management choices for cows, as enteric methane and carbon dioxide emissions are the main responsible for the CC category. Although some interesting findings are available in the literature, with CC values below 1.0 kg CO_2eq/kg FPCM (Mazzetto *et al*., 2022), it is not frequent to observe such results for CC, and they also need to be contextualised in the specific production system. For example, focusing on the Italian context, also Froldi *et al*. (2022) studied the environmental impact of milk production, resulting in impacts on CC ranging between 1.45 and 2.15 kg CO_2eq/kg FPCM based on the herd performance, from high to low productivity, respectively.

In Lovarelli *et al*. (2024), a more complete comparison is possible with the present study due to the use of the same characterisation method and the analysis of a farm with different installed technology levels. The impacts of the present study are much lower for CC, AC, FE, TE, HTc, HTnc, POF, RU-f and RU-mm, but higher for FE, ME, PM, OD, LU and WU. This is also in line with the previously mentioned reasons: efficient management of cows and milk productivity, lower volatilisation of ammonia, production of renewable energy and avoided production of fossil fuels vs the emissions from the digestate distribution on field and the occupation of land and water use for field cultivation.

In this case study, milk production can be categorised as high productivity (>35 kg FPCM/d), which enables a direct reduction in the overall environmental impact per unit of milk produced. This is followed by the efficient management of animals (West, 2003; Halachmi *et al*., 2019) that is in line with the results of Lorenz *et al*. (2019), who analysed low-input pasture systems. It should also be noted that all operations completed at barn level are automated and only consume electricity, some of which is of renewable origin. Furthermore, producing and selling biomethane on farm involves valorising by-products (such as slurry and by-products from the agro-food industry), making better use of slurry and storing it, and producing and using a fuel that avoids the use of fossil-based methane. This has an impact on environmental indicators such as climate change, acidification, eutrophication, ecotoxicity, human toxicity, and resource use.

Consequently, anaerobic digestion is one of the most frequently recommended techniques for mitigating the environmental impact of livestock farming (Battini *et al*., 2014; Rencricca *et al*., 2023; Tullo *et al*., 2019). Furthermore, the direct injection of fresh slurry into the biomethane plant via pipelines reduces emissions from slurry storage (Kupper *et al*., 2020), which therefore is absent on this farm.

In terms of field operations, applying best practices such as minimum tillage, directly injecting the liquid fraction of digestate into the soil, not using mineral fertilisers, and using irrigation water with efficient techniques (such as drip and sprinkler irrigation rather than flood irrigation) support the low environmental impact as well (Lovarelli and Bacenetti, 2017; Bacenetti *et al*., 2016; Vigo *et al*., 2025). It must be noted, however, that the farm has a large land area to cultivate, and that the cultivation and irrigation techniques depend on agronomic variables such as soil texture, cultivated crops, and management requirements.

Regarding the hotspot analysis, the major hotspots for CC (45%), PM (91%), ME (65%) and TE (86%) are emissions to the environment from animals in barns and field operations. The major contributors to CC are biogenic CH_4 emissions that accounted for 42.2% of the impact, carbon dioxide fossil that accounted for 29.3% and dinitrogen monoxide that accounted for 13.2%. NH_3 released from slurry in the barn and during field application was the major contributor to PM (83.4% of the impact), TE (85.5%), and AC (56.0%). On ME the major contributors were NO_3^- (75.9%) of the impact and NH_3 (13.3%). Emissions from slurry storage are negligible since liquid slurry from the barn is pumped directly to the anaerobic digestion plant via pipelines.

Feed purchase represents the main hotspot for FEx (56%), AC (44%), FE (57%), HTc (45%), OD (51%) and WU (48%). This is due to the production of energy- and protein-rich feed mixtures, and their subsequent processing and transportation. Instead, crop production represents the main hotspot for HTnc (94%) and LU (99%), and to a lesser extent for WU (48%), OD (37%), POF (44%) and RU-mm (44%). Field operations play an important role given the use of large tractors and machinery, as well as the necessary diesel fuel and irrigation water for cultivating such a large area of land.

Conversely, producing biomethane on the farm avoids the production of natural gas of fossil origin, which has a negative impact on the RU-f (-100%), HTc (-79%), OD (-40%), POF (-66%) and CC (-27%) categories. Avoided electricity production due to the production and sale of electricity from solar panels also has a negative impact, albeit less evident (almost 8% in RU-mm and below 5% in the other influenced categories). Nevertheless, given that the automation in the livestock barn (e.g. AMS and AFS) requires electricity to work, the availability of electricity from solar panels for the self-consumption of the barn needs supports the environmental sustainability of the farm itself.

Overall, although this farm cannot be considered representative of the Italian context due to its specific characteristics (e.g. herd size, milk productivity, renewable energy production and available land area), several livestock farms are moving towards efficient technology use through PLF and greater attention to animal health, welfare and productivity, as well as evaluating the advantages of producing and using renewable energy, primarily through anaerobic digestion, but also through photovoltaic energy. In particular, a trend has been observed in recent decades whereby the number of farms is decreasing but herd sizes are increasing (Udo *et al*., 2011), as well as is the spread of PLF solutions (Bianchi *et al*., 2022; Lamanna *et al*., 2026).

Consequently, the results of this study could be of interest to stakeholders and policymakers, providing insight into the environmental impact of livestock farms equipped with renewable energy production and farm automation. This could inform strategies for reducing the environmental impact of livestock production in territories or countries with highly efficient livestock farming. Considering that the average carbon footprint of Italian livestock farms (mainly in the Po Valley) has been estimated at 1.42 kg CO_2eq/kg FPCM (Mazzetto *et al*., 2022), improving the environmental sustainability of farms to a level close to this figure could reduce the overall carbon footprint of dairy cattle farms by around 45%. Mazzetto *et al*. (2022) also show carbon footprints ranging from 0.9 to 1.53 kg CO_2/kg FPCM in other EU countries. It must be noted, however, that farm-specific factors and methodological choices are essential aspects of LCA studies that can substantially affect the results (Baldini *et al.*, 2017); therefore, comparisons should be limited to studies with similar assumptions.

It should be noted also that the outcomes of this case study depend significantly on renewable energy production. In particular, the automation of livestock activities is associated with electricity consumption (Finger, 2023), although it is also associated with energy savings compared to traditional systems (Papadopoulos *et al.*, 2025). Automation can contribute to a sustainable system if the consumed electricity is not fossil-based; otherwise, the system's sustainability cannot be guaranteed.

The LCA results were tested for robustness by assessing uncertainty using the Monte Carlo technique. The results reported in Figure 4 showed little uncertainty in almost all environmental impact categories, except for those related to human toxicity, where relatively high uncertainty was observed, as well as for ecotoxicity and photochemical ozone formation. This is due to the active ingredients used in the study. This confirms that the results achieved in terms of environmental benefits are unaffected by uncertainty caused by data selection from databases or by partial model adequacy and data variability, except for the categories linked with toxicity-related impact, for which the selection of data did affect the results.

Daily counter for carbon footprint

Figure 5 shows the farm's daily carbon footprint for the year 2024. Daily variability shows an overall average of 0.59 ± 0.08 kg CO_2eq/kg FPCM.

From early autumn (the end of August to the end of November), a slight drop in daily carbon footprint values can be observed, which may be due to a drop in electricity consumption related to the mechanical ventilation of the barn, small variations in the number of lactating cows and their associated feed requirements, and possible power failures.

The added value of this result lies in the evaluation of daily variability on the farm. The yearly assessment is the most valid, particularly from a methodological point of view. However, the benefit of a daily counter is linked to understanding the variability of the carbon footprint based on daily management practices. The main variables affecting daily variation are herd composition and barn management. In particular, the number of animals in each category varies by a few units throughout the year, but on a daily basis, it influences emissions from animals, particularly enteric CH_4 emissions, as well as the carbon footprint of the diet, which is linked to the number of animals being fed. Furthermore, milk productivity is a key driver as the impact is expressed per unit of product.

The last factor significantly impacting daily variability in carbon footprint is electricity consumption by various systems, including AMS, AFS and the mechanical ventilation system. During the warm season, the mechanical ventilation system has a significant impact on energy consumption as the fans operate continuously to maintain optimal temperature and humidity levels for animal welfare. This increased electricity consumption can be offset in part by renewable energy production from solar panels, though this may be insufficient during peak periods.

This tool provides farmers with information on the variability of their carbon footprint throughout the year and highlights the hotspots and the potential options available to them for reducing it. Some factors, such as the number of lactating cows, cannot be altered, nor can the use of mechanical fans if these are required to guarantee the health and welfare of the animals. However, farmers can: (i) change the energy source to avoid using fossil-based energy, (ii) use energy-efficient machinery, or (iii) use precision livestock farming tools to enable efficient working procedures and the collection of detailed daily data, which supports farmers in developing improved management practices. Lastly, the tool provides a quantified value of the farm's carbon footprint for its daily management operations, enabling farmers to understand the environmental impact of their daily choices. It also makes the farmer aware that solutions recommended as best practice in research and legislation may be better from an environmental perspective, or vice versa.

Limitations of the daily carbon footprint counter

The daily values are consistent with the overall annual assessment, although they are consistently lower. This is probably due to some limitations in the methodology, which the daily calculator is unable to address as effectively as the annual assessment. In particular, the methodology for quantifying emissions from animals and field practices is designed for annual assessments, not daily ones, which may represent a limitation of the methodology.

On this aspect, it should be noted that the emissions from animals are calculated following the procedure for the assessment of emissions on an annual basis and quantified on one single animal. Therefore, the carbon footprint varies daily depending on the actual number of animals in each category. The emission factor associated with each animal category has been calculated using data required for the assessment of emissions from IPCC (2019) refinement, divided by day, and kept constant for each day of the year.

With regard to field practices and, consequently, the carbon footprint of cultivated crops used for animal feed and AD, it should be noted that calculations are not based on daily variability; rather, the carbon footprint relates to field practices and yields from the previous campaign. This is because field cultivation is an annual process. Therefore, the carbon footprint of the product is quantified using the field practices and yields from the previous year, and this value is expressed per tonne of product and multiplied by the amount of crop used daily. This means that, although the amount of feed used changes daily, the value of kg CO_2eq/t of crop remains constant for each specific crop throughout the year.

Similarly, emissions associated with spreading liquid digestate on fields are linked to field cultivation processes and therefore do not reflect daily variability.

As for the other processes, the adopted methodology does not present any limitations because the inputs, such as the amounts of feed and energy, are expressed per day rather than per year. In other words, daily variability can be monitored for inputs and outputs where quantities differ (e.g. the number of animals, the amount of feed used, the amount of energy produced, used or sold), while annual emissions are calculated for processes linked with emissions or for which the production process lasts longer than one day (e.g. crop production), divided by the number of days in the year, and this fixed daily value is then used.

A final limitation of this tool is that it could be developed because the farm organised the data collection system through an external enterprise, to which the daily values of carbon footprint were matched. The results and the structure of this carbon footprint calculator are therefore farm-specific and cannot simply be used in another farming context. Rather, they require an adaptation procedure to the specific characteristics of other farms.

Conclusions

This study analyses the environmental performance of a dairy farm equipped with a data collection system that provides daily data on inputs and outputs at barn level on the number of animals present per category, their productivity, feed ingestion, and energy consumption from single users such as the automatic milking and feeding systems, as well as the renewable energy produced from an anaerobic digestion plant that upgrades to biomethane and a photovoltaic plant. A Life Cycle Assessment study has been conducted, yielding interesting results. A daily carbon footprint counter has been added to the daily data collection system, enabling the carbon footprint of the farm to be calculated daily. Although this tool has some methodological limitations, quantifying daily practices in terms of carbon footprint can help farmers understand their contribution and improve their ability to become more environmentally sustainable. In this context, providing economic support to livestock farms to help them transition to digitalised and automated systems could help to spread technology on farms and create more sustainable livestock systems.

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Figure 1. Picture of the automatic feeding system for cows (on the left) and calves (on the right).

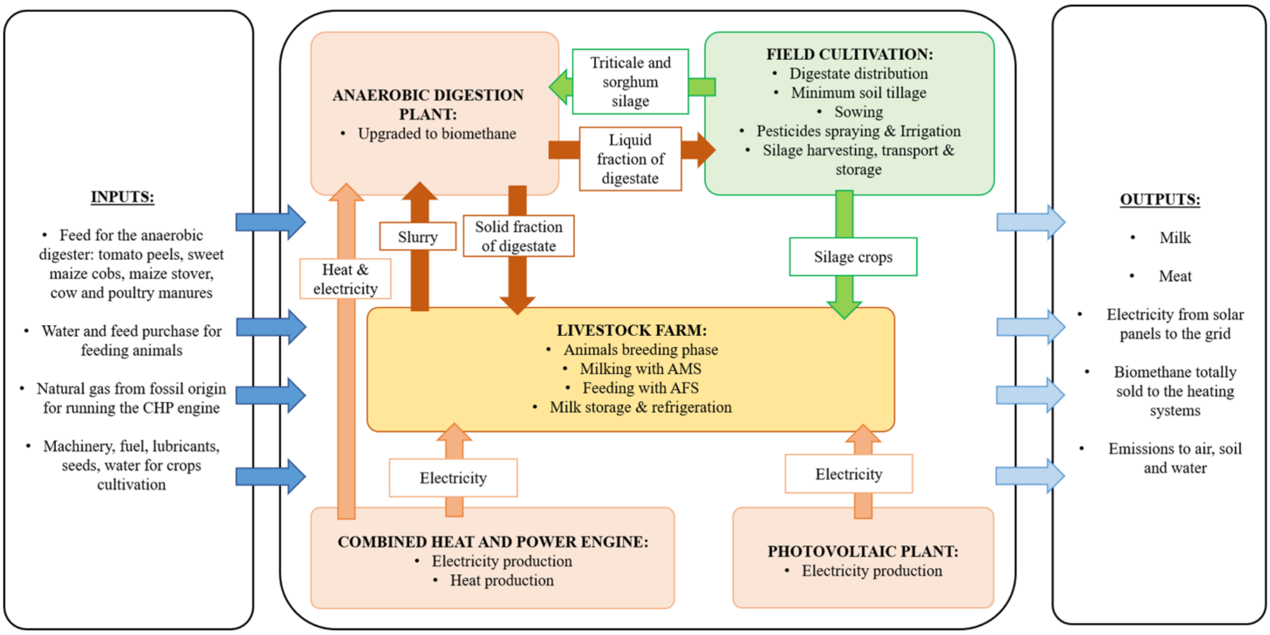

Figure 2. System boundary. Elements inserted in the red dotted lines identify the single sub-systems on farm. Blue arrows refer to inputs to the system; green arrows refer to the outputs from the system; yellow arrows refer to the internal uses of inputs/outputs of the single sub-systems.

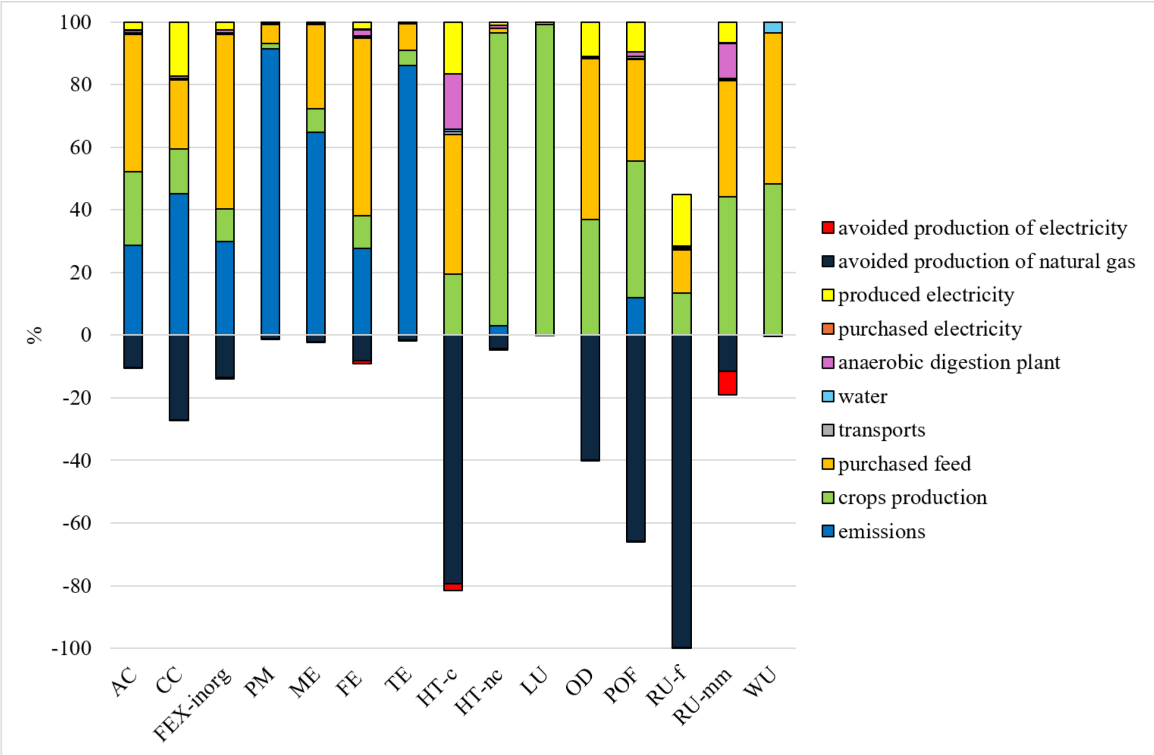

Figure 3. Relative contribution to the environmental impact of the farm. Values below zero refer to the production of renewable energy sold. On the x-axis are reported the impact categories analysed: AC= acidification; CC = climate change; FEX-inorg = ecotoxicity freshwater – inorganics; PM = particulate matter; ME = marine eutrophication; FE = freshwater eutrophication; TE = terrestrial eutrophication; HT-c = human toxicity – cancer; HT-nc = human toxicity – non cancer; LU = land use; OD = ozone depletion; POF = photochemical ozone formation; RU-f = resource use – fossils; RU-mm = resource use – minerals and metals; WU = water use.

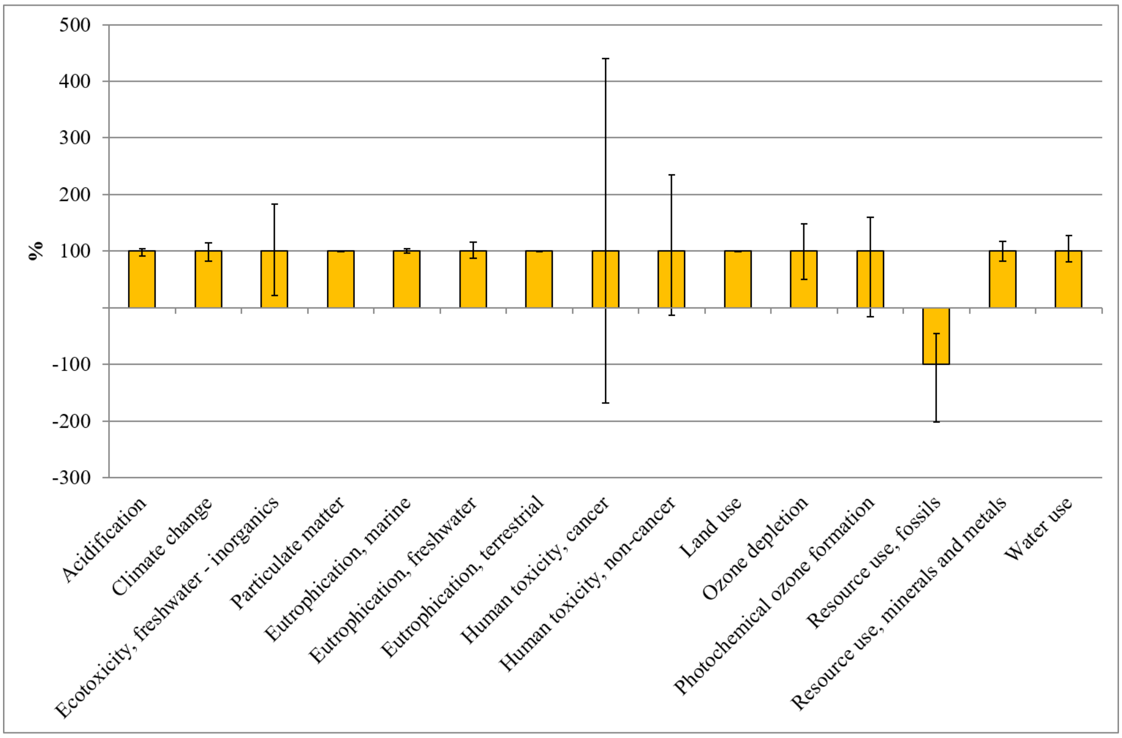

Figure 4. Results of the uncertainty analysis.

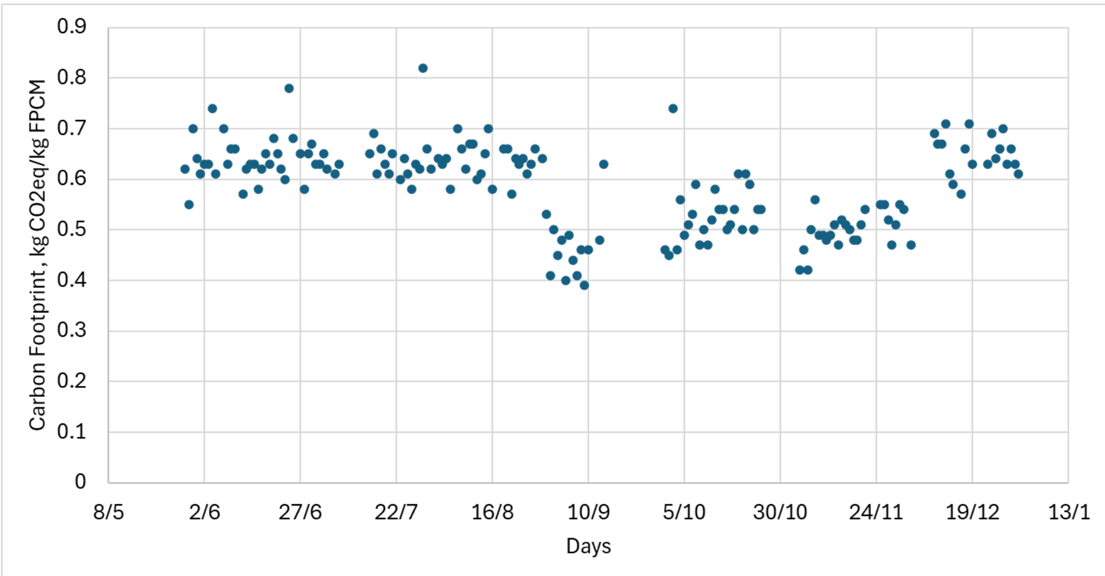

Figure 5. Daily carbon footprint of the livestock farm, expressed as kg CO_2eq/ kg FPCM (fat and protein corrected milk). Data is shown starting from 28 May 2024, when the daily counter was activated. Days with lack of data are caused by a farm power failure.

Table 1. Electric consumption as annual value and percentage of each energy user on farm.

Energy user	Annual electric consumption (kWh)	%
Automatic Milking System	98,284	7.0%
Automatic Feeding System	42,388	3.0%
Lighting of the barn	33,285	2.4%
Mechanical ventilation	138,709	9.9%
Anaerobic digestion plant for biomethane production*	816,148	58.1%
Refrigerating system	113,364	8.1%
Slurry pumping	148,470	10.6%
Slurry scrapers	7,356	0.5%
Other**	5,619	0.4%
Total	*1,403,623*	*100%*

* This includes the energy needed to warm the plant and keep it at the process temperature, the electric consumption for pumping biomass into the plant and the one for the upgrading process to biomethane. It needs to be mentioned that, since the plant produces biomethane and not biogas, the plant has no Combined Heat and Power engine, therefore the heat to warm the plant needs to be produced on purpose. ** This includes minor consumptions like water pumping from the well and energy uses for the offices.

Table 2. Feed ration and related quantities used on a yearly basis for the whole herd.

Feed name	Amount (t DM/year)
Energetic feed mixture for lactating cows	744.7
Energetic feed mixture for dry cows	59.9
Protein feed mixture for lactating cows	650.5
Protein feed mixture for dry cows	2.7
Minerals and vitamins	7.6
Maize flour	888.3
Winter crops silage	208.3
Wheat straw	467.9
Maize silage	2,093.6
Soybean meal	824.6
Sorghum silage	20.7

Table 3. Main characteristics of the field practices of the farm for the monitored year.

Cultivated crops	Area (ha)	Digestate (m^3/ha)	Diesel consumption (L/ha)	Irrigation technique	Yield (t/ha)	Dry matter content (%)	Total Dry Matter (t)
Winter crops, silages	677	50	263.1	-	9.58	32	2,075.20
Maize silage, single crop	281	150	283.1	Drip & Sprinkler	46.49	33	10,446.81
Maize silage, double crop	400						
Sorghum	305	100	286.1	Drip & Sprinkler	19.30	32	1,883.84
Total	1,663 ha*	166,500 m^3	412,200 L	-	44,029 t	-	14,405.85 t

The total area of the farm is 1263 ha; the difference with the value of 1663 ha is related with the double cropping system in maize cultivation.

Table 4. Inventory data referred to milk production, energy and water use and herd dimension on farm.

Variable	Unit	Farm data
Herd composition		
Dairy cows	n.	692
Dry cows	n.	127
Heifers	n.	180
Calves	n.	130
Milk production		
Mean daily milk production	kg/d cow	39.5
Milk production per year	kg/y	8,358,936
Fat content	%	3.91
Protein content	%	3.56
Fat and protein corrected milk	kg FPCM/y	8,429,939
Energy consumption		
- electricity consumption from national mix and fossil origin (CHP*)	kWh/y	2,770,186
- thermal energy consumption from fossil origin (CHP*)	kWh/y	1,405,247
- electricity consumption from renewable energy (photovoltaic plant)	kWh/y	872,396
Energy production		
Electricity production from photovoltaic plant	kWh/y	1,196,000
Biomethane production from biogas upgrading	Sm^3/y	3,450,487
Water consumption		
- cow sprinklers	m^3/y	32,000
- drinking water	m^3/y	57,500
- Automatic Milking System use and cleaning	m^3/y	6,000

CHP = Combined Heat and Power engine.

Table 5. Emission factors used for the assessment of the daily carbon footprint.

Item	Emission Factor	Reference
Energetic feed mixture for lactating cows	0.51 kg CO_2eq/kg wb	Own elaboration
Energetic feed mixture for dry cows	0.19 kg CO_2eq/kg wb	Own elaboration
Protein feed mixture for lactating cows	0.51 kg CO_2eq/kg wb	Own elaboration
Protein feed mixture for dry cows	0.19 kg CO_2eq/kg wb	Own elaboration
Minerals and vitamins	0.56 kg CO_2eq/kg wb	Own elaboration
Maize flour	0.39 kg CO_2eq/kg wb	Own elaboration
Winter crops silage	0.06 kg CO_2eq/kg wb	Own elaboration
Wheat straw	0.08 kg CO_2eq/kg wb	Own elaboration
Maize silage	0.02 kg CO_2eq/kg wb	Own elaboration
Soybean meal	1.13 kg CO_2eq/kg wb	Own elaboration
Sorghum silage	0.06 kg CO_2eq/kg wb	Own elaboration
Maize cobs	0.08 kg CO_2eq/kg wb	Own elaboration
Milk powder for calves	0.12 kg CO_2eq/kg	Own elaboration
Well water	0.41 kg CO_2eq/m^3	Ecoinvent 3.8
Biomethane sold	-0.77 kg CO_2eq/m^3	Ecoinvent 3.8
Electricity from national mix	0.4 kg CO_2eq/kWh	Ecoinvent 3.8
Electricity from Combined Heat and Power engine	0.65 kg CO2eq/kWh	Ecoinvent 3.8
Electricity from solar panels	0.07 kg CO2eq/kWh	Ecoinvent 3.8
Transport with lorry	5.46 kg CO2eq/t·km	Ecoinvent 3.8
Fixed emissions from anaerobic digestion plant	24.67 kg CO2eq	Ecoinvent 3.8

Table 6. Environmental impact results for the dairy cows' farm.

Impact category	**Unit**	**Total value**
Acidification	mol H+ eq	0.0054
Climate change	kg CO_2 eq	0.807
Ecotoxicity, freshwater - inorganics	CTUe	4.635
Particulate matter	disease inc.	$3.02 \cdot 10^{-7}$
Eutrophication, marine	kg N eq	0.0082
Eutrophication, freshwater	kg P eq	0.0002
Eutrophication, terrestrial	mol N eq	0.1166
Human toxicity, cancer	CTUh	$2.90 \cdot 10^{-11}$
Human toxicity, non-cancer	CTUh	$2.95 \cdot 10^{-8}$
Land use	Pt	2745.92
Ozone depletion	kg CFC11 eq	$4.50 \cdot 10^{-8}$
Photochemical ozone formation	kg NMVOC eq	0.0012
Resource use, fossils	MJ	-8.823
Resource use, minerals and metals	kg Sb eq	$1.67 \cdot 10^{-6}$
Water use	m^3 depriv.	11.263