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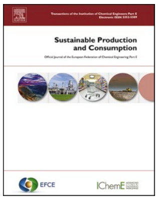

Reducing life cycle environmental impacts of milk production through precision livestock farming

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ABSTRACT

In recent decades, the livestock sector has significantly improved its efficiency, productivity, and environmental sustainability. Precision Livestock Farming (PLF) represents a driver in this direction, since it enables to monitor individual animals and herds, and supports the farmer in making better decisions. Although the benefits are clear on a livestock perspective, it is difficult to quantify the environmental benefit of having technology on farm, mostly due to the complexity of collecting data on the same farm before and after a certain solution.

In this context, this paper focuses on the assessment of the environmental sustainability of a case-study Italian dairy cattle farm where different technologies were installed one by one: first a mechanical ventilation system (MV) and second an automatic milking system (AMS), without introducing other significant changes to the farm management and practices in the meantime. The environmental impact of milk production on the farm was quantified through the Life Cycle Assessment (LCA) method, and the initial farm configuration was compared with the two scenarios in which each technology was incorporated. Fat and protein corrected milk (FPCM) was used as Functional Unit, and a cradle to farm gate system boundary and biophysical allocation method were selected. This enabled to provide valuable insights for stakeholders about the effect on the environmental sustainability of the use of the two technologies. The results show that for all the evaluated impact categories there is an environmental benefit of the improved scenarios. The biggest benefit can be observed with the installation of mechanical ventilation, to which correspond benefits in terms of animal health, welfare and productivity. Then, also AMS entails sustainability improvements, mainly linked with increased efficiency and productivity. In conclusion, the use of technology on dairy farms improves not only the farm efficiency and the animal management, but also the environmental sustainability. Furthermore, the rapid technological advancements may further enhance this positive trend in reducing the contribution of livestock farming to the environmental impacts provided that farmers adopt them.

1. Introduction

In recent decades, to respond to the criticism on livestock activities, the efficiency of the livestock sector is rising considerably, both in terms of productivity and of environmental sustainability (Hyland et al., 2016). Several advancements can be made to achieve an improved efficiency, with a big variety of possible interventions, both acting on animals (e.g., genetics, animal management) (Bernabucci et al., 2014) and on the buildings and installations (e.g., ventilation, animal monitoring) (Lora et al., 2020; Mondaca and Cook, 2019; Snell et al., 2003). Focusing on the installation of tools that enable to monitor animals, the adoption of technology can support the farmer in increasing knowledge of the herd and of the single animals, hence in acting promptly to solve problems or improve animals' health, welfare, and productivity. In more detail, Precision Livestock Farming (PLF) specifically supports the farmer in achieving an improved farming system, in which each animal is monitored, data is collected, processed and decisions are made both on individuals and on the groups (Halachmi et al., 2019). PLF has been spreading worldwide in livestock farms, especially in the most recent years. As the herd dimension in livestock farms increases, farmers also need support in the most labor-demanding operations, which are milking, feeding, and animals monitoring (Atzori et al., 2021; Norton et al.,

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2016). Hence, mechanical ventilation (MV) and indoor environmental sensors, automatic milking systems (AMS), automatic feeding systems (AFS), and wearable accelerometers are the most prevalent technologies (Abeni et al., 2019). This is valid also in the Italian context, since the most interesting aspects to monitor include productivity, early identification of mastitis further supporting the reduction in antibiotics use (Lora et al., 2020), and behavioral and health aspects affecting heat stress, fertility and estrus events, leg lesions, and possible lack of welfare or presence of undesired behaviors (e.g., excessive rest time or excessive activity time) (Riaboff et al., 2022; Stygar et al., 2021).

A further key element to consider is animal stress, which influences their welfare, and consequently their performance. In particular, heat stress is one of the most spread and impacting stressor sources still requiring investigation (Leliveld et al., 2023). Heat stress can have both acute and chronic effects on animals (West, 2003), and several studies regarding its effects and preventive measures recognized heat stress as a strongly negative condition for animal welfare, health, productivity, behavior, and fertility (Bell et al., 2011; Bernabucci et al., 2014; Polsky and von Keyserlingk, 2017). To abate heat stress several interventions can be made, most of which depend on the facility and its equipment, with buildings having insulation materials, proper orientation, shaded areas and proper natural ventilation (Fournel et al., 2017; Lovarelli et al., 2021; Schütz et al., 2009). If in the hot period of the year the microclimate conditions are not suitable for animals, fans and eventual fogging/wetting systems must be installed, resulting fundamental to satisfy animal welfare. In Italy, dairy barns are commonly equipped with mechanical ventilation systems, due to the increasing frequency and strength of heat waves hitting the territories (Ji et al., 2020; Lovarelli et al., 2024) and threatening animals health, welfare and productivity. Mechanical ventilation supports the heat dissipation from the animal, hence reduces thermal distress and the loss of welfare, health issues and productivity (Leliveld et al., 2023). The effects of ventilation were studied valuating both the natural and mechanical system (Snell et al., 2003) as well as the frequency of its use, and the cost-effectiveness of its availability (Mondaca and Cook, 2019). Milk productivity is also positively influenced by ventilation, as this latter supports the maintenance of adequate environmental conditions (Temperature Humidity Index lower than 72) for guaranteeing animal welfare, health and productivity (Leliveld et al., 2024; Lovarelli et al., 2024).

All these aspects play a role also on the environmental and socio-economic points of view. Recent studies are highlighting the benefits from a sustainability perspective of installing technology on farms (Pardo et al., 2022; Tullo et al., 2019; Zhang et al., 2021). Indeed, although the support to the farmer's activity is undeniable, the economic and environmental results must be investigated for an overall sustainability assessment (Gibon et al., 1999; Lebacq et al., 2013; Lovarelli et al., 2020). First, technology needs to be economically sustainable for the farm, and then environmentally sustainable, which also answers to the European policies as in the Farm to Fork strategy (European Commission, 2020).

In this study, Life Cycle Assessment (LCA) was used to quantify the environmental sustainability of a dairy cattle farm, in which data were collected from 2019 to 2023 when the farmer invested to increase the level of technology. By introducing one retrofitting intervention at time, but in different years, the short-term effects of each intervention on the environmental sustainability of the farm can be evaluated and estimated. This enables farmers, researchers and stakeholders to identify the most impacting technologies and should attract future investments and incentive strategies in the livestock farms. In particular, the farm was studied in its initial configuration and then with two installation levels, first the mechanical ventilation (MV), followed by the introduction of an automatic milking system (AMS).

The scientific question that the paper would answer is: can the introduction of technology equipment and the energy requirements for their use, contribute to increase the environmental sustainability of a PLF-equipped dairy farm if compared to a non-equipped dairy farm? This question is preeminent if we consider that currently <40 % of Italian farmers systematically adopt PLF systems.

2. Materials and methods

2.1. Description of the case study farm

The present study was carried out on a dairy cattle barn in the municipality of San Pietro in Casale, province of Bologna, located in a flat countryside in the North-East of Italy. The farm is in a geographical area characterized by Mediterranean climate conditions with hot and humid summer season and temperate and humid winter season.

To have an overall indication of the local climatic conditions, Table 1 reports the average monthly temperature and relative humidity of the five years considered in the study (https://simc.arpae.it/dext3r), from which emerge the substantially unchanged conditions over the years. It is important to note that these climatic conditions, especially during summertime, represent a stressing situation for dairy cows, negatively affecting their welfare, behavior, and milk productivity. Hence, acting on ways to deal with heat stress (such as mechanical ventilation, shaded areas, and cooling systems) in such a context has positive effects on the animals.

2.1.1. The housing system and the equipment

The barn was characterized by a rectangular layout with dimensions of 42.2 m × 80.3 m and had the longitudinal axis (i.e., the longer dimension) SW-NE-oriented (i.e., with −20° azimuth angle). The building had metallic structure (i.e. beams and columns) and roof elements. The inner area of the barn served as the resting place. Closing fences along the symmetry axis enabled to divide the herd into two independent groups. The building elevation resulted in a symmetrical double pitched roof without internal columns and with a ridge line running along the longitudinal axis. It had a continuous ridge opening, a 12.15 m ridge height and a roof slope of 33 % (see Fig. 1). To improve natural ventilation the lateral sides were completely open and only in case of strong wind conditions the animals were protected by using sliding shading nets. The barn had reinforced concrete solid floor, and the bedding cubicles were in precast reinforced concrete filled with wheat straw. The animals had 5 ha of land available for restricted grazing that they could access voluntarily for most of the year, as in line with organic farming requirements.

As in the most of Italian cow barns, the drinking water was directly provided by the well, usually having temperature of about 18 °C. To avoid decreases of milk production, the barn was equipped with an electrical heating system to rise the temperature in the drinking troughs. On the farm, the quantity of drinking water consumed was rather constant over the years and equal to about 35,000 m^3/year.

In the context of the national project “Smart Dairy Farming – Innovative solutions to improve herd productivity” (https://dairysmart.unimi.it/en/) funded by Italian Ministry of Education, University and Research, the livestock barn of the farm considered in this study was equipped with a smart monitoring system (Bovo et al., 2020) to collect and store in real time a wide range of data.

The electricity consumptions detected during the monitored period were represented by the milking systems (between 20 % and 25 % of total yearly electricity consumption), milk refrigeration (17 %–20 %) and water heating (14 %–15 %). Water pumping, including irrigation, represented about 12 %–13 % of the electrical demand, while 12 %–14 % was required for lighting and 3 %–4 % for the automatized animal brushing. Manure removal called for a fraction of 4 %–5 % of energy assessed for slurry management, while the remaining percentage was mainly related to minor operations.

The farm delivered the manure and the cubicle waste on the fields as organic fertilizer.

Table 1

Monthly average data of air temperature and relative humidity in the geographical area of the study farm during the monitored period.

Temperature (°C)													
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Yearly average
2019	1.5	6.0	10.2	12.7	14.5	24.3	25.1	24.9	19.9	16.5	10.2	5.9	14.3
2020	3.7	7.3	8.6	13.5	18.2	21.3	24.0	25.4	21.3	13.9	9.8	6.0	14.4
2021	2.7	7.3	9.4	10.5	16.7	23.9	25.4	25.0	20.8	14.5	10.1	3.5	14.1
2022	2.9	6.4	8.2	12.4	19.8	24.7	26.9	25.6	20.6	17.9	11.2	5.8	15.2
2023	6.0	6.0	11.5	12.3	17.4	23.0	26.2	25.9	22.5	18.7	10.4	5.8	15.5

Relative Humidity (%)													
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Yearly average
2019	90	88	65	78	78	74	69	72	73	77	88	89	78
2020	88	79	66	72	60	71	70	74	76	83	88	91	76
2021	86	81	68	74	70	68	70	65	72	77	89	90	76
2022	90	77	66	73	75	67	58	53	73	79	87	92	74
2023	86	76	71	70	75	67	71	68	73	76	84	88	75

2.1.2. *The herd*

The case study dairy farm managed a gross total of about 770 animals, consisting of about 400 lactating cows, 170 heifers, 140 calves, and 60 dry cows on average over the year. The number of animals, except for the slight and unavoidable fluctuations related to the management of the herd, remained constant during the monitored years. The most present breed was Holstein Friesian (>90 %). The dietary regimen for the dairy herd was designed to guarantee optimal nutrition across diverse production stages and was in line with organic farming requirements. During lactation, cows were provided with a diet consisting of alfalfa hay, grass hay, meadow hay, straw, maize grains, protein-based supplement, soybeans and wheat flour. During the dry period, cows received a diet predominantly consisting of alfalfa hay, grass hay, straw and soybeans. Meanwhile, heifers and younger cattle received alfalfa hay, maize, soybeans and wheat flour. Lactating cows were fed with 26.20 kg/day of dry matter, dry cows with 14.55 kg/day, while heifers and calves with 9.94 kg/day. Throughout the monitored years, the almost constant mortality rate of 2.0 % and culling rate of 30 % were recorded. Leg diseases and abortions were observed with an incidence rate of 1.1 % on average in the herd, accounting for about 5 cases per year on average. The manure and the breeding sewage from the animals were stored in three large reinforced concrete underground open tanks and then spread on field as fertilizer.

2.1.3. *Agronomic crop management*

The monitored farm was registered as an organic farm. Therefore, almost all the necessary feed ingredients were produced on the farm following an organic cultivation regime, and obviously this choice influenced decisions on the production and management of inputs for animal feed. The farm had a total productive farmland area of about 400 ha, allocating 200 ha for alfalfa, 100 ha for wheat, and 100 ha for mixed crops for hay production. Minimum soil tillage operations were carried out. Mechanical soil weeding was conducted typically in January, March, and April, and no pesticides were used in accordance with organic farming principles. One harrowing operation was carried out before seeding. The seed quantities depended on the crop and were 28 kg/ha for alfalfa, 190 kg/ha for wheat, and 200 kg/ha for the mixed crops for hay. Furthermore, during the summer, the farm carried out the fertilization with manure and breeding sewage at a rate of $45 m^3/ha$. Regarding forage and hay production, six cuts per year were realized. Silage was predominantly stored on the farm, while concentrates were harvested as grains and then dried in a diesel dryer internally the farm.

2.1.4. *Improved scenarios in the monitored farm*

In recent years, the farmer decided to introduce improvements to the dairy farm by first installing a mechanical ventilation system and cow sprinklers (MV) to reduce the presence of heat stressing events in summer for the farmed dairy cows, and second placing an Automatic Milking System (AMS) to milk cows with robotic milking. These changes were introduced in 2021 and in 2022, respectively. So, the starting point of the farm observation was in the year 2019. The new technology was added in 2021 (MV) and in 2022 (AMS). No other change was observed in the same period. For the whole period, the farm was monitored, and data was collected on the herd productivity, animals' management and energy and water consumption. Therefore, in this study a comparison was carried out to quantify the environmental impact of the same farm with the three different configurations. The strength of this comparison was that the farm specificity did not affect the results of the comparison, but only the variability due to the installed technology. In addition, since AMS was installed 1 year after the MV, the effect of the first installation could be evaluated without being compromised by the effects of other interventions.

The three scenarios investigated in this paper are referred to the following configurations:

- Baseline Scenario (BS): it provides the initial condition of the farm as described above.
- Improved Scenario by Ventilation system (ISV): it represents the improved situation after the farm installed a ventilation system, consisting in high-efficiency fans with variable frequency drive systems, coupled with cow sprinklers in the barn.
- Improved Scenario by Ventilation system and Automatic Milking System (ISV-AMS): it is the further improved condition that depicts the situation of the farm after the installation of both automatic milking system and ventilation system.

Mechanical ventilation systems have several positive aspects that need to be mentioned: they can ensure consistent air exchange, reduce humidity, odors, and remove harmful gases like ammonia, carbon dioxide, and methane, as well as dust, pathogens and allergens, leading to healthier air for cows. Moreover, ventilation systems can help maintain a stable and comfortable temperature inside the barn, reducing heat stress in summer and preventing cold drafts in winter, finally leading to better animal welfare and increased milk production. Another advantage is that mechanical ventilation systems provide reliable year-round ventilation that can be customized to fit barns of different sizes and layouts, differently from the natural ventilation, which instead can be unpredictable. On the other side, installing mechanical ventilation systems requires significant upfront investment in equipment, and additional operational costs (i.e. electricity and regular maintenance). In areas where electricity is expensive or unreliable, this can be a major drawback.

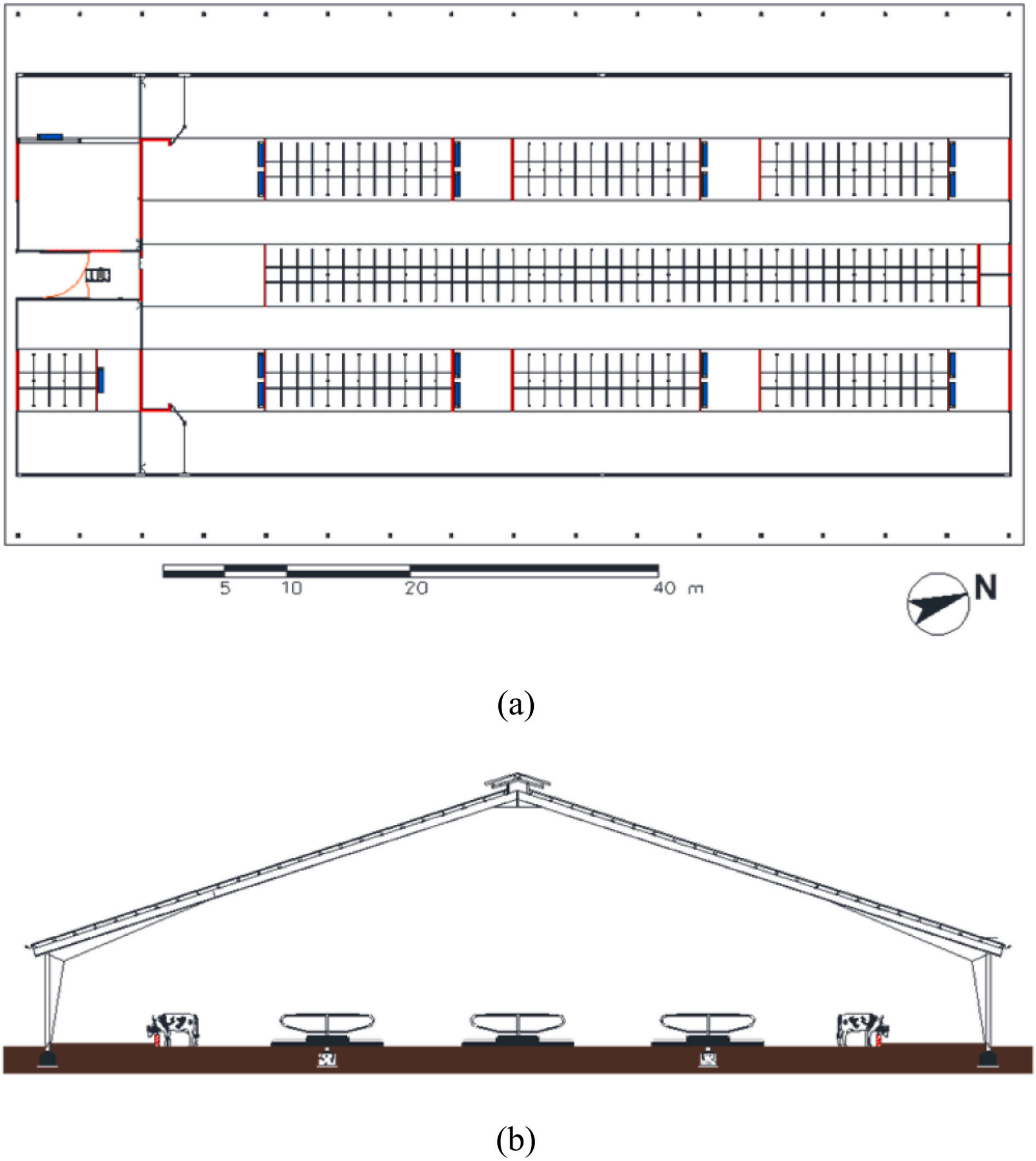


Fig. 1. Views of the case study. (a) Plan view of the barn. (b) Transverse cross-section view of the barn. (c) Aereal view of the farm.

As far as concerns the introduction of automatic milking systems it is possible to state that an AMS significantly reduces the need for manual labor in the milking process and allows cows to be milked at their own pace throughout the day, improving their comfort and reducing stress caused by rigid milking schedules. Due to more frequent milking and reduced stress on cows, many farms report an increase in milk yield per cow after installing an automatic milking system. AMS collects detailed data on each cow's milk yield, milking frequency, udder health, and overall well-being, enabling early detection of health issues like mastitis or lameness. AMS generates a wealth of data that can be used to optimize feeding, breeding, and herd management decisions, potentially leading to overall improved farm efficiency. On the other hand, AMS systems are expensive to purchase and install, require regular maintenance, software updates, and servicing, adding to operational costs. A breakdown of the system can disrupt milking and affect productivity. The system's reliance on technology and automation means that any technical failure or power outage can interrupt the milking process and impact farm operations. Some cows may initially struggle to adapt to the new voluntary milking process, potentially leading to lower production in the short term. While AMS generates useful data, managing and analyzing this information can be overwhelming for farmers who are not accustomed to data-driven management or who lack proper training. Finally, installing AMS may require modifying the barn layout to accommodate robots, feeding systems, and cow movement, which can be costly and time-consuming for existing farms.

(c)

Fig. 1. (*continued*).

2.2. Life Cycle Assessment

To complete the environmental sustainability assessment, the Life Cycle Assessment (LCA) methodology was adopted, following ISO Standards 14040-14044 (ISO, 2006; ISO, 2018). LCA was used to calculate the environmental impact in the three farm scenarios BS, ISV and ISV-AMS described above. The Simapro® software v. 9.5 was used. In the following sections the specific methodological aspects of the LCA analysis are reported.

2.2.1. Goal and scope, system boundary and allocation method

The objective of this study was to quantify the environmental benefit deriving from the installation of different systems in the dairy cattle barn and to investigate which of the system/technology allowed obtaining the maximum reduction in environmental impact, finally supporting the definition of the most environmentally beneficial interventions that farmers can make. Therefore, the final scope was to support policy makers in identifying investments with the most beneficial effect on the environmental sustainability aspects of livestock.

For this specific study, the system boundary was cradle to farm gate type (from inputs production to the sale of milk at the dairy industry), in which beyond the baseline scenario the two additional plants envisaged with ISV and ISV-AMS were included, as shown in Fig. 2. The approach was attributional, and the allocation method used was the biophysical allocation method suggested by International Dairy Federation (IDF) (2019), where the environmental impact was shared between milk and meat production.

The functional unit (FU) selected for the three scenarios was 1 kg of fat and protein corrected milk (FPCM), which was calculated following International Dairy Federation (IDF) (2019) equation.

2.2.2. Life Cycle Inventory

All the data on the farm management, animals and field cultivation was collected directly on the farm through a questionnaire completed by the farmer. In detail, data collected was related to:

- barn and equipment management: consumption of electricity and water, purchase of inputs from the market;
- herd management and production: number of animals, type of animals, composition of the diet, amount of self-produced feed and of purchased feed from the market, yearly average milk yield, fat and protein content in milk;
- field cultivation: cultivated area, crop yield, inputs used (e.g., seeds, water, diesel fuel).

A detailed list of the main inventory data is reported in Table 2, Table 3 and Table 4.

The foreground processes linked to the production of raw milk and feed produced on farm were also collected on farm, and the impact assessment was modelled on the primary data collected on farm; the background processes (e.g., purchased feed and other inputs) were collected on farm for the amounts, while the related processes for impact assessment were retrieved from the data in EF v.3.0, Ecoinvent 3.8 and Agribalyse 3.1 (for the primary data of the BS and improved scenarios ISV and ISV-AMS, see Section 2.1). Construction and installation of new technologies were not included in the system boundary due to a lack of data. It is worth noting that from the analysis of the energy consumption measured in the farm, the electricity consumption of the scenario ISV is practically equivalent to that of the ISV-AMS scenario. This is because the highest power consumption in milking systems is made by the depressor and, in our case, in total, the four depressors that provide

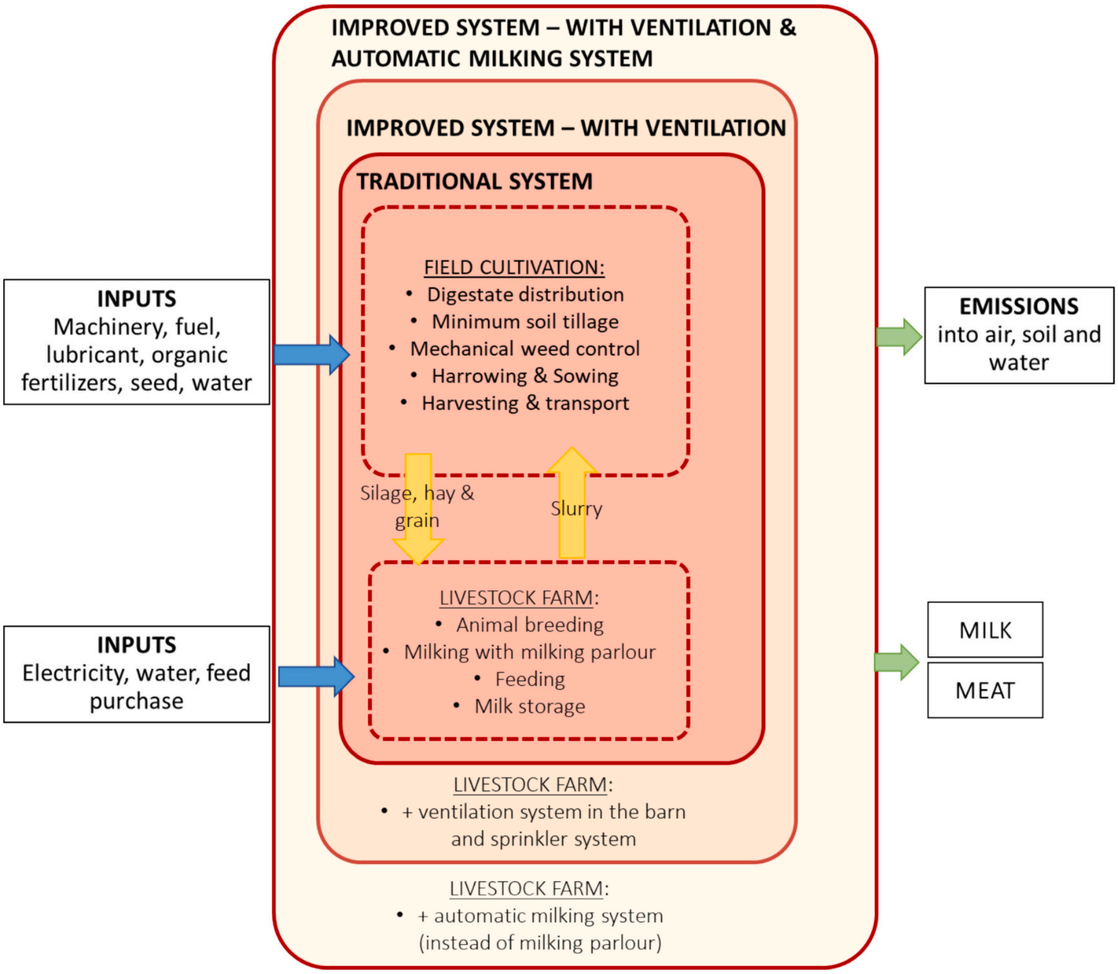


Fig. 2. System boundary for the three scenarios investigated.

Table 2
Inventory data referred to milk production and energy and water use collected on farm for the 3 scenarios, i.e., Baseline Scenario, ISV (Improved Scenario by Ventilation) and ISV-AMS (Improved Scenario by Ventilation with Automatic Milking System).

Variable	Unit	Scenario		
		Baseline	ISV	ISV-AMS
Milk production				
Mean daily milk production	kg/d cow	31.6	36.0	39.0
Mean milk production	t/y	4234.4	4824.0	5226.0
Fat	%	4.1	4.2	4.0
Protein	%	3.3	3.6	3.4
Fat and protein corrected milk	kg FPCM/y	4,285,806	5,054,008	5,265,927
Energy consumption				
Electricity consumption	kWh/y	180,000	220,000	220,000
Water consumption	m^3/y	37,007.5	50,041.5	50,078.0
- cow sprinklers	m^3/y	0	16,644	16,644
- drinking water	m^3/y	35,000	31,390	31,390
- milking parlor/AMS cleaning	m^3/y	2007.5	2007.5	2044.0

Note: ISV = Improved Scenario with Ventilation; ISV-AMS = Improved Scenario with Ventilation and Automatic Milking System; FPCM = fat and protein corrected milk; AMS = Automatic Milking System.

Table 3
Inventory data of the herd (valid for all the scenarios).

Herd composition	Herd dimension (n. heads)	Daily feed ration (kg/d, as dry matter)
Dairy cows	400	26.2
Dry cows	60	14.55
Heifers	170	9.94
Calves	140	9.94

Table 4
Inventory data of the crops' cultivation (valid for all the scenarios).

Variables	Unit	Cultivated crops		
		Alfalfa hay	Wheat grain	Mixed hay crops
Area	ha	200	100	100
Total yield	t/ha	11	7	11
Seeds	kg/ha	28	190	200
Organic fertilization (digestate)	m3/ha	45	45	45

Notes about the field operations performed: minimum soil tillage, mechanical weed control (no pesticide use) and no irrigation.

depression for the four AMSs present in the barn in ISV-AMS consume as much as the depressor of the milking parlor present in BS and ISV.

Animal and field emissions were quantified with different methods based on the emission source, as follows. Enteric methane emissions were modelled following Moraes et al. (2014); emissions from manure storage and application were modelled following IPCC (2019) for methane (manure storage) and dinitrogen oxide (manure storage and application). Concerning ammonia and nitrogen oxide emissions from manure storage and field spreading, the EMEP EEA inventory book (2019) was used. As emissions to water, phosphate emissions followed Ecoinvent report n. 15 (2007), and nitrate emissions followed IPCC (2019).

2.2.3. *Impact assessment and uncertainty analysis*

The EF 3.0 characterization method (Fazio et al., 2018) was used to quantify the environmental impact of the studied farm, focusing on the following impact categories:

- Climate change (CC),
- Ozone depletion (OD),
- Ionising radiation (IR),
- Photochemical ozone formation (POF),
- Particulate matter (PM),
- Human toxicity non-cancer (HTnc),
- Human toxicity cancer (HTc),
- Acidification (AC),
- Eutrophication freshwater (FE),
- Eutrophication, marine (ME),
- Eutrophication terrestrial (TE),
- Ecotoxicity freshwater (FEX),
- Water use (WU),
- Resource use fossils (FRU),
- Resource use minerals and metals (MMRU).

To test the robustness of the environmental impact results, a quantitative uncertainty analysis was performed using the Monte Carlo technique (with 1000 iterations and 95 % confidence interval) as a sampling method. The results are reported in the following section.

3. Results and discussion

3.1. *Comparison of the scenarios*

The scenarios ISV and ISV-AMS highlighted some differences in respect to BS, mostly due to the energy and water use. In particular, the water used for washing the milking parlor in the BS and ISV configurations was about 2008 m^3/year. The water used by the cow sprinklers was on average 16,650 m^3/year. After the installation of the AMS and the decommissioning of the milking parlor, a slight increase of about 36 m^3/year of water consumption for the milking sessions was recorded since the milking robots used about 2044 m^3/year for cleaning and washing operations. In the context of energy consumptions, the introduction of the ventilation system, in the ISV scenario, caused an increase of the annual energy need for the farm of about 4 % with respect to the BS. Even this energy increase was properly introduced in the LCA analysis.

Furthermore, it is worth noting that some differences were obtained on milk productivity, both in terms of quantity and quality, over the year. For each lactating cow in the BS was recorded an average milk production of 31.60 kg/d (with average contents of 4.10 % fat and 3.30 % protein), for the ISV was recorded an average milk production of 36.00 kg/d (with 4.20 % fat and 3.60 % protein), and for the ISV-AMS case was obtained an average milk production per cow equal to 39.00 kg/d (with 4.00 % fat and 3.40 % protein). Moreover, by moving from ISV to ISV-AMS configuration a significant reduction of the cases of mastitis from about 20 to about 10 diagnoses per year were recorded among lactating and dry cows.

Table 5

Absolute values for the environmental impact of the three scenarios, first is the Baseline and then the two scenarios of ISV (Improved Scenario with Ventilation); ISV-AMS (Improved Scenario with Ventilation and Automatic Milking System). The functional unit (FU) selected for the three scenarios was 1 kg of fat and protein corrected milk (FPCM).

Impact category	Unit	Baseline	ISV	ISV-AMS
Climate change	kg CO2 eq	1.854	1.566	1.501
Ozone depletion	kg CFC11 eq	2.88×10^{-8}	2.49×10^{-8}	2.39×10^{-8}
Ionising radiation	kBq U-235 eq	0.044	0.037	0.036
Photochemical ozone formation	kg NMVOC eq	0.002	0.002	0.001
Particulate matter	disease incidence	3.00×10^{-7}	2.43×10^{-7}	2.32×10^{-7}
Human toxicity, non-cancer	CTUh	4.65×10^{-9}	3.93×10^{-9}	3.77×10^{-9}
Human toxicity, cancer	CTUh	1.56×10^{-10}	1.33×10^{-10}	1.27×10^{-10}
Acidification	mol H+ eq	0.043	0.035	0.033
Eutrophication, freshwater	kg P eq	0.00015	0.00013	0.00012
Eutrophication, marine	kg N eq	0.007	0.006	0.006
Eutrophication, terrestrial	mol N eq	0.191	0.154	0.147
Ecotoxicity, freshwater	CTUe	10.608	8.967	8.593
Water use	m^3 depriv.	7.036	6.056	5.809
Resource use, fossils	MJ	2.969	2.569	2.464
Resource use, minerals and metals	kg Sb eq	1.19×10^{-6}	1.02×10^{-6}	9.76×10^{-7}

Note: ISV = Improved Scenario with Ventilation; ISV-AMS = Improved Scenario with Ventilation and Automatic Milking System.

3.2. *Life cycle assessment*

Table 5 summarizes the results of the environmental impact assessment, as absolute values, of the three scenarios investigated. Fig. 3 reports the relative results comparing the three scenarios, with BS scenario set at 100 % value.

The Baseline Scenario resulted the configuration with the highest impact values for all the impact categories considered. In particular, focusing on Climate Change category, BS impacted for 1.85 kg CO_2eq/kg FPCM. This result is quite high, but still in the range of medium performing milk farms, and especially for organic ones (Froldi et al., 2022; Mazzetto et al., 2022). The two improved scenarios, ISV and ISV-AMS, determined a relevant reduction of all the environmental impacts, with the highest benefit obtained in the transition from the BS to the ISV-AMS, which was the second upgrading level. As for the above-mentioned impact category of Climate Change, ISV reduced the impact of 16 % and ISV-AMS of 19 % respect to BS, with absolute values equal to 1.56 and 1.50 kg CO_2eq/kg FPCM for ISV and ISV-AMS, respectively. As clearly highlighted in Fig. 3, after the first upgrading (from BS to ISV) the impact categories registered a reduction ranging from about −14 % (for OD) to about −19 % (for TE, AC and PM) with respect to the values provided in the BS, followed by Marine Eutrophication (−16 %), and Freshwater Ecotoxicity (−15 %). The second upgrading intervention (ISV-AMS scenario) brought the reduction of the different impact categories in a range going from −17 % (for OD, WU and FRU) to −23 % (for PM, AC, and TE) of BS, so overall contributing in a more evident way to the whole reduction of environmental impacts. This impact reduction was linked first of all with the technological improvement introduced in ISV and ISV-AMS; in fact, the presence in the barn of the ventilation system coupled with the sprinklers significantly supported the reduction of the negative effects caused by heat stress, and in particular supported the improvement of animal welfare and the increase of milk productivity (West, 2003). Being the selected FU equal to 1 kg of FPCM, the increased milk productivity directly influenced the environmental results. Furthermore, the results were influenced by the different inputs use in

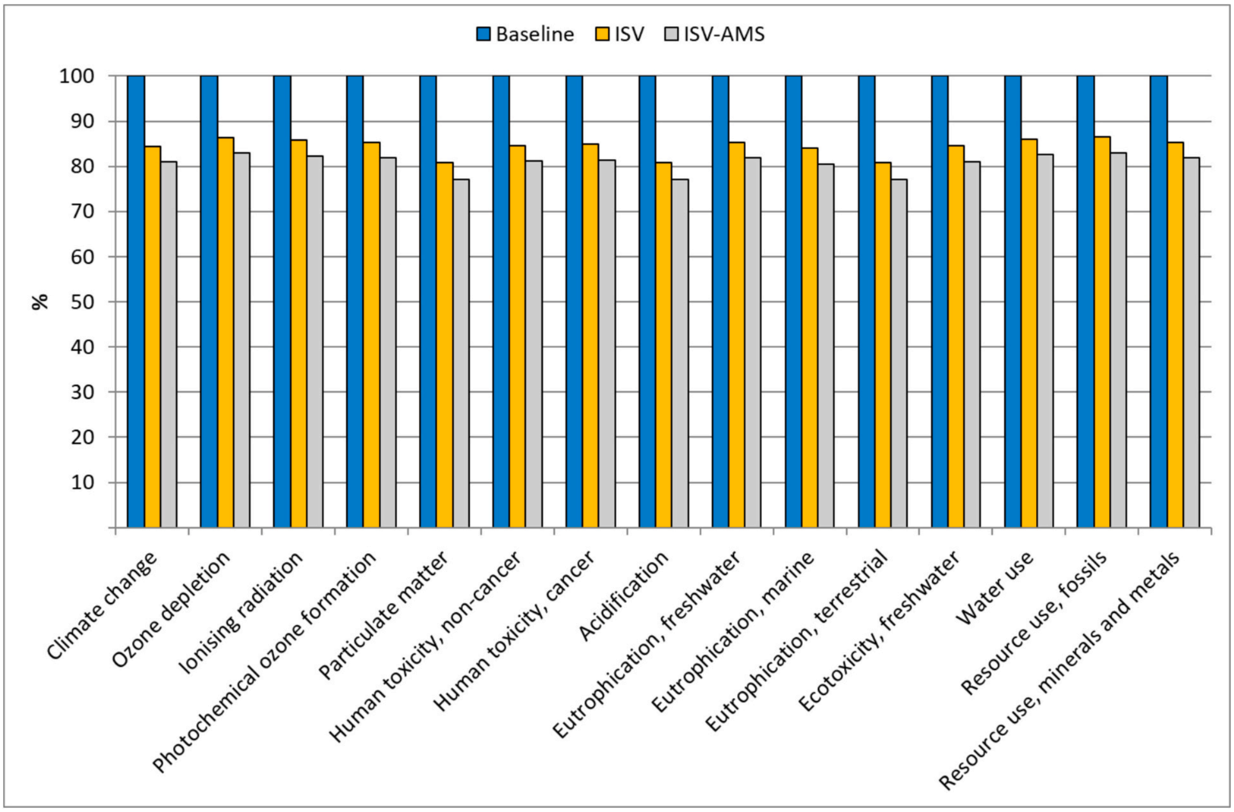


Fig. 3. Comparison of the impact categories for the three scenarios: the Baseline, ISV (Improved Scenario with Ventilation) and ISV-AMS (Improved Scenario with Ventilation and Automatic Milking System).

the scenarios, and especially by the different electric energy use (determined by the installation of the ventilation system) and volume of water used for the sprinklers and for the washings of the milking systems. The main difference of these inputs could be observed between BS and ISV, since in the BS the use of electricity and water was much lower than in ISV. From ISV and ISV-AMS, the differences were small, therefore, the higher environmental sustainability of ISV-AMS could be attributed to the higher milk productivity of the most advanced scenario (impacts reduction of about 4 % in all impact categories between ISV and ISV-AMS). Although ISV-AMS is the scenario reaching the best results in terms of reduction of the environmental impact, it must be highlighted that it is ISV the scenario that achieves the greatest relative reduction, since the environmental impact benefits are relatively higher after the introduction of the ventilation system.

Accordingly, when comparing the impact reduction achievable from BS to ISV (e.g. for CC equal to −15.5 %) and the one from ISV to ISV-AMS (for CC -4.1 %), it can be observed that the previous largely outperformed the latter. The AMS in ISV-AMS further supported this improvement by bringing an additional environmental benefit to all the impact categories, but it can be stated that the introduction of a suitable ventilation system alone provided greater benefits on the environmental sustainability than the condition in which a robotic milking system was introduced along with ventilation. Therefore, mechanical ventilation represents the first intervention to be suggested to dairy farms to reduce their environmental impact. This result is in line with the literature findings of researchers that studied the effect of installing an AMS (Tse et al., 2018). Instead, it is in contrast with the results by Herzog et al. (2021) who did not find significant improvements in the environmental impact of two Austrian milk dairy farms before and after the installation of a mechanical ventilation. Probably, as also suggested by the authors themselves, the heat stress showed low peaks in the studied region during the monitored period, hence a bigger difference in the environmental impact of scenarios without vs with ventilation systems can be expected in areas with different climatic conditions, such as the area investigated in this study. Furthermore, the herd management of the farms in Herzog et al. (2021) was less intensive than in this study. Therefore, further research could support findings in the evaluation of the effect on the environmental sustainability of installing a ventilation system effectively contrasting the negative effects on the animals induced by heat load.

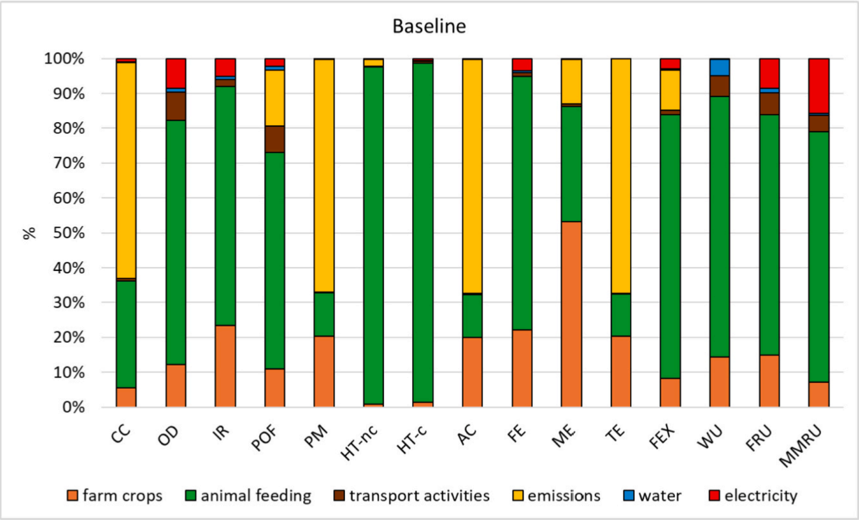
Considering the two improved systems, the reduction in environmental impact achieved by ISV-AMS respect to ISV ranged from 4.1 % to 4.6 % for all the impact categories. The difference between the results of these two scenarios can be explained by milk productivity, which was higher in ISV-AMS than in ISV; since milk productivity was the FU (expressed as FPCM), it had a direct effect on the results.

Fig. 4 shows the results of the hotspot analysis, from which the major findings are:

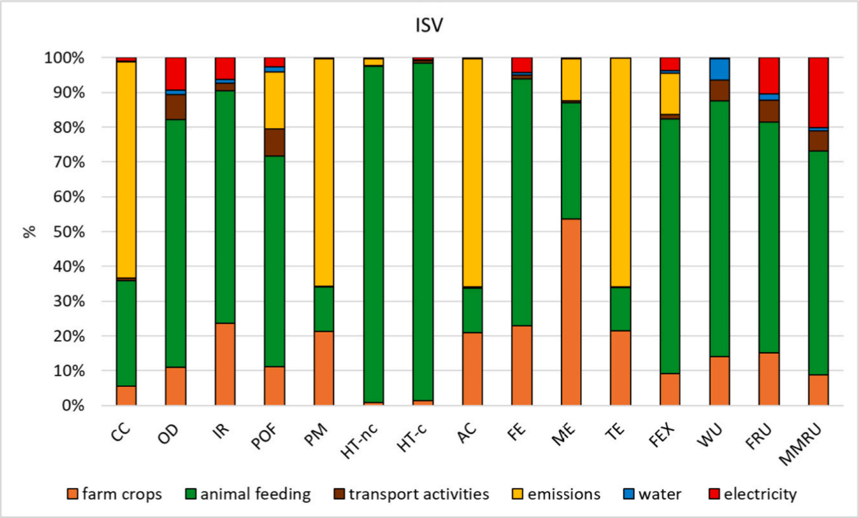
- enteric methane emissions on CC (about 31.8 % in the 3 scenarios),
- methane emissions from manure management on CC (about 21.0 % in all scenarios),
- ammonia emissions from manure management on PM (48 % in BS, 47 % in ISV and ISV-AMS), AC (49 % in BS, 48 % in ISV and ISV-AMS), and TE (49 % in BS and 48 % in ISV and ISV-AMS),
- feeds, mainly purchased feeds (grain maize and soybean meal) and farm cultivated crops (hay mixture) for HTc and HTnc, followed by FE, ME, FEx, WU, FRU and MMRU.

The hotspot analysis showed results consistent with literature studies on the environmental impact assessment of dairy cattle production.

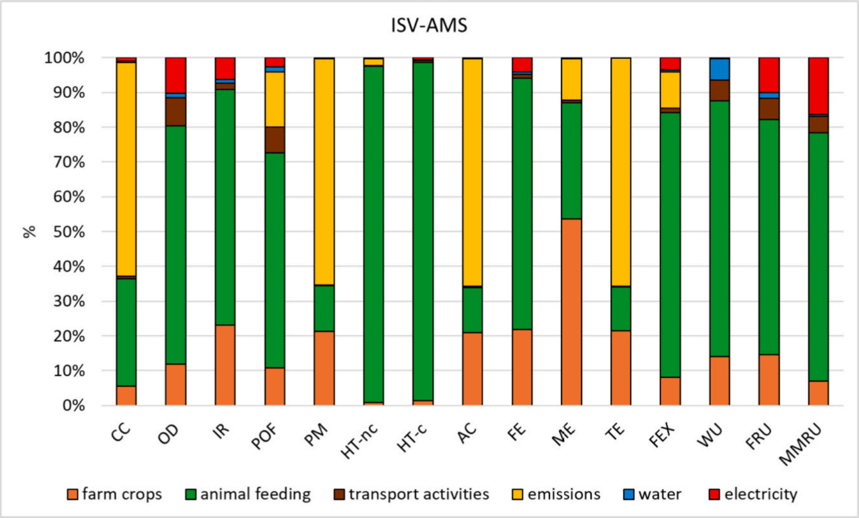
Then, by testing the robustness of the results obtained when comparing the three scenarios, the uncertainty analysis performed using the Monte Carlo technique highlighted a very small uncertainty in the overall outcomes. Fig. 5 shows the results of the uncertainty analysis for BS vs ISV scenarios, while Fig. 6 shows the results of the uncertainty



(a)



(b)



(c)

Fig. 4. Hotspot analysis of each scenario. (a) Baseline Scenario; (b) Improved Scenario by Ventilation system (ISV); (c) Improved Scenario by Ventilation system and Automatic Milking System (ISV-AMS).

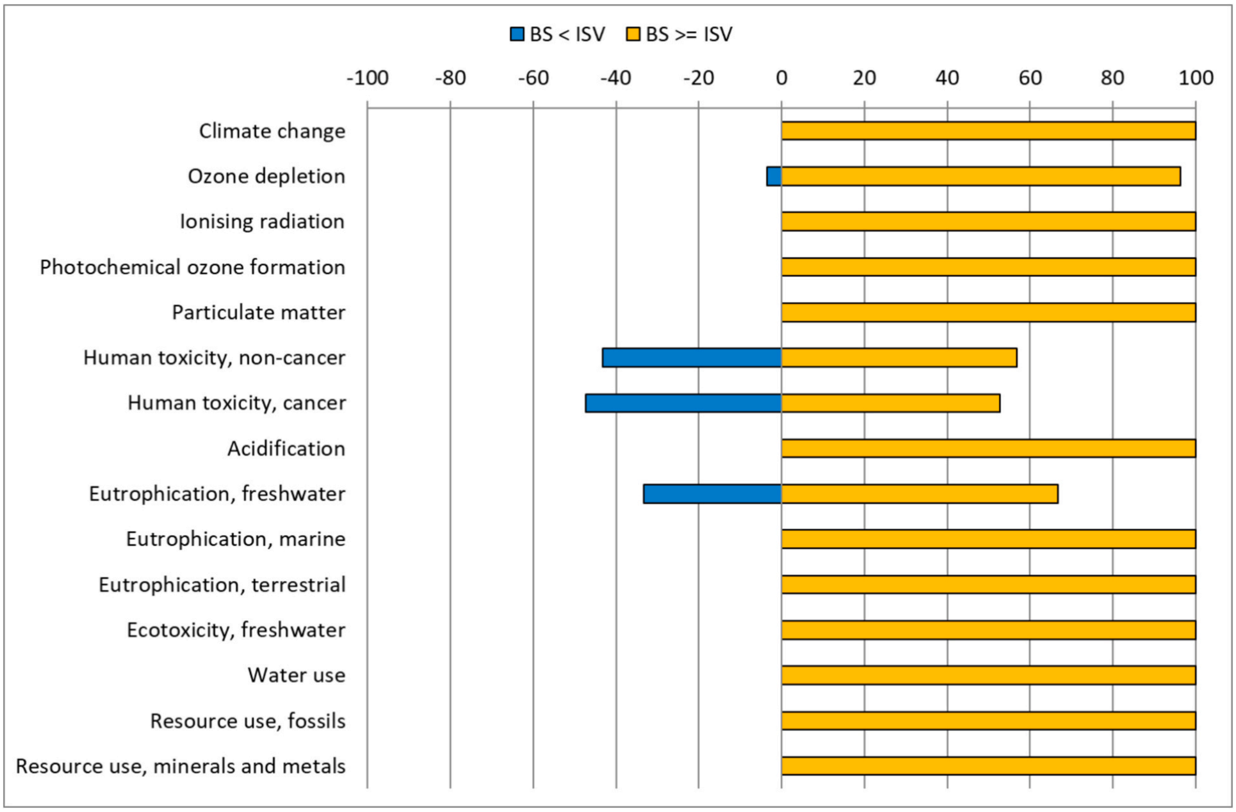


Fig. 5. Uncertainty analysis between Baseline Scenario (BS) and Improved System with Ventilation (ISV). Orange bars represent the probability that the environmental impact of the baseline is greater than or equal to the alternative scenario, blue bars on the left represent the opposite probability.

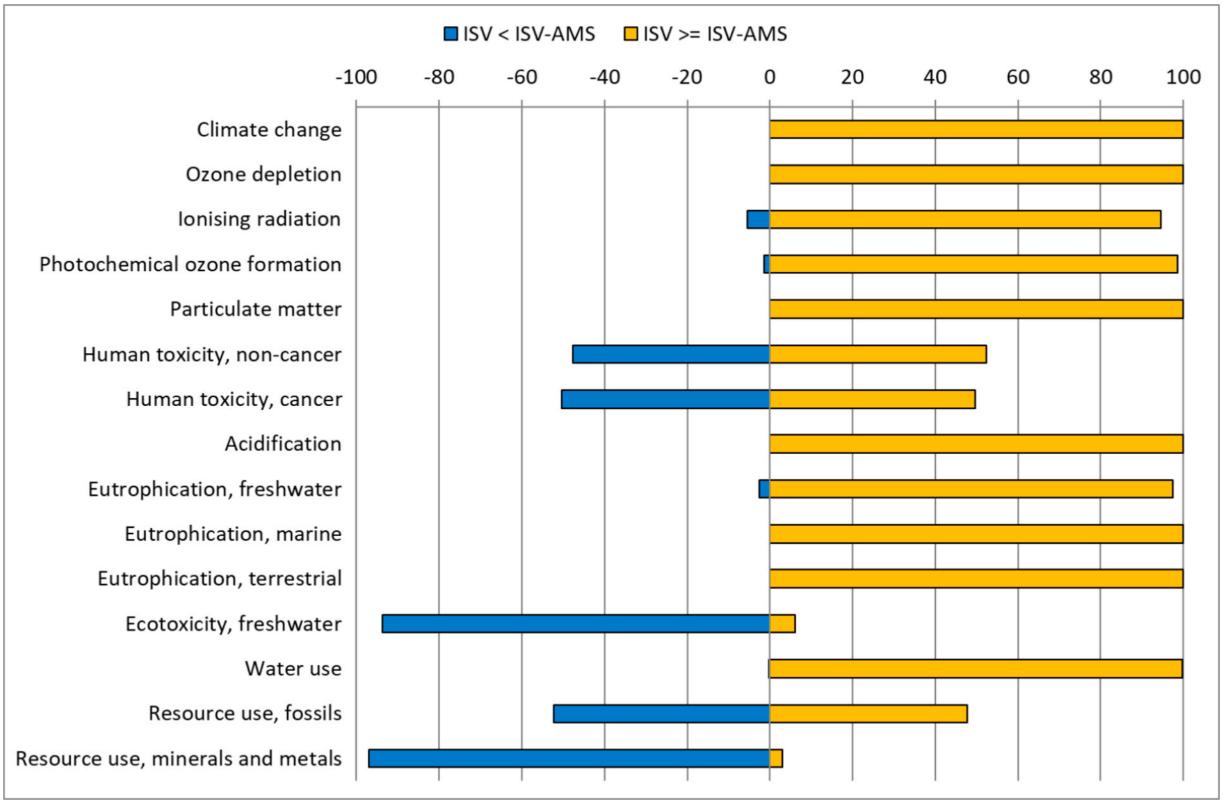


Fig. 6. Uncertainty analysis between Improved System with Ventilation (ISV) and Improved System with Ventilation and Automatic Milking System (ISV-AMS). Orange bars represent the probability that the environmental impact of the ISV scenario is greater than or equal to the alternative one, blue bars on the left represent the opposite probability.

analysis for ISV vs ISV-AMS scenarios. In both graphs, the bars represent the probability that the environmental impact of one scenario was greater than, or equal to, the alternatives; the bars on the opposite side represent the opposite probability. The results of the uncertainty analysis highlighted that:

- BS vs ISV: BS scenario had always environmental impacts higher than ISV, except for HTc, HTnc and FE, where different probabilities in the results could be observed;
- ISV vs ISV-AMS: 8 out of 12 impact categories showed that the differences in the results were significant, therefore no uncertainty was present, and it could be stated that the environmental impact of ISV was higher than ISV-AMS; instead, for the remaining categories (i.e. HTc, HTnc, FEx, FRU) there was some uncertainty, while MMRU showed almost always impacts higher in ISV-AMS than ISV.

This confirmed that the environmental benefits presented above were not affected by uncertainty caused by the data selection from databases, or by partial model adequacy and data variability.

3.3. *Possible future improvements*

Considering the importance of the use of electricity and water consumption in the scenarios using ventilation and automatic milking system, hypotheses were made based on possible improvements that can be made on livestock farms. In particular, researchers are investigating on the use of sprinklers able to activate only based on the real presence of cows in the feed alley or to work at lower flow rates (Grossi et al., 2022; Macavoray et al., 2023; Tresoldi et al., 2019). This advancement could make it possible to reduce water consumption for wetting cows, with further benefits on animal health and welfare, other than the environmental ones. If the farmer adopted this solution, a − 25 % of water consumption for the sprinklers could be achieved. Furthermore, also by acting on an advanced system for the barn lightening, electric energy consumption could be reduced by 5–10 %. Coupling with these improvements (−25 % water use and − 10 % electric energy), the ISV and ISV-AMS could further reduce their associated environmental impact. This reduction is small in almost all impact categories, affecting by 0.7–1.7 % the impact categories of OD, IR, and FRU. Although the benefit is small, it can be achieved by simple advancements in input use.

The results presented in this paper, although referred to a single case study, offer however the possibility of quantifying and comparing the benefits introduced by different technological upgrades that are much discussed and debated today. In fact, in the context of the dairy sector, there is a strong market demand to increase production but with the need to ensure animal welfare, animal health and reduced environmental impacts. Within this production framework, PLF, by providing real-time data and insights, enables farmers to make informed decisions that enhance animal welfare, health and productivity, and reduce the environmental footprint of their processes. For instance, sensors can monitor water consumption, light intensity, indoor temperature and gases concentrations and adjust distribution systems and equipment to minimize waste, thereby addressing several of the most critical issues related to input needs by the animal production sector.

The European Commission has recognized the potential of PLF tools to contribute to sustainable agriculture and has integrated them into its broader strategy for the sector. As part of the European Green Deal and the Farm to Fork Strategy, the Commission aims to promote practices that reduce greenhouse gas emissions, promote a green transition, conserve natural resources, and enhance biodiversity. This paper has demonstrated that PLF can align with these goals by improving the efficiency of resource use and reducing the environmental impact of livestock farming. The effective achievement of these goals depends on the real installation of technology on farm, for which the role of policy makers that introduce regulations and incentive practices is fundamental.

4. Conclusions

The main outcomes of this paper showed that the introduction of technology in the context of dairy production can improve the environmental sustainability of milk production. In particular, in the studied dairy farm, the mechanical ventilation with cow sprinklers, installed as first upgrading solution, contributed to reduce the impact on Climate Change of 16 % in respect to the baseline scenario, whereas the subsequent installation of an Automatic Milking System determined a further reduction of the environmental impact on CC of an additional 3 %. The main reason for this improvement is linked with the improved milk productivity achieved thank to the installed plants. In this context, LCA has demonstrated to be a valid method to evaluate and prioritize the interventions on farm based on the environmental perspective. In fact, not all technological upgrading interventions lead to significant benefits in terms of environmental sustainability. For this reason, it is useful to have a validated tool to help the farmer in the hierarchy of interventions on farm and to help policy and decision-makers to distribute resources and incentives in the most rational and efficient way to effectively observe environmental improvements in the livestock sector. In fact, policy makers play a crucial role as they can create favorable conditions through regulatory frameworks, research funding, and extension services that support farmers in transitioning to more sustainable practices. Furthermore, they can design and implement economic incentives to encourage the uptake of PLF technologies, first of all for small and medium-sized farms, which may lack the financial resources to invest in new technologies.

In conclusion, the integration of precision livestock farming into sustainable agricultural practices offers a promising pathway to address the environmental impacts of livestock production. By reducing water consumption and energy needs, PLF can help create a more efficient and sustainable agricultural system. The European Commission‘s strategy, supported by policy makers and economic incentives, can drive the widespread adoption of PLF, ultimately contributing to a more sustainable food system.

CRediT authorship contribution statement

Daniela Lovarelli: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Marco Bovo:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Claudia Giannone:** Writing – original draft, Investigation, Data curation, Conceptualization. **Enrica Santolini:** Methodology, Investigation, Conceptualization. **Patrizia Tassinari:** Supervision, Conceptualization. **Marcella Guarino:** Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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