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The growing, resilient, inclusive and sustainable (GRINS) project for the development of life cycle inventory databases of beef cattle raised in Italy: The statistical datasets and the environmental assessment

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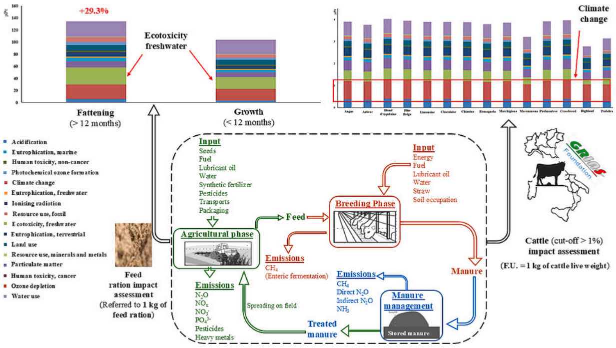
HIGHLIGHTS

- 84 statistical LCI datasets concerning Italian beef cattle have been developed.
- CH_4 emissions from enteric fermentation play a pivotal role.
- Climate change is the main environmental impact category.
- Breed type influences the impact assessment results (±20 %).
- Feed ration composition affects the environmental profile (±29.3 %).

GRAPHICAL ABSTRACT



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ABSTRACT

Within the framework of the Growing, Resilient, Inclusive and Sustainable (GRINS) project (Spoke 1, WP3, Next Generation EU program), this work aims to overcome the absence of Italian beef cattle Life Cycle Inventory (LCI) datasets through a capillary analysis of several parameters. Specifically, the contribution to the environmental impact of livestock breeding of breed features (age, gender, weight, daily weight gain, breeding, feed intake and composition, milk and manure production), as well as stable management and crop cultivation was investigated. Statistical inventory datasets (84 in total) were developed for the predominant (<1 % population cut-off) beef cattle breeds in Italy.

A key finding was the quantification of CH_4 emissions from enteric fermentation (ranging from0.259 to 0.714 g kg^{-1} of live weight *per* day) and its contribution to the overall environmental impact of beef cattle breeding. The composition of feed rations emerged as critical, influencing both cattle emissions and environmental impacts associated with the cultivation and transport of raw materials. Intensive and langer breeds like *Aubrac*, *Blond d'Aquitaine*, *Blue Belga*, *Charolaise*, and *Chianina*, exhibited higher eco-indicator values compared to the extensive beef cattle breeds (*Podolica*, *Highland*, and *Maremmana*). The life cycle assessment identified several key impact categories (climate change, water use and ecotoxicity freshwater) mainly contributing to the total eco-indicator. Climate change (22.1 %) represented the greatest impact category, with beef cattle emissions over their lifespan

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averaging 9.3 Mg CO_2-eq. Methane (enteric fermentation) and NH_3 (manure management) emissions, as well as irrigation and pesticide use, represented the main hotspots. A comparative analysis evaluated the environmental footprint of Italian beef cattle against benchmarks outlined in the "Made Green in Italy" brand's Product Category Rules. This comparison revealed a 32.4 % reduction in total eco-indicator for Italian beef cattle, due to a significant decrease in freshwater ecotoxicity (−72.5 %), land use (−34.2) and climate change (−7.5 %).

1. Introduction

To meet the growing need for comprehensive Life Cycle Assessment (LCA) data, databases (DB) now include agricultural processes, driven by standards like the Environmental Product Declarations and the Product Environmental Footprint (EU, 2013; ISO, 2006a). These standards, which aim to enhance the adoption of environmental schemes in industry, require specific inventory or "selected generic" data covering at least 90 % of the total environmental impact, making database data crucial for creating accurate declarations (EPD, 2019). National initiatives, notably in Italy, such as the ILCIDAF project, are pivotal in developing of comprehensive DB for key agri-food chains like bread, pasta, wine, olive oil, and citrus fruits (Notarnicola et al., 2022). These efforts, funded by entities such as the Ministry of University and Research, aim to improve the quantity and the quality of the Italian agri-food sector's datasets.

The Growing, Resilient, Inclusive and Sustainable (GRINS) project (Spoke 1 Project, WP3), supported by the Next Generation EU program and PNRR funds (Extended Partnership activity "Economic-financial sustainability of systems and territories"), is focused on the establishment of Life Cycle Inventory (LCI) datasets for Italian cattle breeding (Notarnicola et al., 2023a). Livestock farming, notably cattle breeding, significantly impacts the environment, with studies indicating that approximately 24 % of Europe's overall environmental footprint from food consumption can be attributed to milk and meat production. In the last decade the world cattle annual average population has reached a total of 1.5 billion, while beef production amounts to 70 million tons per year. Countries such as Brazil and India are world leaders in terms cattle population and the United States represents the first world bovine meat producer of, covering 17 % of the world production (FAOSTAT, 2023). The environmental impact of the livestock, particularly beef production, is of significant concern due to its substantial contribution to greenhouse gas (GHG) emissions, water use and land degradation (de Vries et al., 2015; Sakadevan and Nguyen, 2017; Leip et al., 2015; Herrero et al., 2021). The IPCC AR6 highlights livestock as a major driver of climate change, contributing significantly to greenhouse gas emissions (especially methane), deforestation, water use, and biodiversity loss. Livestock accounts for around 14.5 % of global emissions, with beef production being particularly resource-intensive (IPCC, 2021). Mitigation strategies recommended include shifting to plant-based diets, improving livestock management, and restoring degraded lands. These actions could reduce emissions, preserve ecosystems, and alleviate pressure on water and land resources.

Understanding and quantifying disparities among beef production systems is crucial for promoting sustainable practices and mitigating environmental impacts, which are essential for ensuring the long-term resilience and sustainability of food production systems on a global scale (Béné et al., 2019; Campi et al., 2021).

Beef cattle LCI datasets sourced from major international databases, such as the Swiss "Ecoinvent" DB (Ecoinvent, 2023) and "World Food" DB (Nemecek, 2019), the French "Agribalyse" (2017) DB and the Dutch DB called "Agri-footprint" (Blonk, 2014) (Table 1), are exclusively focused on breeding in foreign territories, particularly Brazil, South Africa, and New Zealand, or are generalized to cover the entire planet, while the description of scenarios referred to the Italian territory has been neglected.

The need for national and regional dataset systems stems from the requirement to conduct accurate environmental assessments. These must consider the unique traits of local bovine populations, including breed and aptitude, and the various rearing methods (stall, semi-stall or pasture). It is also essential to account for stable management and the region's pedo-climatic features, such as forage crops and agricultural practices (Nitschelm et al., 2016; Hong et al., 2019).

The purpose of this research is to describe the above-mentioned LCI study of the Italian beef cattle breeding in accordance with the ISO 14040, and ISO 14044 standards (ISO, 2006b; ISO, 2006c). To this regard, 84 statistical Italian datasets referred to 14 meat cattle breeds have been developed, by distinguishing the contribution associated with each age and gender. For each category the emissions related to both enteric fermentation and manure management have been quantified and analysed, as well as the contribution of the agricultural cultivation (providing the feed ration raw components) in terms of emissions to air, water, and soil, water consumption and soil occupation. Furthermore, the activities related to the stable management (water use, electricity consumptions and soil occupation) have also been included in the datasets, as well as the transports and the waste end-of-life.

Furthermore, in the life cycle impact assessment, the inventory data were converted into indicators analysing environmental implications and resource consumption. This analysis identified the sector's strengths and weaknesses, leading to the identification of interventions that promote sustainable agricultural and livestock practices to minimize environmental impact.

2. Materials and methods

2.1. Italian cattle population

The Statistical section of the Veterinary Information System within the Italian Ministry of Health database offers comprehensive data on the bovine population. These data are categorized by breed, gender (F = female; M = male), and age group (0–6, 6–12, 12–24 and > 24 months) at national and regional level (BDN, 2023). The bovine population is

Table 1
LCI datasets related to cattle farming found in the main international databases.

Age (month)	Bovine	Database				Total
		Ecoinvent 3	Agribalyse 3	Agri-footprint 5	World Food LCA Database	
6–12	Male calves	10	9	/	/	28
	Female calves	6	3	/	/	
12–24	Steer	11	7	/	7	39
	Heifer	10	4			
> 24	Bull	3	2	1	/	16
	Cow	5	6			
Total		45	31	1	7	84

segmented into calves (0–6 months), yearlings (6–12 months), young steers and heifers (12–24 months), bulls, and cows (over 24 months). In the period 2019–2022 the Italian yearly bovine population averaged 5,563,668 heads per year (BDN, 2023). Beef cattle over six months old amounted to 2,168,162 heads considering only breeds with a cut-off population < 1 %, both at national and regional levels. In this study, life cycle inventory of beef cattle aged less than six months was not considered due to the not fully developed rumen which acquires full functionality around 4 months or later, after weaning (Beauchemin et al., 2011). Thirteen pure beef breeds (*Piedmontese, Limousine, Marchigiana, Chianina, Blond d'Aquitaine, Angus, Charolais, Maremmana, Romagnola, Aubrac, Podolica* and *Highland*) and *crossbreeds* were selected. Due to uncontrolled crossbreeding, resulting in randomly mixed hybrids, the crossbreed composition was assumed to inherit 50 % of the traits from meat-specialized bulls (70 % *Piedmontese* and Limousine) and 50 % from milk-specialized cows (approximately 80 % *Frisona*). The population of each breed is reported in Fig. 1.

Crossbreed (1,102,659 heads) represented >50 % of the whole beef cattle population, while *Piedmontese* (282,922 heads), *Limousine* (270,468 heads) and *Charolaise* (222,931 heads) are the most abundant pure breeds. An analysis of the categories highlighted the prevalence of cattle belonging to the $F_{>24}$ group (898,711 heads), followed by $F_{12–24}$ (428,481 heads) and $F_{6–12}$ (336,079 heads) categories.

2.2. Functional unit and system boundary

In accordance with the Livestock Environmental Assessment and Performance guidelines (FAO, 2022), the chosen Functional Unit (FU) for beef cattle LCI was 1 kg of live weight of animal leaving the farm (Nguyen et al., 2012). A cradle-to-farm gate perspective was the adopted system boundary (Fig. 2).

Impacts arising from post-production transport, processing, distribution, consumption, and all associated waste disposal were omitted from the inventory.

Methane emissions from enteric fermentation and manure management, as well as N_2O emissions were estimated *via* IPCC models (IPCC, 2019). Methane emissions from enteric fermentation were estimated according to IPCC Tier 2 approach, based on gross energy requirements and digestible energy of feed. For each category, several parameters, including daily weight gain, live weight, type of farming (stall, semi-stall, and pasture system), forage/concentrate ratio in the feed ration, and for lactating cows, daily milk production, and its proteins and fat concentration were considered. Italian sector associations provided morphological information related to the average weight of each category, as well as daily weight gain and rearing methods. The enteric CH_4 emissions were expressed in terms of grams of CH_4 per kg of live weight per day (Table S1, supplementary materials). The gross energy (GE) intake was calculated using the feed composition hypothesized for each beef cattle category (Cevolani, 2022; INRA, 2008; INRA, 2018). A CH_4 conversion factor (Y_m) of 6.3 was selected for feedlot husbandry categories characterized by feed quality digestibility values (DE%) within the range of 63–65, with diets consisting of either mixed concentrates or high-quality forages. Reliable estimates for grazing cattle on very poor-quality diets were not available; due to this lack of data, a Y_m value of 7.0 has was hypothesized (IPCC, 2021). In the case of both the grazing and feedlot systems, a weighted average of the two values was used. Then CH_4 emission factors were determined as a function of the gross energy intake (GE) considering the CH_4 conversion factors (Y_m) for each diet.

Methane emissions from manure management were estimated according to the IPCC Tier 1a using default values of CH_4 conversion factors, maximum CH_4 producing capacity and waste management systems implemented for non-dairy cattle raised in the Western Europe (IPCC, 2019). According to the tier 1a approach of the IPCC methodology, for each livestock category, parameters such as climate zone, quantity of volatile solid, manure storage fraction and default emission factor should be evaluated (IPCC, 2019). Following this approach, each Italian region was categorized into a climate area by collecting detailed data (1990–2020) from ISPRA (Istituto Superiore per la Protezione e la Ricerca Ambientale) database (ISPRA, 2022). Average temperature, annual rainfall, potential evapotranspiration ratio, as well as frost annual days and average altitude allowed to classify the Italian regions as “Warm Temperate Moist”, except for South Tyrol, Trentino and Aosta Valley ranked as “Cool Temperate Moist”. Feed ratio composition allowed to calculate the amount of volatile solids, while maximum CH_4 producing capacity and CH_4 conversion factors were evaluated employing data related to different animal waste management systems (liquid/slurry, solid storage, pasture/range/paddock and daily spread) suggested for the default geographical area.

For direct N_2O emissions from manure management, the IPCC Tier 1a algorithm was used, which is based on the amount of nitrogen excreted (N_{ex}) as faeces and urine, and the manure management system.

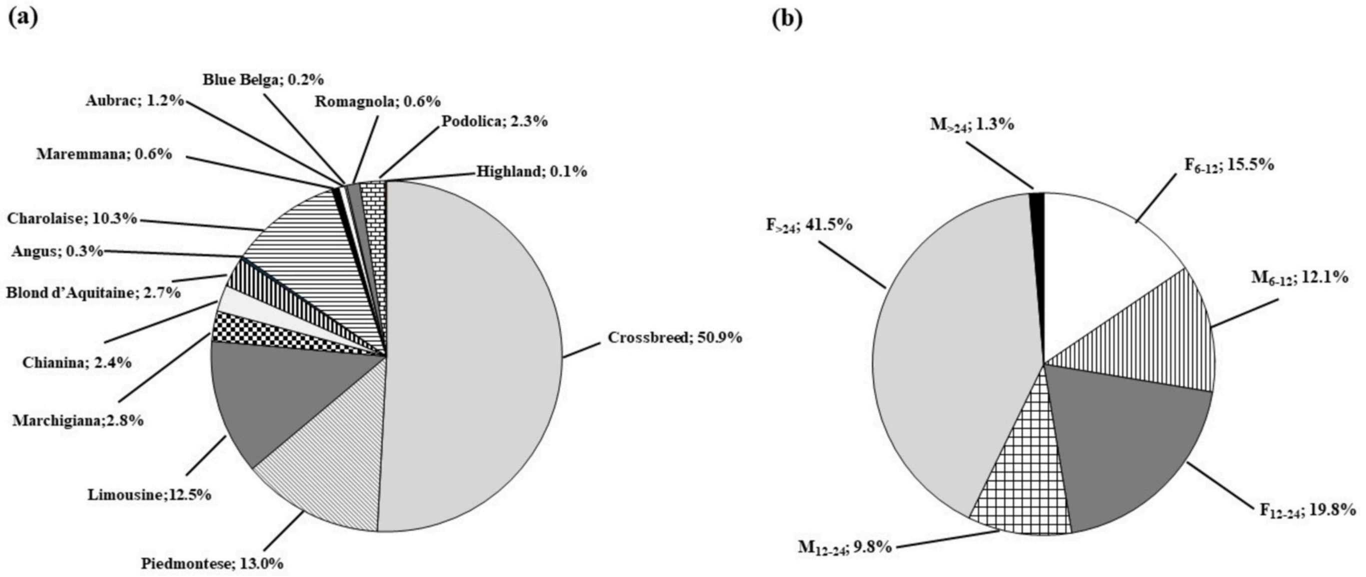

Fig. 1. Population distribution of beef cattle (over 6 months of age) in Italy by breed (a) and age category (b) referred to the period 2019–2022. F = female; M = male. (Source: BDN, 2023).

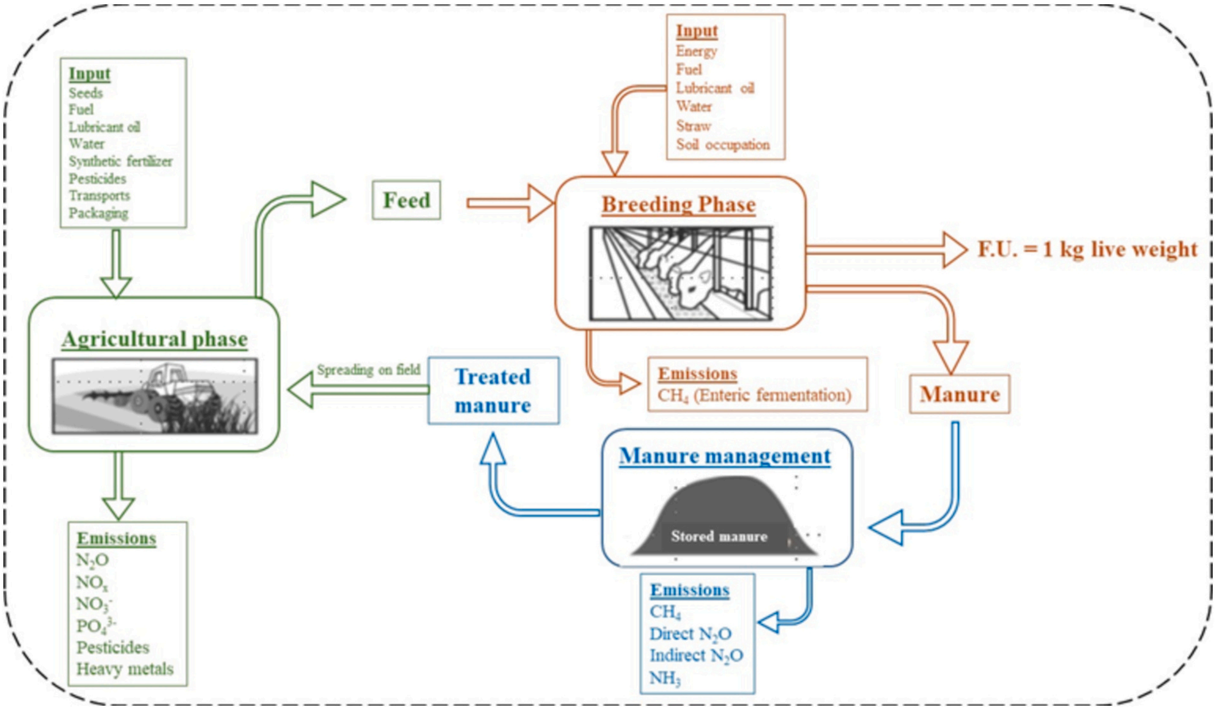

Fig. 2. Schematic framework of the rearing system.

Different emissions factors were employed based on the manure manage system, according to the default values provided from IPCC and referred to non-dairy cattle raised in the Western Europe (IPCC, 2019). Similarly, indirect N_2O emissions related to volatilization and leaching processes of manure N management were also assessed based on IPCC Tier 1a (non-dairy cattle raised in the Western Europe) approach considering N_{ex} and manure management system.

Ammonia emissions were estimated using the method proposed by the EMEP/EEA air pollutant emission inventory guidebook (EMEP/EEA, 2019). Default values of total ammoniacal nitrogen and emission factors are referred to non-dairy cattle considering different type of manure composition (slurry or solid).

In crop production, boundaries encompass manufacturing processes (including raw material extraction), as well as the supply and utilization of inputs essential for the whole production cycle (fuels, fertilizers, pesticides, transport, seeds, electricity, other necessary materials). Data on these processes were retrieved from a national agricultural handbook (Ribaudo, 2017). The inputs related to the stable management (water, soil occupation, fuel, electricity, and manure management) were also considered (Ribaudo, 2017).

Additionally, to enable a comparative impact assessment between the growing and fattening feed rations, the same quantity of feed ration (1 kg) was used for the comparison.

2.3. *Impact assessment*

In the Life Cycle Impact Assessment phase, inventory data are translated into indicators that reflect environmental burdens as well as resource scarcity. The dataset was characterized by means of the Environmental Footprint 3.1 (version 1.01, released in July 2022). In total, 16 impact categories were evaluated: Acidification (AC); Climate change (CC); Ecotoxicity, freshwater (EcF); Particulate matter (PM); Eutrophication, marine (EuM); Eutrophication, freshwater (EuF); Eutrophication, terrestrial (EuT); Human toxicity, cancer (HTC); Human toxicity, non-cancer (HTnC); Ionising radiation (IR); Land use (LU); Ozone depletion (OD); Photochemical ozone formation (POF); Resource use, fossils (RUF); Resource use, minerals and metals (RUMM); Water use (WU).

Current IPCC 100-year global warming potential (GWP) characterization factors were applied to convert greenhouse gas emissions into carbon dioxide equivalent ($CO_{2\text{-eq}}$) emissions (IPCC, 2021). The characterization factors used were 1, 29.8, 27.2 and 273 for carbon dioxide, fossil methane, biogenic methane (for enteric fermentation emissions) and nitrous oxide, respectively.

3. Results and discussion

3.1. *Life cycle inventory*

The emission due to enteric fermentation and manure disposal, as well as stable management and feed ratio preparation, were estimated by employing different literature sources and available national and international databases.

3.1.1. *Emissions from enteric fermentation and manure management*

The methane from enteric fermentation played a pivotal role and the recorded emissions ranged from 0.259 to 0.714 g kg^{-1} of live weight *per* day in the overall environmental impact of beef cattle breeding. The IPCC's Sixth Assessment Report (AR6) assigns a Global Warming Potential (GWP_{100}) of 27.2 to biogenic methane, which enabled the conversion of the results into kg CO_2-eq *per* kg of live weight *per* year, yielding values ranging from 2.6 to 7.0. These results are slightly lower but in the same order of magnitude of a study that analysed a specific Italian beef cattle farm (calves, bullock, heifers, cows, and bulls) with an average value of biogenic methane equal to 9.3 kg CO_2-eq *per* kg of live weight *per* year (Buratti et al., 2017). Berton et al. (2017) recorded a comparable biogenic methane value of 6.9 kg CO_2-eq *per* kg of live weight *per* year, which are in line with the findings of Veysset et al. (2014) for fattened bulls in the French beef sector (6.4 CO_2-eq *per* kg of live weight *per* year). The results are also in line with those of Gac et al. (2010) which report a value of 7.1 kg CO_2-eq *per* kg of live weight *per* year. These values are consistent with ranges reported in review studies conducted within the EU and internationally (*e.g.* de Vries et al., 2015). Furthermore, two scenarios (baseline management and optimized nitrogen management) were compared on two beef cattle farms in northern Italy (“open cycle” system, where calves are weaned externally from pasture-based farms and fattened until slaughter). The inventory data were assessed (ReCiPe 2016 Midpoint (H) method) and the GWP ranged from 13.37 to 15.74 kg CO_2-eq *per* kg of live weight *per* year (Costantini et al., 2023; Costantini et al., 2024). Interestingly, a study describing meat production in South Tyrol is highlighted as the predominant of the extensive practices, with limited use of concentrate feed and no artificial fertilizers or herbicides, ensuring good environmental performance (Angerer et al., 2021). In this case, organic farming enhances biodiversity, while suckler cow husbandry and heifer/ox fattening have lower environmental impacts compared to veal production and other European systems. The same research group also incorporated the slaughtering phase into their environmental evaluation, finding that the GWP was 19.5 kg CO_2-eq *per* kg of live weight *per* year for slaughter at 12 months (Sabia et al., 2024). This was significantly lower than the 22.9 kg CO_2-eq *per* kg of live weight *per* year recorded for slaughter at 24 months.

If the specific breed is considered, the highest CH_4 daily emissions were recorded for M_{6-12} *Charolaise* (351.55 g kg^{-1} day^{-1}) and M_{6-12} *Blond d'Aquitaine* (351.14 g kg^{-1} day^{-1}) categories. These categories of cattle experience rapid growth in their first year of life, which has a detrimental effect on enteric CH_4 emissions. On the contrary, the lowest CH_4 values were estimated for beef cattle with moderate growth rates and total weights with values equal to 131.57 g kg^{-1} day^{-1} (M_{6-12} *Highland*).

The emissions in air of CH_4, N_2O and NH_3 from manure management are reported in Table S2 (supplementary material) as mass of pollutant referred to the live weight of beef cattle *per* day. The results indicate that the main contributor to the environmental impact of manure storage in beef production is methane, with nitrogen emissions playing a secondary role (Berton et al., 2017; Dalby et al., 2021).

CH_4 emissions from manure management typically tend to be lower than enteric emissions, with the most significant emissions occurring in confined animal management operations where manure is managed in liquid-based systems (IPCC, 2019). According to the literature, CH_4 emissions from manure management are lower than the emissions from enteric fermentation (Buratti et al., 2017). Specifically, literature data confirms that methane emissions from manure typically remain below 2 kg CO_2-eq *per* kg of live weight *per* year and are closely linked to the management system used (Vitali et al., 2018). Our approach used default data provided by IPCC for the Western Europe, which estimates that daily CH_4 emissions referred to mass of live weight range from $6.69 \cdot 10^{-3}$ (*Blond d'Aquitaine* $M_{>24}$) to $3.38 \cdot 10^{-2}$ (*Crossbreed* F_{6-12}) grams *per* kg of live weight *per* day. These values in terms of CO_2-eq have an average value of 0.4 kg CO_2-eq *per* kg of live weight *per* year. As far as animal category CH_4 emissions are concerned, the daily emissions ranged from 6.67 (*Podolica* F_{12-24}) to 17.59 (*Charolaise* M_{6-12}) grams *per* head *per* day.

The estimation of both direct and indirect N_2O emissions associated with the storage and treatment of manure requires the employment of appropriate methodologies considering different parameters, such as nitrogen excretion rates, emission factors for N_2O emissions, as well as volatilization and leaching factors. Estimating N_2O emissions from manure involves quantifying nitrogen excretion by animals and using detailed emission factors influenced by management practices. Direct emissions occur from specific sources like manure management, while indirect emissions result from downstream effects, such as land-use changes. Management methods like anaerobic lagoons or composting influence N_2O release, along with nitrogen volatilization and leaching. In the IPCC at tier 1a level, key parameters such as manure management system, breed, and productivity class (high or low) need to be considered in the estimation of the annual average N excretion, as well as different animal waste management systems and specific emission factors. In the present study, daily direct N_2O emissions referred to live weight of animal are reported for each category in Table S2 and these ranges from $2.27 \cdot 10^{-3}$ (*Charolaise* $M_{>24}$) to $7.81 \cdot 10^{-3}$ (*Romagnola* F_{6-12}) grams *per* kg of live weight *per* day. Additionally, the lowest daily direct N_2O emissions were recorded for *Highland* M_{6-12} at 1.11 g *per* head *per* day. In contrast, *Charolaise* and *Blond d'Aquitaine* M_{6-12} exhibited a value of 3.86 g *per* head *per* day, almost 3.5 times higher. In Tier 1a calculations, nitrogen volatilization and leaching from manure management systems are estimated by multiplying the total excreted nitrogen by specific fractions. These fractions represent the proportion undergoing volatilization or leaching. Greater nitrogen losses occur in dry lots, pens, and uncovered manure heaps, particularly during dormant growth periods. In drier climates, runoff losses range from 3 to 6 % of excreted nitrogen, while runoff and leaching vary from 5 to 19 % and 10 to 16 %, respectively, depending on management practices (Bierman et al., 1999; Rotz, 2004). In the present study, daily indirect N_2O emissions are reported for each category in Table S2 (Supplementary materials) and ranges from $9.69 \cdot 10^{-4}$ (*Podolica* $M_{>24}$) to $3.64 \cdot 10^{-3}$ (*Piedmontese* M_{6-12}) grams *per* kg of live weight *per* day. The lowest daily indirect N_2O emissions referred to each beef cattle were recorded for *Highland* M_{6-12} at 0.45 g *per* head *per* day. In contrast, *Piemontese* M_{6-12} exhibited a value of 1.99 g *per* head *per* day, more than four times higher. About two orders of magnitude values were recorded for manure nitrogen that is lost due to leaching. Daily indirect leaching N_2O reported in Table S2 (Supplementary material) range from $2.31 \cdot 10^{-5}$ (*Charolaise* $M_{>24}$) to $7.95 \cdot 10^{-5}$ (*Romagnola* F_{6-12}) grams *per* kg of live weight per day. The lowest daily indirect leaching N_2O emissions *per* beef cattle were observed for *Highland* M_{6-12}, with a value of 0.0113 g per head *per* day. In contrast, *Charolaise* and *Blond d'Aquitaine* M_{6-12} showed increased emissions (0.0393 g kg^{-1} of live weight *per* day), more than three times higher.

Considering a conversion factor for dinitrogen dioxide equal to 273 (IPCC, 2021), the total N_2O emissions, in this study, from manure management were quantified with a range of 0.33 to 1.14 kg of CO_2-eq *per* kg of live weight *per* year. These values are in the same order of magnitude as those reported in the literature, approximately 3 kg of CO_2-eq *per* kg of live weight (Vitali et al., 2018). This slightly variability is due to several parameters such as production systems, and/or methodological approaches used (*e.g.*, functional unit, system boundaries, emission factors, and allocation methods). As a result, direct comparisons between studies are challenging due to significant differences in the evaluated systems and methods applied (Beauchemin et al., 2011).

The emission of NH_3 from manure management were evaluated *via* the EMEP/EEA air pollutant emission inventory guidebook (EMEP/EEA, 2019). Emissions of NH_3 during one stage of manure management, such as housing, can impact NH_3 emissions during subsequent stages, like manure storage and land application (Holly et al., 2017). Tier 2 level calculations were performed sequentially using a mass-flow approach to account for these dynamics. Daily NH_3 emissions referred to mass of animal live weight are reported for each category in Table S2 (Supplementary materials) ranging from 0.0443 (*Blue Belga* $M_{>24}$) to 0.1460 g kg^{-1} day^{-1} (*Romagnola* F_{6-12}). Considering the value referred to each head, the recorded values were in the range 21.18 (*Highland* M_{6-12}) - 77.92 (*Blond d'Aquitaine* M_{6-12}) grams of NH_3 *per* day.

3.1.2. Stable management

The inputs (water consumption, fuel, lubricating oil, electric energy, straw for bedding and soil occupation) associated with the stable management were quantified for each category, based on data taken from sector handbooks (Ribaudo, 2017; Cevolani, 2022). These data considered various scenarios, accounting for both breed and geographical location of the farm (Central hill, Tiber valley, and foothill areas). Table 2 categorizes the daily consumption inputs for each age and gender category per head.

Beef cattle daily water consumption is due to both temperature and feeding regimen (Cevolani, 2022). The amount of drinking water depends on both age and gender of the beef cattle, and it has been recorded in the range 18.0–55.0 daily litres *per* head *per* day. Water needs rise

Table 2
Daily consumption inputs for each age and gender category per head.

	Beef cattle category					
	$F_{6–12}$	$M_{6–12}$	$F_{12–24}$	$M_{12–24}$	$F_{>24}$	$M_{>24}$
Drinking water (L)	18.0	21.0	25.0	34.4	55.0	41.0
Hygiene water (L)	5.0	5.0	5.0	5.0	5.0	5.0
Air conditioning water (L)	20.0	20.0	20.0	20.0	20.0	20.0
Straw for bedding (kg)	1.197	1.495	2.603	3.125	3.678	2.723
Energy Electricity (kWh)	0.083	0.104	0.176	0.156	0.247	0.027
Fuel (MJ)	0.00353	0.00442	0.00795	0.01148	0.01130	0.01501
Lubricant oil (kg)	0.000193	0.000241	0.000433	0.000626	0.000616	0.00082
Soil occupation (m^2)	2.709	3.383	5.884	6.977	8.311	5.922
Manure (kg)	9.05	11.98	21.12	24.36	32.36	38.82

Sources: Ribaudo (2017); Cevolani (2022). F = Female, M = Male.

with environmental temperatures for heat dissipation and dehydration prevention, with differences between seasons and day-night cycles. Slaughter-focused farms require minimal water hygiene needs (5.0 daily litres *per* head *per* day), while air conditioning systems in the stable, featuring fans and water jets, ensure year-round comfort. Water jets are selectively activated in summer for evaporative cooling, with average consumption of approximately 20.0 daily litres *per* head *per* day.

Various scenarios outlined in Ribaudo (2017) facilitated estimating additional parameters pertinent to stable management. This approach addresses the lack of detailed data for each breed, as available data only covers certain representative breeds in Italian beef cattle systems (*e.g.*, *Chianina* in the Tiber Valley, *Marchigiana* in the Central Italy hills, and *Piedmontese* in the foothill regions). The data in Table 2 reports the average contributions of these scenarios. However, it is worth pointing out that the role of stable management in beef cattle breeding, in terms of greenhouse gas emissions, is generally considered minor compared to emissions from enteric fermentation, manure management, and agricultural practices related to feed production. The emissions directly associated with stable management, such as those from energy use for lighting, ventilation, and machinery, represent a minor contribution to the overall impact. Literature data provides a global perspective on the environmental impact of the livestock systems and highlights the predominant sources, such as enteric fermentation and manure management, with stable management emissions playing a comparatively smaller role (Gerber et al., 2013; de Vries and de Boer, 2010; Herrero et al., 2015).

3.1.3. *Crop cultivation of the fodder fraction*

Feed composition was estimated *via* literature data and tailored on the age and the mass of each animal (INRA, 2008; INRA, 2018; Cevolani, 2022). Two distinct feed rations (FR) were considered: for beef cattle aged between 6 and 12 months (referred as $FR_{6–12}$), and for those older than 12 months ($FR_{>12}$). Suitable fodder/concentrate ratio was identified for each category and the contribution of the vegetable fats and mineral salts was also considered (Table S3, supplementary material). Literature data suggested two main feed ratios for the beef cattle breeding (INRA, 2018). For beef cattle aged lower than 12 months a higher content of fodder (57.3 % *w*/w) than the concentrate ratio (38.1 % w/w) is suggested. Fodder composition is mainly based on corn silage (66.6 % w/w), while the fodder mixture includes different raw materials (Alfaalfa, sulla, lupinella, clover, loietto, permanent lawn or other legumes and grasses). In this study both corn silage and fodder mixture were assumed to be produced in the farm and thus no transport was considered. When the animal reaches an age of one year, the diet is changed, and corn silage represents the main component without any fodder. Specifically, corn silage characterizes the whole fodder fraction (45.0 % w/w of the ratio), while corn flour (33.7 % w/w of the ratio) is the main component of the concentrate fraction. This step, including the fixing phase, (forty days before slaughter) is characterized by the highest contribute of the concentrate fraction (53.9 % w/w) to the whole ration. The daily feed intake for each cattle category was estimated by considering the average weight (typically ranging from 2 % to 3 % w/w) and the activity level.

The agricultural phase of each crop was evaluated *via* the use of secondary data from sector handbooks (Ribaudo, 2017), while crop yield and cultivation area were obtained from the Italian statistical database (ISTAT, 2023). The fodder composition was estimated considering the contribution of each crop cultivated in the Italian territory as follow: Alfaalfa (20.8 %); Sulla (2.9 %); Lupinella (0.4 %); Clover (0.3); other legumes (2.7 %); Loietto (2.7 %); Mixtures (29.1 %); Permanent lawn (23.9 %); other grasses (2.8 %); Poor laws (14.4 %). Detailed data are summarized in Table 3 and are referred to 1 ha of cultivated area.

Manure transport was assumed to be equal to 30 km (PCR fresh and chilled beef meat, 2018), while 50 km distance was assumed for the other materials, such as seeds. Finally, the transportation of the chemicals (synthetic fertilizers and pesticides) was assumed to occur only by road and amounted to 182.35 tkm per hectare (EUROSTAT, 2023).

According to ISTAT data, corn stands out as the primary crop in terms of cultivated area, production volume, and yield (Table 4) (ISTAT, 2023). It can be harvested at the waxy ripeness stage to produce silage or as grain for the processing of corn flour.

A relevant portion of the corn grain, sunflower, soybean grains and straw from common wheat cultivation is imported from other countries. Table S4 in the supplementary material reports the various fractions of each crop imported in Italy from each exporting country. Based on statistical data from Institute of Services for the Agricultural and Food Market (ISMEA), an Italian imported mix was hypnotized for each crop (ISMEA, 2023).

Statistical data highlighted that corn is sourced from foreign countries, while the milling phase typically occurs in Italy. In contrast, soy is imported as both grain and flour, with 40.1 % of the total flour marketed in Italy being imported. During the considered period, only 18.0 % of soy flour was produced from domestically cultivated grain. Additionally, Italy does not import sunflower seeds, with flour covering 87 % of the national needs. To estimate the transportation the Italian mix of each raw material was considered, while the distance (by road, rail, or sea) was estimated using online software (Overland distance, 2023; Sea distance, 2023).

Emissions to air, water, and soil related to the agricultural phase were evaluated by specific methodologies. Emissions to air primarily arise from the utilization of both synthetic and organic fertilizers, as well as the application of active substances aimed at fostering plant growth, safeguarding crops, and ensuring their upkeep. N_2O, NO_x, and NH_3 emissions from manure and synthetic fertilizers spreading were evaluated *via* the indications reported in the IPCC (IPCC, 2019), while the estimation emissions to air stemming from active substances (9 % in air, 1 % in water and 90 % at soil of the applied amount) in pesticides was based on the data outlined in the JRC technical report (Zampori and Pant, 2019). IPCC also provided the methodology to evaluate the emissions to water of nitrates and phosphates, while leached and eroded heavy metals emitted to the ground and in the water due to agricultural

Table 3
Yield, and input data of the agricultural phase of crops making the fodder fraction referred to 1 ha of cultivation area for the period 2019–2022.

	Alfaalfa	Sulla	Lupinella	Clover	Loiessa	Permanent lawn	Other legumes	Other grasses	Mixtures
Yield (kg/ha)	27,089	11,866	12,860	46,664	22,871	11,211	11,313	9810	13,629
Seeds (kg)	6.67	10.00	60.00	12.88	41.00	33.00	120.00	52.50	25.07
Fuel (kg)	166.73	55.93	53.99	118.32	70.24	292.67	57.85	149.42	157.49
Lubrificant oil (kg)	3.44	1.06	0.96	2.23	1.28	5.43	1.06	2.36	3.06
Irrigation water (m^3)	–	–	–	5050	–	2800	–	900	552
Soil occupation (m^2)	0.2084	0.0287	0.0044	0.0034	0.0268	0.2389	0.0264	0.0278	0.2909
Manure as N (kg)	62.73	–	–	54.89	–	188.19	–	–	62.16
Fertilizer (N) (kg)		15.00	–		160.00	–	–	157.50	62.62
Fertilizer (P) (kg)	78.33	60.00	30.00	66.67	60.00	50.00	60.00	56.25	67.01
Fertilizer (K) (kg)	135.00	60.00	30.00	134.38	–	150.00	110.00	72.50	88.64
Belfluraril (kg)	1.34	–	–	–	–	–	–	–	0.64
Piridate (kg)	0.78	–	–	–	–	–	–	–	0.37
Dimethenamid (kg)	–	–	–	–	–	–	–	–	0.48
Terbuthylazine (kg)	–	–	–	–	–	–	–	1.50	1.28
Nicosulfuron (kg)	–	–	–	–	–	–	–	–	0.33
Pesticides water (m^3)	0.2084	0.0287	0.0044	0.0034	0.0268	0.2389	0.0264	0.0278	0.2909
Pesticides packaging (kg)	0.4415	0.2767	0.1230	0.4120	0.4508	0.7171	0.3483	0.5896	0.4535
Manure transport (tkm)	300.00	–	–	262.50	–	900.00	–	–	449.20
Chemicals transport (tkm)	39.29	24.62	10.94	36.66	40.12	63.82	52.47	31.00	5.24
Material transport (tkm)	1.28	0.654	3.48	0.64	2.05	1.65	6.00	2.63	1.25

Sources: ISTAT (2023); Ribaudo (2017).

operations were calculated *via* the approach described in Notarnicola et al. (2023b).

3.1.4. *Waste management*

Waste included waste oil from agricultural machinery and packaging from chemicals. The disposal of these products was assessed using the Italian waste management scenario generating specific end-of-life processes. The end-of-life management for used oil was evaluated based on data published by the National Consortium of Used Oils (CONOU, 2022). A dataset was developed, indicating 98 % regeneration and 2 % energy recovery. The end-of-life of plastic packaging followed the methodology outlined in Annex C of the European Platform on Life Cycle Assessment (OEF) method (EC, 2021). The end-of-life scenario considered recycling (28.0 %), energy recovery (41.5 %), and disposal (30.5 %). The disposal of the paper has been accounted as 100 % recyclable (EC, 2021).

3.2. *Environmental impact assessment*

3.2.1. *Environmental impact of feed ration*

Environmental impacts of the crop cultivation phase were referred to both scenarios ($FR_{6–12}$ and $FR_{>12}$) and expressed as kg of dry matter. Table 5 reveals significant differences in the eco-indicators for all categories between the two hypothesized feed ration scenarios.

Relevant differences (>50 %) occur in the acidification (AC), human toxicity cancer (HCT) and resource use, minerals and metals (RUMM) impact categories, mainly due to the transport of the raw materials (AC and POF), heavy metal release in the soil and water compartments (HCT). Additionally, intermediate (20–50 %) differences have been detected in most of categories including photochemical ozone formation (POF), climate change (CC), ecotoxicity freshwater (EcF), and ozone depletion (OD), due to fuel consumption (OD) and pesticides employment (EcF) and raw material transportation and field operation (CC). On the contrary, the feed ration composition impacts less on the water use (WU) and the ionization radiation (IR) categories. The contribution of each cultivation to the specific impact category is illustrated in Fig. 3.

The preparation of soybean flour (constituting 9.52 % of the daily ration) has a significant impact on the most representative categories: CC, EcF, and WU (Fig. 3a). Additionally, corn silage also accounts for approximately one-third of the water consumption.

The increased daily intake of corn flour for beef cattle older than 12 months influences all the indicators. When combined with soybean production, it covers approximately 80 % of each indicator, as depicted in Fig. 3b.

The total eco-indicator displayed an increase (29.3 %) in $FR_{>12}$ category compared to $FR_{6–12}$ (Fig. 4).

In both cases, the most significant contributions are attributed to CC, EcF, and WU, accounting for nearly 60 % of the total impact. The increased impact on CC category is primarily attributed to fossil CO_2 emissions due to raw material transportation and field operation fuel usage, along with nitrogen oxide emissions associated with corn grain cultivation. It is recognized that certain ingredients commonly sourced externally by livestock farms play a significant impact owing to transportation (Greenwood, 2021; Costantini et al., 2023), multiple processing stages, and the specific characteristics of their agroecosystems origin (*e.g.*, soybean, both grain and flour, from Argentina, Brazil, Canada and United States). The recorded value for the EcF category is primarily linked to the use of pesticides, notably Deltamethrin, Bifenox, and Terbuthylazine, which are extensively employed in the cultivation of common wheat and corn grain. In addition, synthetic nitrogen fertilizers play a dominant role due to their energy-intensive production process. Hence, it is evident that their efficient utilization yields environmental advantages across various categories (*e.g.*, global warming potential, ozone depletion, freshwater ecotoxicity, and fossil resource scarcity) linked to energy consumption, alongside economic benefits (Bacenetti et al., 2020). Finally, WU was predominantly associated with the irrigation of corn cultivation and electricity consumption.

3.2.2. *Environmental impact of beef cattle breeds*

The evaluation of the impacts of each category displayed significant differences related to breed, age and gender of the cattle (Fig. 5).

CC, WU, EcF, PM, AC, EuT and LU were identified as the most impactful categories (cut-off <5 %), collectively ranging from 85.5 % ($M_{12–24}$ *Aubrac* and *Blond d'Aquitaine*) to 90.6 % ($F_{12–24}$ *Highland*) of the total impact. Specifically, CC (22.1 ± 2.1 %) appears related both to the breeding and agricultural phases that mainly caused high levels of CH_4 (45.3 ± 4.9 %), but also the production of fossil CO_2 (18.9 ± 5.3 %), mostly from the transportation of the raw crops, and N_2O (17.6 ± 5.0 %) from aerobic digestion of the manure. EcF is in large amount caused using phytosanitary products in the agricultural phase. A comprehensive analysis of the single crop and the feed ration composition, considering both the amount of fodder/concentrate and the total amount of ration, revealed that Lambda-cyhalothrin (39.4 ± 2.0 %) and Chlorpyrifos (20.3 ± 1.1 %), used in the cultivation of imported crops, are the main contributors to the EcF indicator. NH_3 production mostly during the manure management deeply influences the EuT, AC and PM categories, which is in accordance with literature data (Behera et al., 2013; Sailesh

Table 4
Yield, and input data of the agricultural phase of crops making the corn silage and raw concentrate fraction referred to 1 ha of cultivation area for the period 2019–2022.

	Corn silage	Corn grain	Sunflower grain	Soybean grain	Common wheat
Yield (kg/ha)	45,868	10,100	2435	3316	5455
Seeds (kg)	29.30	38.60	6.00	80.00	187.69
Fuel (kg)	218.71	542.77	111.85	212.85	101.20
Lubrificant oil (kg)	4.04	5.32	2.03	3.94	1.82
Irrigation water (m^3)	1800	1600	–	1200	–
Soil occupation (m^2)	0.55	1.00	1.00	1.00	1.00
Electricity (kWh)	–	157.50	0.50	0.02	0.85
Manure as N (kg)	125.46	125.46	–	–	–
Fertilizer (N) (kg)	165.00	240.00	120.00	20.00	145.77
Fertilizer (P) (kg)	55.00	70.00	120.00	80.00	68.46
Fertilizer (K) (kg)	30.00	37.50	–	80.00	132.69
Terbuthylazine (kg)	2.34	1.25	–	–	–
Dimethenamid (kg)	0.95	–	–	–	–
Nicosulfuron (kg)	0.65	–	–	–	–
Metribuzin (kg)	–	0.50	–	–	–
Pendimethalin (kg)	–	1.46	–	–	–
Isoxaflutole (kg)	–	0.05	–	–	–
Methamidophos (kg)	–	0.10	–	1.50	–
Indoxacarb (kg)	–	0.65	–		–
S-metholachlor (kg)	–	–	1.20		–
Oxyfluorfen (kg)	–	–	0.26		–
Quizalopof-ethyl (kg)	–	–	–	3.00	–
Oxasulfuron (kg)	–	–	–	1.25	–
Etravon (kg)	–	–	–	0.13	–
Cyhexatin (kg)	–	–	–	0.40	–
Exitiazox (kg)	–	–	–	0.14	–
Iodosulfuron (kg)	–	–	–	–	0.28
Fenoxaprop-P-ethyl (kg)	–	–	–	–	0.21
Mefenpyr diethyl (kg)	–	–	–	–	0.21
Bifenox (kg)	–	–	–	–	0.12
Prochloraz-Mn (kg)	–	–	–	–	0.82
Pyraclostrobin (kg)	–	–	–	–	0.42
Deltamethrin (kg)	–	–	–	–	0.08
Fluvalinate (kg)	–	–	–	–	0.10
Pesticides water (m^3)	1.00	1.00	1.00	1.00	1.00
Pesticides packaging (kg)	0.5203	0.7203	0.0129	0.4948	0.8249
Manure transport (tkm)	600.00	600.00	–	–	–
Chemicals transport (tkm)	46.30	64.10	–	–	62.39
Material transport (tkm)	1.47	1.93	0.30	4.00	9.38

Sources: ISTAT (2023); Ribaudo (2017).

et al., 2013; Zheng et al., 2020; Klimasmith and Kent, 2022). Finally, the categories LU and WU are associated with corn and soybean production (Ribaudo, 2017).

The overall trend observed across all breeds revealed a higher impact of the youngest beef cattle for both male and female genders. This is attributed to a combination of factors, including increased daily weight gain and emissions of climate-altering gases, particularly biogenic CH_4 referred. Literature data confirmed that CH_4 emissions, feed production, and manure management practices greatly contribute to this variation (Chiriacò and Valentini, 2021). In general, *Maremmana* $M_{6–12}$ present the highest values of the total eco-indicator, whereas the *Highland* $F_{>24}$ category was identified as the most eco-friendly.

Table 5
Results, expressed *per* 1 kg of dry matter, relating to the cultivation of component of the feed rations for each age category.

Impact category	Unit	$FR_{6–12}$	$FR_{>12}$	Δ
AC	mol H^+ eq	5.1E-03	3.0E-03	+68.8
CC	kg CO_2-eq	8.6E-01	6.9E-01	+24.4
EcF	CTUe	8.3E+01	5.7E+01	+46.6
PM	disease inc.	6.8E-08	5.3E-08	+29.1
EuM	kg N eq	3.7E-03	2.5E-03	+46.1
EuF	kg P eq	1.3E-04	9.7E-05	+34.9
EuT	mol N eq	3.4E-02	2.4E-02	+39.3
HTC	CTUh	2.1E-10	1.3E-10	+56.0
HTnC	CTUh	1.4E-08	1.0E-08	+35.0
IR	kBq U-235 eq	1.5E-02	1.3E-02	+11.3
LU	Pt	9.7E+01	8.3E+01	+16.6
OD	kg CFC11 eq	1.9E-08	1.3E-08	+42.5
POF	kg NMVOC eq	4.4E-03	2.9E-03	+53.7
RUF	MJ	6.1E+00	4.5E+00	+35.1
RUMM	kg Sb eq	7.6E-07	5.0E-07	+52.1
WU	m^3 depriv.	3.4E+00	3.2E+00	+6.6

$FR_{6–12}$ = Feed ration for beef cattle 6–12 months; $FR_{>12}$ = Feed ration for beef cattle >12 months; AC = Acidification; CC = Climate change; EcF = Ecotoxicity, freshwater; PM = Particulate matter; EuM = Eutrophication, marine; EuF = Eutrophication, freshwater; EuT = Eutrophication, terrestrial; HTC = Human toxicity, cancer; HTnC = Human toxicity, non-cancer; IR = Ionising radiation; LU = Land use; OD = Ozone depletion; POF = Photochemical ozone formation; RUF = Resource use, fossils; RUMM = Resource use, minerals and metals; WU = Water use.

Additional insights can be obtained by treating each breed as the aggregate sum of contributions from each category (Fig. 6).

Fig. 6 shows that the highest contribution to the total impact consistently stems from CC, ranging from 20.42 % (*Piedmontese*) to 23.63 % (*Maremmana*), with an average value of 22.1 ± 2.1 %.

Fig. 7 shows the comparison of the environmental impact, in terms of CC, of the different breeds considering the entire life cycle until slaughtering. This analysis was thus performed considering the average overall mass of the animal for different periods (6–12, 12–24, and > 24 months) and the daily emissions refereed to each period. The animal weights ranged from 650 kg (*Maremmana*) to 800 kg (*Chianina* and *Blue Belga* breeds) for male cattle and from 525 kg (*Highland*) to 700 kg (*Chianina*) for female. Additionally, the age at slaughter was in the range of 603 (*Charolaise* male) - 1000 days (*Podolica* and *Highland* female).

The values in Fig. 7 indicate that the *Romagnola* female emits the lowest amount of CO_2 equivalent in its lifespan (7.1 Mg CO_2-eq), while the *Aubrac* male emitted the highest value recorded at 11.7 Mg CO_2-eq. Male beef cattle tend to produce a higher amount of CO_2 equivalent (10.0 ± 1.1 Mg CO_2-eq) compared to females (8.6 ± 1.0 Mg CO_2-eq). This is primarily due to their larger mass, which requires a greater amount of feed and results in more significant enteric emissions and manure that needs to be managed. Among beef cattle breeds, larger-sized breeds, such as *Aubrac*, *Blond d'Aquitaine*, *Blue Belga*, *Charolaise*, and *Chianina* have a more evident impact on climate-altering gas production for both genders. Conversely, rustic breeds like *Highland*, *Podolica*, and *Maremmana* exhibit a reduced impact. Remarkably, all breeds demonstrated a significantly higher environmental impact compared to a utility car traveling an average of 13,000 km *per* year for three years (5.5 Mg CO_2-eq) (data taken from an automotive reference booklet -Alfa Romeo - for a medium size car).

The values reported in Fig. 7 appear to have the same order of magnitude of the values recorded in literature reporting the rearing of different kinds of cattle intended for slaughter (9.2–58.7 kg CO_2-eq) (Asem-Hiablie et al., 2019; Costantini et al., 2021).

Finally, a comparison (Fig. 8) was made between the environmental impact (calculated as an average of all the breeds reported in Fig. 7) and the impact calculated in the environmental footprint study for fresh and

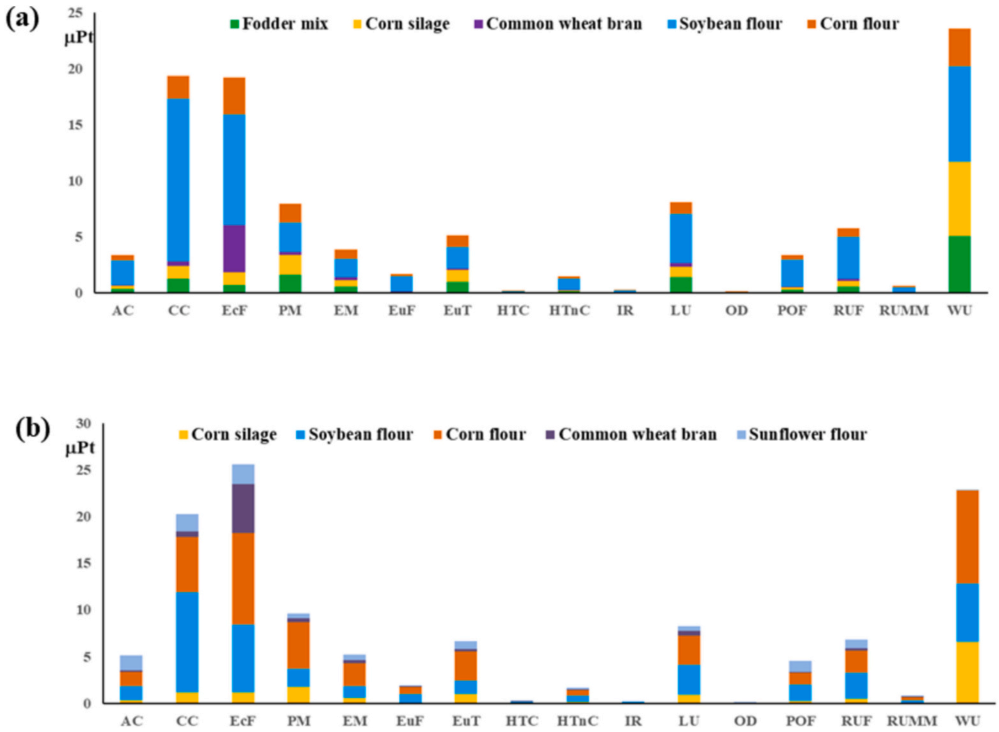

Fig. 3. Influence of each cultivation enclose in $FR_{6–12}$ (a) and $FR_{>12}$ (b) to the impact categories. AC = Acidification; CC = Climate change; EcF = Ecotoxicity, freshwater; PM = Particulate matter; EuM = Eutrophication, marine; EuF = Eutrophication, freshwater; EuT = Eutrophication, terrestrial; HTC = Human toxicity, cancer; HTnC = Human toxicity, non-cancer; IR = Ionising radiation; LU = Land use; OD = Ozone depletion; POF = Photochemical ozone formation; RUF = Resource use, fossils; RUMM = Resource use, minerals and metals; WU = Water use.

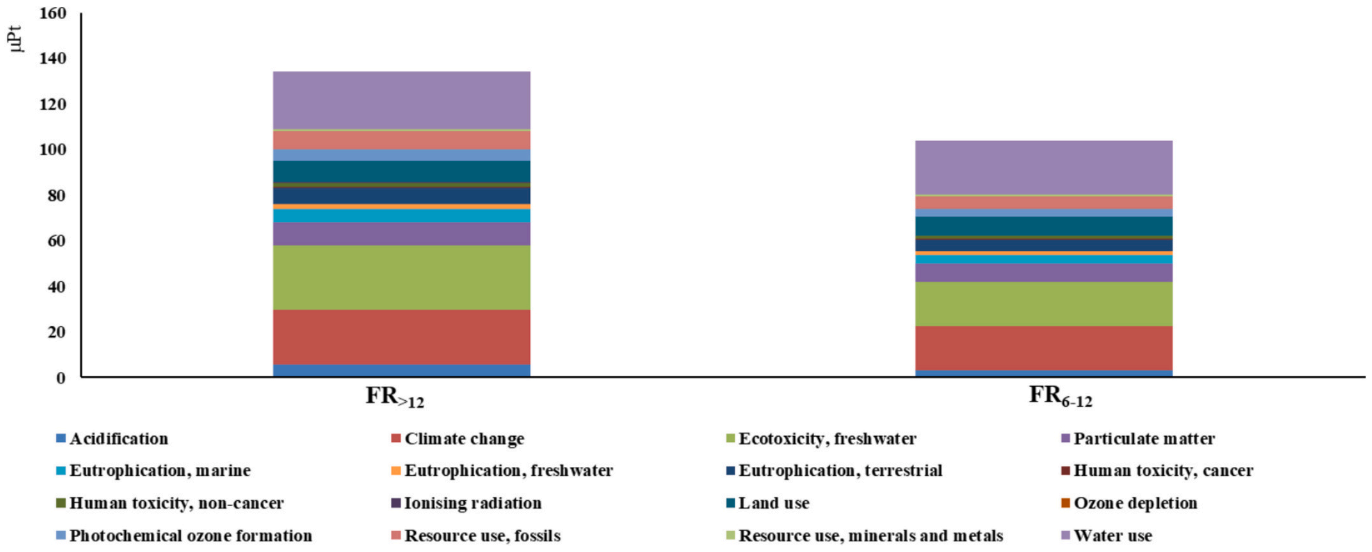

Fig. 4. Total impact of the feed rations in the beef cattle diet.

refrigerated meats (NACE/CPA code 10.11.11), as reported in the Product Category Rules (PCR) for obtaining the “Made Green in Italy” brand (PCR fresh and chilled beef meat, 2018). Fig. 8 reports a lower value (−32.4 %) of the total eco-indicator of the present study when compared to that of the Made Green in Italy (referred to the FU).

Six categories (cut-off<5 %) from those reported in Fig. 8 were analysed, to identify the differences between the two models. In the Italian beef cattle mix (of the present study), there was a notable decrease in EcF (−72.5 %), LU (−34.2 %), AC (−10.7 %), CC (−7.5 %), and PM (−5.0 %). Conversely, there was an increase in WU (+83.3 %), mainly due to the employment of water for irrigating the crops used in the preparation of the feed ration. The significant difference observed in EcF may be attributed to the impact of certain pesticides, particularly Lambda-Cyhalothrin, Chlorpyrifos, and Bifenthrin, which are more relevant in the PCR system. The variation in AC is attributable to the reduced impact in N_2O emissions generated during manure management. The differences in CC are the combined result of CH_4 (+5.1 %), fossil CO_2 (−7.7 %) and N_2O (−3.9 %) emissions. Finally, a decrease in the PM is due to NH_3 emissions from manure management and crop cultivation and $PM_{<2.5}$ from diesel consumption in the crop cultivation and stable management.

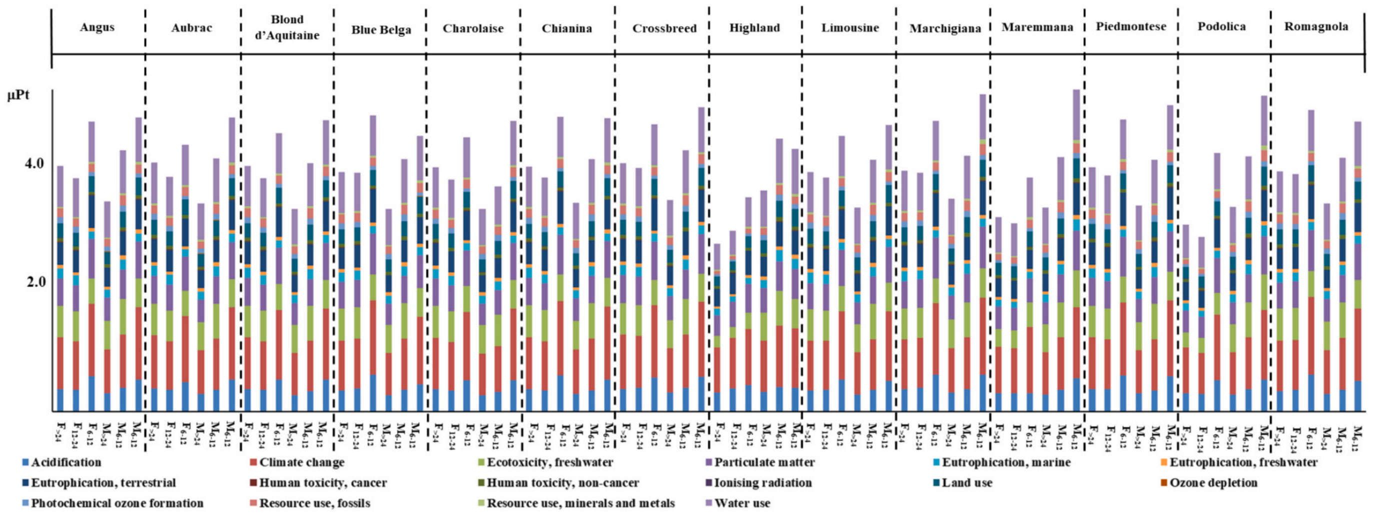

Fig. 5. Environmental impact of the analysed beef cattle considering the different age and gender categories.

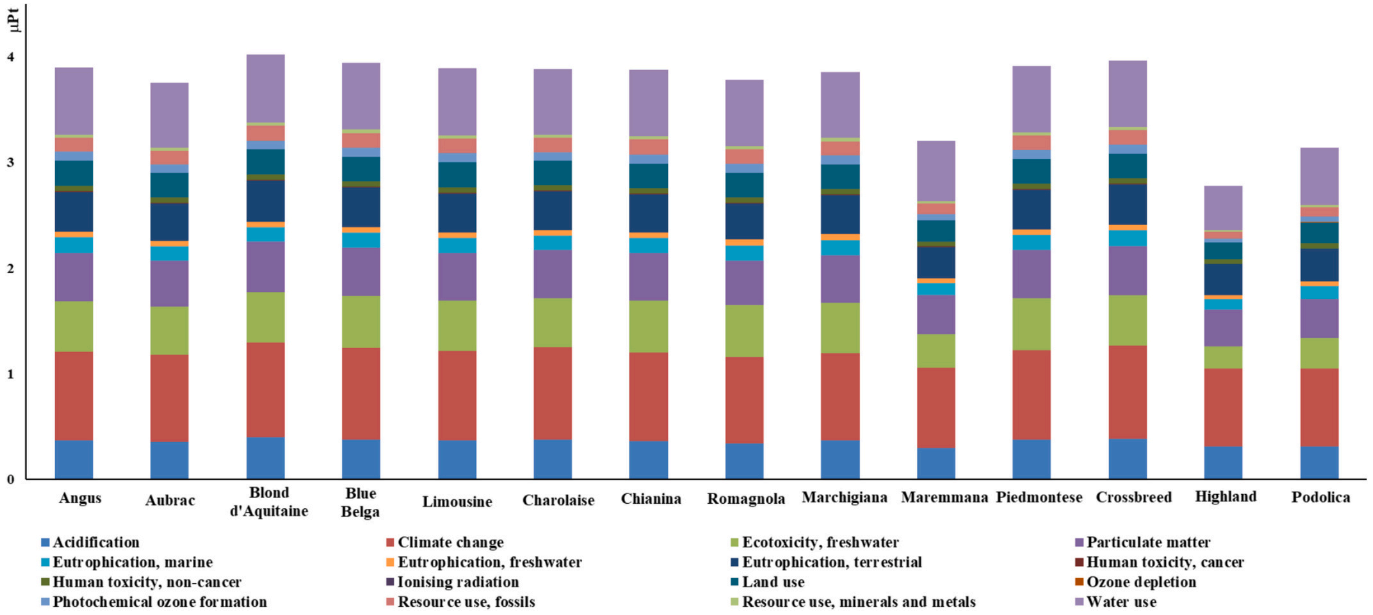

Fig. 6. Environmental impact of the analysed beef cattle considering the different breeds.

4. Conclusions and future perspectives

This research aims to systematically develop Italian datasets of beef cattle breeding through a meticulous analysis that consider distinct characteristics of each breed as well as specific agricultural practices. A total of 84 statistical datasets was built in accordance with the ISO 14040 and 14,044 standards. The breeding phase primarily contributes to CH_4 emissions from enteric fermentation. Stable management displayed a minimal impact, while feed ration composition plays a pivotal role. Specifically, the concentrate fraction, mainly supplied from foreign countries, presents significant impacts associated with the transport of the raw materials. The life cycle impact assessment reveals that the CC, EcF, WU, and PM categories are the major contributors to the total eco-indicator. CH_4 and NH_3 emissions, as well as crop irrigation, and pesticide use represent the main hotspots. Climate change (22.1 %) is the most impactful category, and the emissions at slaughter are estimated to be, on average, approximately 9.3 Mg CO_2-eq per year. A comparative analysis with the “Made Green in Italy” study (NACE/CPA code 10.11.11) footprint study, indicates a lower eco-indicator value (−32.4 %) for the present study, primarily attributed to significant decreases in EcF, LU, AC, and CC.

This research emphasizes the importance of having datasets that are highly representative of beef cattle farming in Italy, highlighting opportunities for implementing more sustainable practices within the industry. By thoroughly understanding the factors contributing to environmental degradation and actively monitoring and mitigating these impacts, stakeholders can significantly advance towards a much more sustainable and environmentally conscious approach to Italian beef cattle production.

CRediT authorship contribution statement

U. Gianfranco Spizzirri: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Bruno Notarnicola:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Francesco Astuto:** Methodology, Formal analysis, Data curation,

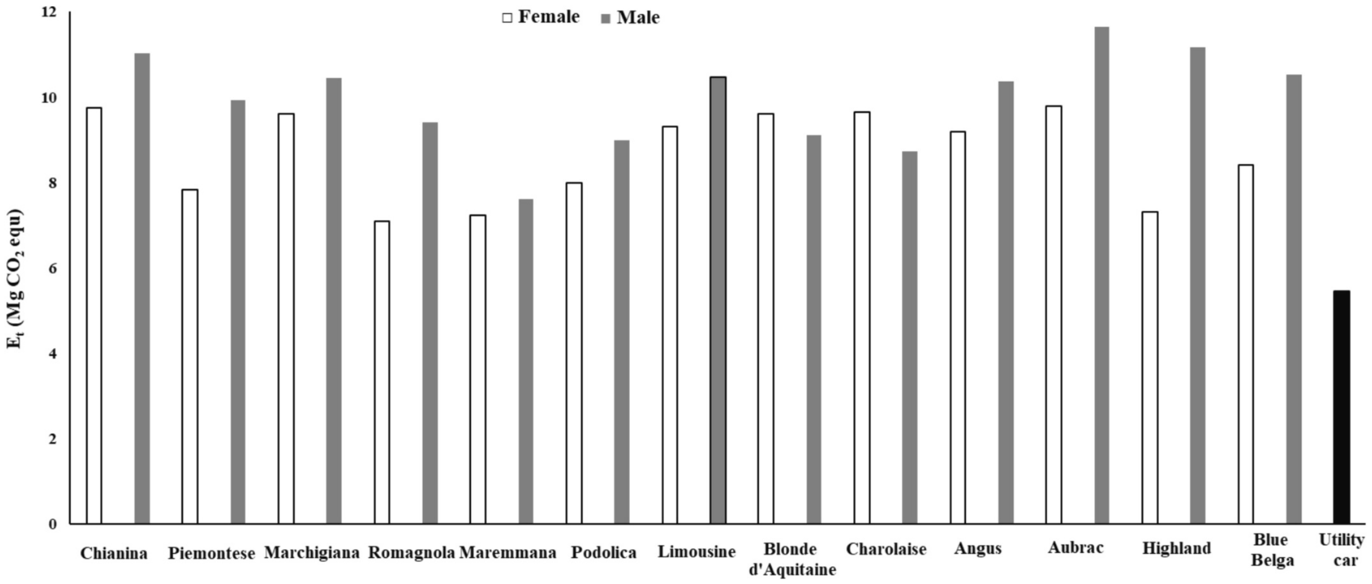

Fig. 7. Greenhouse gas emissions, measured in CO$_2$ equivalent per breed, assessed over the entire lifespan of the beef cattle.

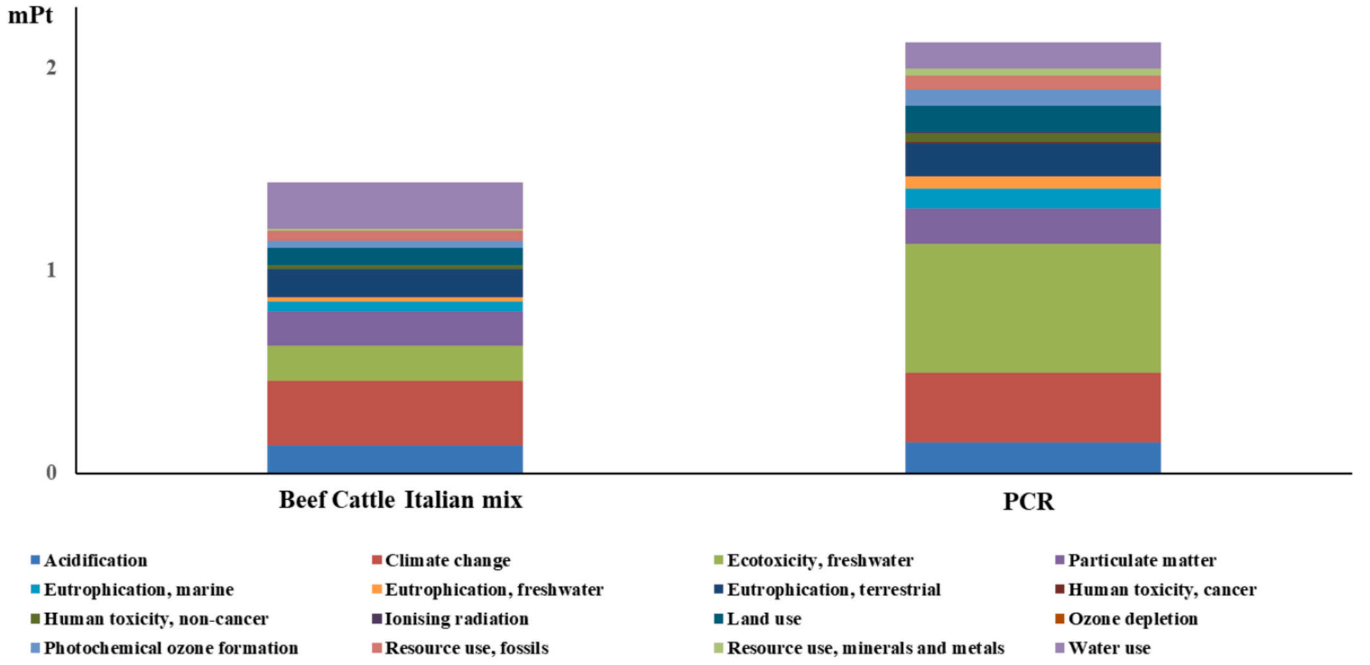

Fig. 8. Environmental impact of the analysed beef cattle Italian mix against the impact suggested in the environmental footprint study for fresh and refrigerated meats (NACE/CPA code 10.11.11), as reported in the Product Category Rules (PCR) for obtaining the "Made Green in Italy" brand.

Conceptualization. **Pietro A. Renzulli:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Rosa Di Capua:** Writing – original draft, Methodology.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.177644.

Data availability

Data will be made available on request.

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