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Study on the suitability of life cycle assessment for the estimation of donkey milk environmental impact

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ABSTRACT

In the last decades, western Countries increased their interest in innovative products like donkey milk and other activities carried out with donkeys (onotherapy, onotourism). Donkey milk is considered a high-added-value food and is very similar to human breast milk. It is also used as an ingredient in cosmetics. The growing public interest suggests the need for a pilot study on the sustainability of donkey milk production, according to Life Cycle Assessment (**LCA**) criteria. Milk was used as the Declared Functional Unit (**DFU**) and two different models were described, a Real Scenario Model (**RSM**, i.e. a farm with its declared milk yield), and an Increased Milk Production Model (**IMPM**, i.e., the same farm with theoretically increased milk yield). Allocation was applied both in RSM and IMPM; thus, different values of impact categories, i.e., Global Warming Potential (**GWP**, kg CO_2 equivalents), Acidification Potential (**ACP**, g SO_2 equivalents) and Eutrophication Potential (**EUP**, g PO_4^{3-}) were observed. GWP improved after mass allocation and showed the lowest equivalents in IMPM, compared to economic and reference allocation criterion ($P < 0.05$). In RSM, allocations affected GWP in a different way: the smaller size of the DFU resulted in the largest estimation of CO_2 equivalents ($P < 0.05$) for reference allocation, whereas the mass allocation estimates were lower than with economic allocation ($P < 0.05$). ACP and EUP followed the same trends. No differences were found in IMPM results across the three allocation methods used. Moreover, mass allocation values recorded in RSM did not significantly differ from IMPM. ACP and EUP of RSM improved after economic allocation, although they were less sustainable ($P < 0.05$) than all IMPM values and RSM equivalents after mass allocation ($P < 0.05$). As expected, the theoretical model with increased milk yield improved the sustainability of the system. Both scenarios were affected by allocation criteria. In RSM, the economic and mass allocations described a representative scenario where donkey meat contributed to subtracting equivalents from milk (the main product). The present paper is a pilot study estimating for the first time the environmental impact of donkey milk production, with the aim to stimulate further research.

Implications

This study investigates the sustainability of donkey milk, a high-added-value food. The production of donkey milk and its by-products is partially based on the pasture. Its study requires a holistic approach, given the multiple products obtained in the system. The life cycle assessment method was used to assess the environmental impact of donkey milk, both in a scenario based on real data and in a theoretical increased milk yield scenario. Results suggest that increasing production would improve donkey milk sustainability. These findings could help promote donkey milk availability, making it accessible for babies allergic to breastmilk, in a more sustainable framework.

Introduction

Food production is one of the main contributors to global emissions and environmental impact. This is particularly true for cattle, where the relationship between the intensity of production and

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environmental impacts (commonly expressed per unit of the main product, i.e. milk or meat) has been subjected to an extensive number of studies, investigating their global warming potential (**GWP**) or carbon dioxide equivalents (Baldini et al., 2017; Bragaglio et al., 2018; Pirlo and Lolli, 2019; Rotz et al., 2019). The **LCA** (Life Cycle Assessment) method specifically considers the entire history of a product (from cradle to grave) to quantify its environmental burden and/or benefits. It is a useful method to analyse and improve the production process by identifying its main trade-offs (EPLCA – European Platform on LCA, 2015).

Although the LCA criterion is largely adopted to estimate the environmental impact of several foods, to our best knowledge, no studies focusing on donkey seem to be available. This study validates the preliminary results obtained using the LCA method in this context (Bragaglio et al., 2023a), using a similar allocation criterion for the description of a multi-product system (milk and meat).

The Intergovernmental Panel on Climate Changes list methane (**CH_4**) and nitrous oxide (**N_2O**) as the main **GHGs** (Greenhouse gases) from the agricultural sector (IPCC, 2019a and 2019b). Farms are responsible for the production of CH_4 from enteric fermentations, N_2O deriving from fertilisers, CH_4 and N_2O emitted from manure management (in indoor farms) or direct manure deposition (in pasture-based systems) (O'Mara, 2011). LCA studies compare different rearing systems, sometimes with small sample sizes (Romano et al., 2021a; 2021b). However, the sustainability of scarcely investigated products (such as buffalo milk) can be estimated within the same farm, including only GWP (Pirlo et al., 2014b) or additional impact categories (Pirlo et al., 2014a). Berlese et al. (2019) estimated GWP, acidification potential and eutrophication potential of buffaloes reared in six intensive farms, considering Fat Protein Corrected Milk (**FPCM**) or mozzarella cheese as functional units and using different allocation criteria to investigate the role of by-products.

The LCA is a multipurpose method that can be used to investigate the sustainability of foods and products provided by different sectors (e.g. agriculture, fishery, mining) (Baldini et al., 2017; Baldini, 2018). The LCA method follows the international standards 14040 and 14044 (ISO, 2006a and 2006b), to guarantee a harmonic approach among comparable studies. Nowadays, LCA is one of the most used methods for environmental studies and can be used as a tool for strategic management and decision-making to improve the sustainability and resource efficiency of our society (Wolf et al., 2012; Teixeira, 2015). The systems perspective is one of the main strengths of this method, as it avoids "shifting the burdens" across environmental impacts and production stages (Hellweg and Milà I Canals, 2014).

In recent years, donkey farming is receiving increasing interest, due to the appeal of innovative and nutraceutical foods. As suggested by Faccia et al. (2019), donkey milk is a high-added-value food. In addition, as a niche product, it does not replace bovine milk in consumers' habits. Several authors (Guo et al., 2007; Massouras et al., 2020; Martini et al., 2021) emphasise the properties of donkey milk, arguing that it is more similar to human milk than the milk of other mammals. In the framework of European policies encouraging agricultural diversification and local breeds, donkeys can thrive in marginal areas (that would be unsuitable for highly specialised dairy cows). They show a better adaptation than cattle to warm Mediterranean climates compared to cosmopolitan breeds such as Holstein Friesian or Brown Swiss, although local well-adapted cattle breeds exist. Donkey rearing does not require complex infrastructures. It can be combined with agrotourism, "educational farms" and onotherapy, improving the farm revenue. Donkeys, compared to horses, are generally smaller in size and have a more docile temperament. For these reasons, farming donkeys for raw milk is a promising activity in Italy (Camillo et al., 2018). Donkey milk is increasing its popularity also in Europe as an alternative to breast milk and infant formula for babies allergic to cow milk, with multiple food intolerances, or when breastfeeding is not possible (Sarti et al., 2019). In addition, it would be an interesting product for low-calorie diets and elderly people, since it has a delicate, slightly sweet taste, a pleasant milky aroma and a sweet flavour (Malissiova et al., 2016).

In Italy, donkey meat is the main ingredient of typical dishes. In the past, working animals at the end of their careers provided meat. Donkey meat is a food with high market value although it was not considered as the main product (i.e., the Declared Functional Unit – **DFU**) in the present study. Our research was carried out on a farm located in the Apulia Region, using the LCA approach. This method, recognised as standardised and versatile, is widely used in dairy systems. Bovine milk production is a multifunctional process that obtains meat as a by-product from calves and culled cows. In donkey systems, meat by-product is a niche food with a high market value. According to the farmer interview, culled jennies are negligible (approximately one animal slaughtered every two years), whereas a significant amount of meat is ensured by young males, which are sold at 2 years of age and around 340 kg BW. Mu et al. (2017) investigated specialised milk production systems and identified also culled cows, calves, straw and crops as outputs. Similarly, the farm investigated in this study has a multifunctional profile, and thus the wheat (*Triticum durum* Desf. and *Triticum aestivum* L.) is included in the system boundaries also according to previous studies (Romano et al., 2021a; 2021b).

This study represents the first assessment of the environmental impact of donkey milk production. A comparison is carried out between the sustainability of the Real Scenario Model (**RSM**) and a hypothetical Increased Milk Production Model (**IMPM**) scenario. In the RSM, jennies are milked depending on consumers' requests. If there is demand for donkey milk, jennies are milked and the milk is bottled and sold in the shortest time possible. In the theoretical IMPM scenario, we hypothesise that jennies would be milked all year round. In both scenarios, jennies are milked once a day. Reference, mass and economic allocation were also applied in both scenarios.

Material and methods

Goal and scope definition

According to ISO 14040–14044 criteria (ISO, 2006a and 2006b) and LCA principles, the study was carried out "from-cradle-to-far m-gate". The sustainability of a specialised donkey farm was assessed using the software SimaPro 8.03 (Pré Consultants, Amersfoort, The Netherlands). We estimated the environmental impact of two scenarios, comparing the RSM to the IMPM. The IMPM was built considering a milk yield eight times higher than the RSM, and consequently adapting the DFU-related inputs.

System boundaries

This study was carried out using raw milk as the main product (i.e., the DFU), even though milk was produced in a cereal-based context, typical of southern Italy. About half of the arable land of the farm where the study was carried out is dedicated to wheat crops (*Triticum durum* Desf. and *Triticum aestivum* L.), whose caryopsis (i.e., grain) is sold as food. The Apulia region historically produces wheat, which is mainly intended for pasta. Straw, the wheat by-product, is entirely used as feed or litter. The farm hosts Martina Franca donkeys (132 heads, including adult and young animals), a native Apulian breed characterised by large size and distinguished appearance. The study included all livestock operations (animal feeding and care, milking procedures, males fattening) and forage production (e.g. agricultural routine, arable land, organic fertilisers) (Fig. 1). Energy use and emissions from off-farm activities were retrieved from databases of the SimaPro 8.03 software. The transportation of feed, fossil fuels, bedding materials and their emissions was also included in the assessment. In agreement with Ross et al. (2014) and Baldini et al. (2018), medicines, detergents and disinfectants were excluded. A kg of raw milk was chosen as the (DFU). As reported by the farmer, raw milk yield is low (about 10 kg heard^{-1} day^{-1}, corresponding to 0.25 kg head^{-1}), several times lower than the estimated maximum production (about 4–6 litres/day^{-1} in the first 6 months of lactation, Raspa et al., 2019). Milk high price (10 EUR kg^{-1}) and consumer demand drive milking frequency. This study compared an RSM to an IMPM scenario. Milk yields were 3.7 and 29 tonnes milk year^{-1}, respectively. The RSM yield was based on the farm data, whereas the IMPM yield was based on a reasonable daily production (2 kg head^{-1} day^{-1}). Although milk ejection is stimulated by the milking routine (animal managing and handling), the increased amount of inputs (roughages, concentrates) required to obtain higher yields was also considered.

Allocation

Dairy systems are multifunctional processes providing, in addition to milk, other by-products. Meat (from male calves or culled cows) and cereals are the most common by-products (Pirlo and Lolli, 2019; Romano et al., 2021b). We tested three allocation criteria (reference allocation, mass allocation, economic allocation) to distribute the equivalents across the DFU and the by-products. This study excluded from allocation all female foals (kept on farm as replacement), and the culled jennies (given their long productive life). Allocation involved wheat grain (which is sold for human consumption) and meat from fattened males. Recently, LCA practitioners prefer the term "reference allocation" to "no allocation" to indicate that all burdens and environmental impacts are allocated to the main product (Lauri et al., 2020; Bragaglio et al., 2023b). The same terminological choice was made in the present work. In the allocation procedure, economic and mass methods were used and allocation partitioning (**P**) was carried out using the following equation, as indicated by Ardente and Cellura (2012) and used in other studies on dairy systems (Romano et al., 2021b):

$$AF_{(eco,mass)} = (V_{eco,mass} * P)milk/\Sigma(V_{eco,mass} * P)_{milk,wheat\ grain,live\ weight\ male\ donkeys}$$

where:

AF = allocation factor;
V_{eco} = economic value (€/kg);
V_{mass} = amount (kg);
P = total production on farm (kg/year), milk as raw milk, wheat as harvested grain without straw, live-weight as fattened male donkeys.

Quantities (in tonnes) and economic values (EUR/tonnes) are shown in Tables 1 and 2, respectively. Raw milk (kg) was used as the DFU in the analysis, and the by-products considered where wheat (bread and durum) harvested grain without straw, and male donkeys after fattening.

Life cycle inventory

The profile, inputs and outputs of the farm are summarised in Table 1. A detailed description of the inventory is available in the supplementary material (supplementary Tables S1 and S2). The study was carried out in a specialised farm (40°43′09.4″N, 16°47′05.6″E, approximately 370 meters above sea level) in Taranto province, Apulia Region, Italy. The farm is located in a karst plateau called *Le Murge*, which is the area of origin of Martina Franca donkey, the breed reared at the farm. Despite the growing interest in donkey milk, producers are very few, so it is difficult to draw comparisons. The farm can be classified as large and professional, considering the size of the agricultural land (i.e., arable land and pasture), the number of lactating jennies and the milking parlour. The owner was interviewed about farm management.

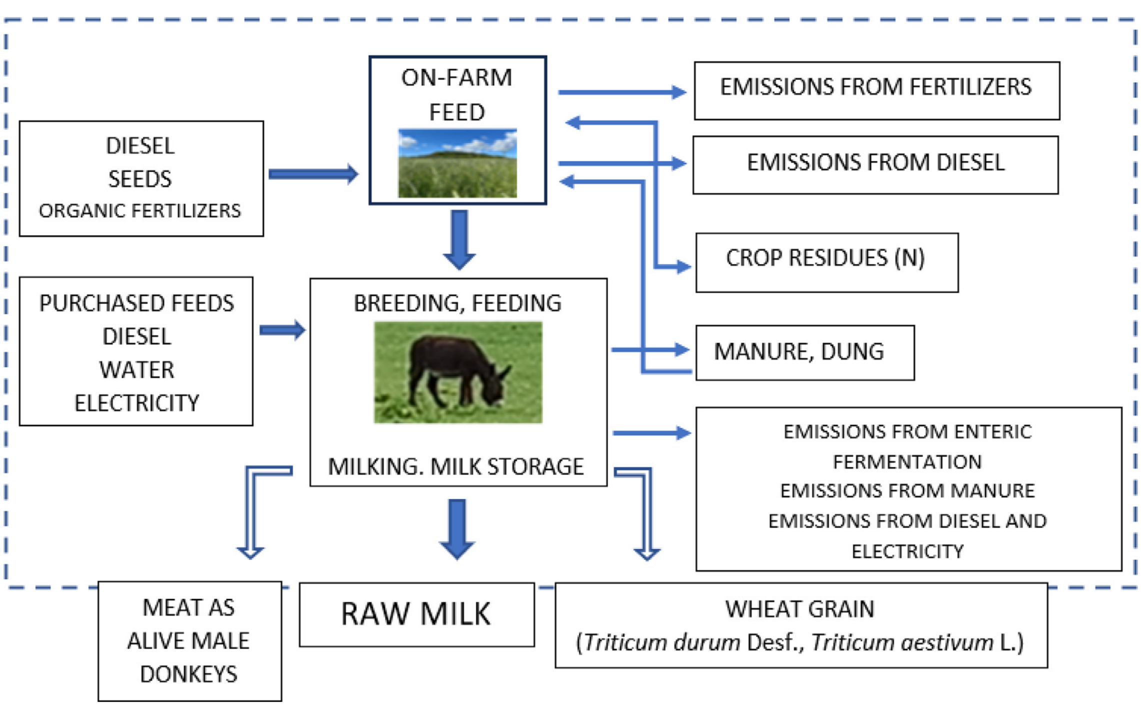

Fig. 1. System boundaries of the donkey farm; declared functional unit (DFU) = raw milk; by-products of the farm = wheat grain and meat from male donkeys.

Table 1
Profile, input and output of the donkey farm in the RSM* (Real Scenario Model) and IMPM** (Increased Milk Production Model) scenarios. Electricity consumption refers only to milking, milk refrigeration and water heating for disinfection of the milking parlour. The specifics about farm extension are indicated in the 'Farm extension and Utilised Agricultural Area' subsection.

Item	Values	
Farm Input		
Farm extension, Ha		
Total	70	
Wheat	40	
Oat	4	
Hay	14	
Pasture	12	
Energy sources and fertilisers		
Diesel, t y^{-1}	25	
Electricity kWh, y^{-1}	150*	1 500**
Organic N, t y^{-1}	1.32	
Zeolite, t y^{-1}	0.28	
Buildings and services		
Paddock, m^2	6 000	
Shed, m^2	450	
Milking parlor, m^2	40	
Milk tank, m^3	0.2	
Herd, heads no., Total	132	
	Females	Males
0–6 months	10	10
7–12 months	5	5
13–19 months	5	10
20–24 months	5	15
25–40 months	11 non-pregnant 4 pregnant	-
>40 months	40 lactating 10 dry	2 jacks
Farm Output		
Raw milk, t y^{-1}	3.7*	29**
Fattened males, t y^{-1}	5.2	
Bread wheat grain, t y^{-1}	5.2	
Durum wheat grain, t y^{-1}	5.0	

Table 2
Selling prices of the donkey farm outputs, expressed as EUR tonnes$^{-1.}$

Farm Output	EUR t^{-1}
Raw milk	10 000
Fattened males (live BW)	5 500
Bread wheat grain	270
Durum wheat grain	320

Even though the farm was chosen for the present study as a rare case of donkey dairy farm, its economic sustainability is ensured mainly by the sale of organic wheat and, when possible, of the surplus hay produced.

Primary data collected for the inventory included livestock care, cereal cultivation, hay management, straw for the litter, purchased feed, energy sources (electricity, fossil fuels), fertilisers, farm extension (arable and pasture hectares), shed and milking parlour data (assuming a productive life of 50 years for these buildings, as suggested by the Ecoinvent 3 allocation default database in the Simapro software). A different inventory for each of the two scenarios was done, due to the different inputs required for RSM and IMPM.

The main diet components are available on farm and, as suggested by other authors (Nguyen et al., 2010; Bragaglio et al., 2018), these feeds were assumed to have been transported for 1 km with a tractor (Transport, tractor and trailer, agricultural {GLO}, processing, Alloc, Def, S). Animals are partially kept at pasture with night access to shelter, except milking jennies and fattening males, that are always inside the barn. Oat grain is administered in increasing amounts to foals, young animals, fattening males and lactating jennies (1 and 1.2 kg DM head^{-1}for RSM and IMPM, respectively). Foals are nursed for as long as possible to stimulate milk production (Raspa et al., 2019). A commercial concentrate feed is supplied to lactating jennies and fattening males and contains ingredients from different origins. Maize (crushed, flaked or as flour) is the main component, followed by soybean. The chemical composition of the commercial concentrate is shown in Table 3. Diet formulation for the different livestock categories and scenarios is shown in Tables 4 and 5.

Soybean is sourced outside Europe (Argentina) as suggested by the literature (Bragaglio et al., 2018; Nguyen et al., 2010; Romano et al., 2021a; 2021b), whereas maize, oat and alfalfa are assumed to be cultivated in Northern Italy (Bragaglio et al., 2018; Romano et al., 2021a; 2021b). For soybean, travel by transoceanic cargo (Transport, freight, sea, transoceanic ship {GLO}, market for, Alloc, Def, S) and then with a truck (Transport, freight lorry > 32 metric ton, EURO 5, {GLO}, processing, Alloc, Def, S) from the Italian harbour to farm gate was considered. For maize, only road transportation with a truck only was computed. Likewise, other national feed ingredients (e.g. oat, both as an ingredient of the concentrate and administered as grain), were assumed to be transported by truck up to farm gate (Transport, freight lorry > 32 metric ton, EURO 5, {GLO}, processing, Alloc, Def, S). Diesel fuel, was transported by the seller with a truck to the farm gate (Transport, freight lorry 3.5–7.5 metric ton, EURO 5, {GLO}, processing, Alloc, Def, S).

Data on energy sources (diesel fuel, electricity, liquefied petroleum gas) and the kind of water used was provided by the farmer. Liquefied petroleum gas consumption is unrelated to the activities object of the present study, thus out of system boundaries. Tap water (fit for human consumption) was used for disinfection (e.g. of the milk tank), whereas well water was provided to animals as drinking water. Arable land was not irrigated. Although this research neglected water impact categories, water use was recorded because of its relation with energy source consumption, i.e. pumping water from a well and heating water for disinfection. Data were recorded for the year 2021, from January to December.

Farm extension and utilised agricultural area

A large area of the farm is devoted to pasture (12 hectares), whereas the arable land is divided into 40 hectares for wheat, 4 for oat and 14 for hay. Although located in a geographical region (Apulia) historically dedicated to produce durum wheat (*Triticum durum* Desf.) mainly for pasta or typical foods, in the farm wheat production is equally subdivided between durum and bread wheat (*Triticum aestivum* L.). According to data reported by the owner, both species provide approximately the same harvest, each producing 2.5 (*Triticum durum* Desf.) and 2.6 (*Triticum aestivum* L.) tonnes per hectare of grain, and 2.8 tonnes per hectare of straw each. All the caryopsis is sold, and all the straw are kept on farm. The oat is entirely used as grain and straw for the reared animals.

Table 3
Chemical composition of the commercial concentrate feed used in the donkey farm.

Item	Value
DM % (as-fed basis)	87.5
Chemical composition (DM%)	
CP	12.97
Crude fibre	5.90
Ether extract	5.94
Ash	3.61
Lysine	0.39
Methionine	0.18
Sodium	0.25

Table 4
Donkey feed characteristics of RSM (Real Scenario Model) and IMPM (Increased Milk Production Model) scenarios.

Framework	RSM	IMPM
UFC maintenance day^{-1} head^{-1}	2.4	2.4
UFC milk requirements day^{-1} head^{-1}	1.0	1.5
UFC total requirements day^{-1} head^{-1}	3.4	3.9
Oat grain year^{-1} tonnes	16.6	19.8
Concentrate feed year^{-1} tonnes	8.3	9.5
Electricity for milking, kWh year^{-1}	150	1 500

Abbreviations: UFC = Unité Fourragère Cheval [Equine Forage Units].
Notes to the table: UFC requirements, grain and concentrates are referred to lactating jennies only. Electricity consumption is exclusively related to milking routine (i.e. milking and water heating for disinfection).

The meadow provides a mixed oat-vetch hay. In addition to oat (*Avena sativa*) and vetch (*Vicia sativa*), other less represented Gramineae are triticale (×*Triticosecale* Wittmack) and ryegrass (*Lolium perenne*). A single cut of hay is carried out, with a harvest of 5–6 tonnes/year per hectare, ensuring about 70 hay tonnes/year. According to Table 5, feeding requires about 48 tonnes of hay. Based on the average hay prices in 2021 (Ismea Mercati, 2021), the sale of the hay would be not profitable, therefore, the farmer decided to keep the surplus as stock. For this reason, hay was not considered as a by-product. The pasture soil is characterised by low fertility, as found by studies (Braghieri et al., 2011) carried out under very similar geographical conditions (338 m above sea level and 40°45′02.1″N, 16°14′11.7″E). According to these authors, the pasture is characterised mainly by Gramineae (70%), Composites (15%) and less by Legumes (6%). Manuelian et al. (2020) found the highest grass production during spring and the lowest one during summer in comparable conditions (360 m above sea level and 40°38′N, 15°49′E).

Feeding regime and diets

Feeding has a primary role in livestock LCA, since diet source inputs and their related emissions are considered. Most research on equids was carried out on horses; therefore, most data were obtained in this study by analogy. Data from interviews were integrated with the background and formulas available in the literature (Martin-Rosset et al., 2006; Martin-Rosset and Tisserand, 2015; Martin-Rosset, 2018).

With respect to energy requirements, Wood (2010) studied feeding of mature donkeys and found that the season (winter vs. summer) significantly affected digestible energy (**DE**), DM and CP requirements. No significant effect of sex was found. Although the study was carried out under different environmental conditions compared to ours, their assumptions were used in the present study. Martin-Rosset (2018) suggested the use of different DE maintenance requirements, depending on the metabolic weight ($BW^{0.75}$) or live weight of the adult animal. In addition to maintenance requirements, models were proposed to assess the energy requirements of lactating jennies and growing animals (De Palo et al., 2016; Polidori and Vincenzetti, 2017; Raspa et al., 2019).

As concerns protein requirements, Raspa et al. (2019) reported scarce knowledge about donkeys. Smith and Burden (2013) suggested for these animals a maintenance requirement of 40 g CP/100 kg of BW/day. The estimated requirement for maintenance of a 200 kg BW donkey is 106–117 g of horse digestible CP (commonly known as Matiéres Azotée Digestibles Cheval, MADC) (Martin-Rosset and Tisserand, 2015; Martin-Rosset, 2018). Raspa et al. (2019), focusing on Martina Franca donkey, estimated a requirement of 310–330 g MADC/day for lactating jennies weighing approximately 300 kg BW and having a daily milk production of 5L, including the milk for foals. Donkey foal requirements could be assimilated to those reported by Martin-Rosset and Tisserand

Table 5
Inventory analysis of feed inputs per each livestock category in the donkey farm. For lactating jennies, two different diets are reported: Real Scenario Model (RSM) and Increased Milk Production Model (IMPM); The inventory analysis for framework depiction recorded data from the year 2021 (January-December).

Item	0–6 months young animals (females and males)	7–12 months young animals (females and males)	13–19 months young animals (females and males)	20–24 months growing females	20–24 months fattening males	25–40 months		Lactating jennies		Dry jennies		Jacks
						Non-pregnant	Pregnant	RSM	IMPM	7–8 months	9–12 months	
Feed consumption (kg DM /head)												
Diet period (days)	150	210	210	150	150	90	365	180	180	60	125	365
Mixed hay	60	170	270	225	230	110	730	540	540	120	315	730
Grass at pasture	-	170	170	120	-	135	440	-	-	90	260	730
Oat grain	145	45	105	90	150	-	290	180	215	-	-	-
Concentrate feed	-	-	-	-	75	-	-	90	150	-	-	-
Straw	-	-	-	-	-	135	-	-	-	30	-	550
Feed nutrition value (g/kg/DM)												
CP	140	120	120	119	120	105	120	123	123	100	120	100
MADC	na	65	63	63	70	50	63	75	78	50	60	50
Crude fiber	235	276	257	220	193	335	255	244	228	268	286	321
Cytoplasmic carbohydrates*	145	140	150	170	276	87	170	218	253	85	90	90
Ether extract	11	27	29	29	35	20	30	35	38	20	24	21
Ash	12	97	87	85	67	92	86	52	51	87	100	94
UFC	na	0.75	0.72	0.73	0.76	0.55	0.68	0.75	0,78	0.60	0.66	0.60

Abbreviations: MADC = Matiéres Azotée Digestibles Cheval, (Digestible Nitrogenous Matter Horse); UFC = Unité Fourragère Cheval (Horse Feed Unit) equivalent to 9.42 MJ net energy (NE); na = data not available.
* Water soluble carbohydrates + starch (Martin-Rosset et al., 2006).

(2015) for light horses (400 kg adults) with moderate growth. Values are equal to 360, 270 and 200 g MADC/day at 12, 24 and 36 months, respectively. Despite the availability of a larger number of studies on MADC than CP for equids, the LCA equations to assess nitrogen losses focus on CP. Consequently, MADC will be translated into CP for each of the different raw materials in the diet (for example, for 1 kg barley grain DM, 92 g MADC will be 117 g CP).

As for other dairy animals, given the strategical role of donkey milk, Table 5 describes the feeding scheme differentiated by livestock category. The table shows the diet of all donkey categories involved in the study. The input and output of animals younger than a year were processed with the software and related pollutants were included within the system boundaries. Foals can be kept with the mother for up to 10 months; thus, their diet is partially milk based. The milk ensured to suckling foals by the mothers is considered in both scenarios.

The list of raw materials in the diets was obtained by interviewing the farmer. However, according to the available literature (Martin-Rosset, 2018; NRC, 2007), the diets of the different livestock categories (foals, jennies, jacks) were estimated and checked for net energy (**NE**) requirements, expressed as UFC, (i.e. Unité Fourragère Cheval = Horse Feed Unit = 9.42 MJ NE). We considered a requirement of 0.27 UFC for 1 kg of milk (Martin-Rosset, 2018; NRC, 2007).

Description of the two scenarios (Real scenario Model and increased milk production Model)

Milk was arbitrarily chosen as the DFU, and the other outputs were processed as by-products. Inputs recorded on farm (RSM), were recalculated and sized on the theoretical increased production (IMPM). This study compared RSM and IMPM sustainability. The IMPM framework was modeled considering a potential milk yield of 2000 g head^{-1}. The lactating jennies category in IMPM required a specific model, in which diet and electricity were modified to keep into account the increased production. In agreement with the literature (Martin-Rosset et al., 2006, 2012; NRC, 2007; Martin-Rosset, 2018), requirements for RSM dams (3.4 UFC) were adjusted up to 3.9 UFC head^{-1} day^{-1} (IMPM); therefore, the diet showed different amounts of commercial concentrate and oat. Hay administration was supposed to be the same in the two scenarios (Table 5). Emissions from animals were recalculated based on the different diets. Electricity consumption was also affected by milked yield, due to the fact that electricity in dairy farms is almost exclusively used for milking and milk refrigeration, whereas electricity use for illumination is negligible.

There are very few studies about the energy requirements of donkey milking, but a large body of literature is available on dairy cattle. Moerkerken et al. (2021) reported a range between 20 and 170 Wh/kg milk in a conventional milking parlour (milking machine, refrigeration, water heating for disinfection, illumination and water pumps). To the best of our knowledge, the most accurate study about energy consumption for donkey mechanical milking was carried out by Failla (2008) in Sicily. The author collected data from three farms and reported values between 26 and 55 Wh/donkey, and between 32 and 74 Wh/l milk. Therefore, a mean electricity consumption of 50 Wh/l milk was used in this study, being inaccurate the data reported by the farmer. The modeling of IMPM did not involve changes in diesel fuel for crops and its emissions. For the transportation of commercial concentrate, the increased number of journeys was considered but had a negligible impact on the overall fuel consumption. The oat produced on farm was assumed to be fed to all livestock categories, excluding lactating jennies, which were fed with purchased oat. For this feed, a 100 km road travel was computed.

Table 4 shows the characteristics of RSM and IMPM scenarios for the lactating jennies.

Emissions

When carrying out a life cycle inventory on ruminants, emissions by livestock are usually calculated accordingly to IPCC (2019a and 2019b) guidelines. On the other hand, the availability of studies assessing emissions in equids is scarce and IPCC suggests default values related to donkeys, horses and mules. These data are not accurate and their range is often very wide; thus, other models should be adopted to assess the emissions of these animals.

Martin-Rosset et al. (2012) developed several formulas for enteric methane emissions, faecal and urinary nitrogen excretion. Those formulas were used in this study. Methane emissions from manure were calculated according to IPCC (2019a and 2019b) equations, which were considered to be precise and applicable to equids, also considering the very low amount of CH_4 originated by manure in horses and donkeys. Specific emission factors for electricity and fuel combustion, crop residues and nitrogen fertilisers were also applied. In the two scenarios (RSM and IMPM), the different animal-based emissions affected the assessments. Lactating jennies was the unique livestock category interested.

Table 6 shows the main elementary flows and the characterisation factors that were used to assess the impact categories investigated (GWP, Acidification Potential (**ACP**) and Eutrophication Potential (**EUP**)).

Enteric emissions

The following formula, developed by Martin-Rosset et al. (2012), was used to assess methane emissions:

$$ECH_4\ (\%DE) = 7.57 - (0.12 \times 28.4CF) - (0.01 \times CP) - (0.05 \times CC) \tag{1}$$

where

ECH_4 = estimated methane amount;
DE = digestible energy, estimated according to the requirements for each livestock category (Martin-Rosset, 1990);
CF = crude fibre (%DM);
CC = cytoplasmic carbohydrates (%DM), including water-soluble carbohydrates (WSC) and starch (Martin-Rosset, 1990).

In agreement with our results, Martin-Rosset et al. (2012) estimated the enteric methane emissions of ponies and donkeys in 12.1 kg head^{-1} year^{-1}.

Methane emissions from manure

The main cause of methane emissions from manure is anaerobic decomposition in manure pits, while less methane is produced

Table 6
Characterisation factors of the main elementary flows of the impact categories investigated in the donkey farm.

Impact category	Main elementary flow	Characterisation factor	Reference
GWP kg CO_2	CO_2	1	IPCC (2019a)
	CH_4	28	
	N_2O	265	
ACP g SO_2	NH_3	1.6	Huijbregts (1999)
	NOx	0.76	
	SO_2	1	
EUP g PO_4^{3-}	NO_3	0.1	Heijungs et al. (1992)
	P_2O_3	3.06	

Abbreviations: GWP = Global Warming Potential; ACP = Acidification Potential;

when dung is deposited on pastures, rangelands or paddocks, (IPCC, 2019a). Animals involved in this study are kept mainly at pasture with a resting area (paddock with straw litter); therefore, a very low methane emission is expected. IPCC (2006) guidelines indicate for donkeys low default values (1.10 kg CH_4 head^{-1} year^{-1} in developed countries) and the subsequent guideline refinement (IPCC, 2019a) suggests very similar amounts, however, in this work, we relied on more accurate data, based on specific equations (Tier 2 method). The first step was to assess the volatile solid excretion of manure and urine, according to the following equation:

$$VS = [GE \times (1 - Def\%/100) + (UE \times GE)] \times (1 - ASH/18.45) \quad (2)$$

where

VS = volatile solid excretion per day on a dry-organic matter basis, kg day^{-1};
GE = gross energy intake, MJ/day;
Def % = digestibility rate of the feed.

The amount of feed considered was adapted to each livestock category. Different feeding periods were considered, in agreement with Table 5, excluding all animals from birth to 19 months of age, because their emissions are assumed to be negligible.

(UE × GE) = urinary energy expressed as a fraction of GE. IPCC (2019a) indicates 0.04 GE as the average value of urinary energy excreted by ruminants, whereas the current study adopted as default value 0.05 GE, value obtained in ponies feed with a mixed diet (70% hay and 30% pelleted maize) (Vermorel et al., 1997); ASH = ash content of manure calculated as a fraction of the DM feed intake; 18.45 = conversion factor for dietary GE per kg of DM (MJ kg^{-1}).

Subsequently, methane was estimated with the emission factor (EF) provided by IPCC (2019a) guidelines:

$$EF = (VS_T \times x) \times \left[B_{0(T)} \times 0.67 \times \Sigma_{S,k} \times MCF_{S,k}/100 \times AWMS_{(T,S,k)}\right] \quad (3)$$

where

EF = CH_4 emission factor of livestock category T, kg CH_4 animal^{-1} days^{-1};
VS_T = daily volatile solid excreted by livestock category T, previously estimated with Eq. (2), kg DM animal^{-1} days^{-1};
x = basis for calculating annual VS production, days/year;
$B_{0(T)}$ = maximum methane emitting capacity from manure produced by livestock category T, m^3 CH_4 kg^{-1} of VS excreted. A default value of 0.33 for donkeys in Western Europe was suggested (IPCC 2019a, Table 10.16, updated);
0.67 = conversion factor of m^3 CH_4 to kilograms CH_4;
$MCF_{S,k}$ = methane conversion factors for manure management system S in climate region k, percentage. The default value is 47%, regardless of climatic areas and relative humidity (IPCC 2019a, Table 10.17, updated);
$AWMS_{(T,S,k)}$ = fraction of livestock category T's manure handled using manure management system S in climate region k, dimensionless. For donkeys, the same default value (72%) of goats in pasture/range/paddock in Western Europe is used (IPCC 2019a, Table 10A.8, updated).

Emissions from manure

Manure emissions are closely related to CP intake. Little is known about the protein requirements of donkeys (Raspa et al., 2019), and the most accurate estimates are based on MADC requirements. Martin-Rosset et al. (2012) developed specific formulas for equids, focusing on nitrogen balance and distinguishing between faecal (Eq. (4)) and urinary (Eq. (5)) excretion. Those equations were used in the present study.

$$gCPf/kgBW^{0.75} = 0.331 + 0.256\ gCpi/kgBW^{0.75} \quad (4)$$

where

f = faecal;
i = intake;
$BW^{0.75}$ = metabolic BW.

$$mgNu/kgBW^{0.75} = 548.13Ni\left(g/kgBW^{0.75}\right) + 47.17 \quad (5)$$

where

N = nitrogen;
u = urine;
i = intake;
$BW^{0.75}$ = metabolic BW.

After the assessment of nitrogen balance, N_2O emissions were estimated in agreement with IPCC equations (IPCC, 2019a and 2019b), as shown in Table 7. Estimates included both direct and indirect (from volatilisation and leaching) emissions.

With respect to emissions from manure and barns, according to IPCC (2019a), "indirect emissions result from volatile nitrogen losses that occur primarily in the forms of ammonia and NOx". To estimate these losses from "other animals" from solid manure, only the FracGAS (emissions from manure and organic fertilisers, at volatilisation) was considered using the default value (0.12), while the FracLEACH portion (emissions from crop residues, organic fertilisers and manure, at leaching) was used to assess N_2O. Ammonia losses were assumed to be zero. Similarly, Sabia et al. (2018) excluded FracLEACH while studying buffaloes, and Baldini et al. (2018) found in dairy cattle a negligible percentage of NOx in comparison with ammonia. Therefore, in this study, NOx emissions from housing and manure storage were not considered.

The nitrogen balance was also used to assess ammonia (NH_3) emissions, classified as: (i) from housing, (ii) from storage and (iii) from grazing/outdoor. According to the European Environment Agency (EEA, 2009) recommendations, we used the total ammoniacal nitrogen (TAN), to quantify NH_3 emissions, which are also affected by manure management (Table 7). For equids, the manure type indicated by EEA (2009) guidelines is solid.

Emissions from organic fertilisers, fuels and electricity

As concerns organic fertilisers, the farmer interview revealed a low amount of nitrogen applied to arable land, in addition to nitrogen provided by manure. IPCC (2019b) suggests specific methods for organic agrochemicals. Information on how N_2O emissions from fertilisers were calculated is provided in Table 7. However, given the very low percentage of nitrogen available in organic fertilisers, their ammonia and NOx emissions were excluded as well from the model.

In agreement with previous studies (Romano et al., 2021a; 2021b), to estimate CO_2 release from the combustion of 1 kg of diesel fuel, we used the standard value of 0.85 kg per litre for diesel density, and a 3.13 eq. emission factor. The Italian emission factor (0.47 eq., Pirlo et al., 2014b) was used to estimate 1 kWh of electricity mix available in the Country. Table S1 and Table S2 show fuel amounts (kg), type of transportation and travel distances (km), uploaded in the software for the inventory analysis. Sulphur dioxide total amount (output to the environment) includes inputs from the technosphere (i.e., the energy sources used to obtain processed materials such as dehydrated alfalfa or flaked/crushed

Table 7
Emission factors and equations used to estimate N_2O and NH_3 in the donkey farm.

Pollutants	Origin	Equations	Emission factors		Reference
N_2O direct	Manure and organic fertilisers	$N_2O = (F_{ON} * EF_1 + F_{PRP} * EF_3) * 44/28$	$EF_1 = 0.005$ $EF_3 = 0.003$		IPCC (2019a and 2019b)
N_2O indirect volatilisation		$N_2O = (F_{ON} + F_{PRP} * Frac_{GAS} * EF_4) * 44/28$	$Frac_{GAS} = 0.12$ $EF_4 = 0.01$		IPCC (2019a and 2019b)
N_2O indirect leaching	Crop residues, manure and organic fertilisers	$N_2O = (F_{CR} + F_{ON} + F_{PRP} * Frac_{LEACH} * EF_5) * 44/28$	$Frac_{LEACH} = 0.24$ $EF_5 = 0.011$		IPCC (2019a and 2019b)
NH_3	Housing	$EF_{TAN} * Nex * EFa * 17/14$	$EF_{TAN} = 0.6$	EFa = 0.22	EEA (2009)
	Storing	$EF_{TAN} * Nex * EFb * 17/14$		EFb = 0.35	EEA (2009)
	Grazing/outdoor	$EF_{TAN} * Nex * EFc * 17/14$		EFc = 0.35	EEA (2009)

Abbreviations: F_{ON} = fertilisers organic nitrogen; F_{PRP} = fertilisers paddock, pasture, ranging; F_{CR} = fertilisers crop residues; EF_1 = emission factor for organic amendments in dry climates; EF_3 = emission factor for manure; EF_4 = emission factor for manure and organic fertilisers, at volatilisation; EF_5 = emission factor for manure, organic fertilisers and crop residues at leaching; FracGAS = factor for manure and organic fertilisers, at volatilisation; FracLEACH = factor for crop residues, organic fertilisers and manure, at leaching; 44/28 = conversion of N_2O-N to N_2O; TAN = total ammoniacal nitrogen; EF_{TAN} = TAN emission factor; Nex = nitrogen excretion per head (kg of N/animal/year); EFa = emission factor (NH_3 losses) for manure of housed equids; EFb = emission factor (NH_3 losses) for stored manure of equids; EFc = emission factor (NH_3 losses) for manure of grazing/outdoor equids; 17/14 = conversion from NH_3-N to NH_3.

maize for example) in addition to energy and chemicals (e.g., diesel).

Impact assessment

We estimated the sustainability of donkey milk investigating three impact categories: GWP (kg CO_2 equivalents, considering a 100-year time horizon), ACP (g SO_2 equivalents) and EUP (g PO_4^{3-}) using the EPD (2013) method (SimaPro, 2020). Despite the significant utilised agricultural area, descriptors such as land use and agricultural land occupation were not estimated. This choice is explained by the absence of studies about these impact categories, whereas a few studies are available about the impact on climate change of working equids (Cerutti et al., 2014; Aguilera et al., 2019). Moreover, a previous study from Berlese et al. (2019) on dairy buffaloes, carried out with a similar model involved co-products but based on different allocation criteria, investigated the same impact categories as those assessed in the present study.

Statistical analysis

The calculated values from the LCA process for GWP, (kg CO_2 equivalents), ACP (g SO_2 equivalents) and EUP (g PO_4^{3-}), were processed by **LSD** (Least Significance Difference) statistical test (Fisher, 1937), setting the alpha level at 0.05, to show any significant differences between the real (RSM) and projected (IMPM) scenario and among the different allocations. For the LSD test, the following formula was used:

$$LSD = t_{0.05} * \sqrt{MS\frac{1}{n}}$$

where $t_{0.05}$ is the t-critical value from the t-distribution table with $\alpha = 0.05$; MS is the mean squares within groups; n is the number of values. Statistical tests were carried out using agricolae package of R software (R Core Team, 2013), and then, the LSD test was applied, using the LSD.test function (De Mendiburu Delgado, 2009). In agreement with Steel et al. (1997), the LSD test was chosen because it is best suited for comparisons involving a small number of values.

Results

Milk was chosen as the DFU in this study, wheat grain was considered as by-product and included in the allocation. Meat was also considered as a by-product. In agreement with the literature on dairy systems, mass and economic allocation were used to share equivalents between commodities. In the reference allocation, all the burdens and environmental impacts of the farming system are allocated to the main product (i.e., milk). Table 8 shows the results of RSM and IMPM scenarios, in the reference allocation (**RA**), mass allocation (**MA**) and economic allocation (**EA**) models.

As concerns Global Warming Potential, in the RSM, this study estimated 43.7, 8.5 and 23.6 kg CO_2 equivalents per DFU (1 kg of raw donkey milk) after RA, MA and EA, respectively. These equivalents are significantly different ($P < 0.05$) among them; in addition, all these values are higher than those obtained in the IMPM ($P < 0.05$). In the IMPM scenario, RA and EA equivalents (5.8 and 5.3 kg CO_2) show no significant differences ($P > 0.05$), and equivalents after MA are the lowest (3.8 kg CO_2) of both the scenario and the entire study ($P < 0.05$).

With respect to Acidification Potential and Eutrophication Potential, these LCA descriptors showed the same trend for RSM and IMPM. In RSM, similarly to what we observed for GWP, the estimated ACP and EUP significantly differ ($P < 0.05$) between them, with the following values: 258, 50, and 140 g SO_2, for ACP and 86, 17 and 46 g PO_4^{3-} for EUP in the three allocation methods used (RA; MA, and EA, respectively). In the IMPM scenario, ACP and EUP values (34, 22, 31 g SO_2 and 11, 7, 10 g PO_4^{3-} for RA, MA and EA, respectively) did not show significant differences ($P > 0.05$) across allocation modes. In addition, these values are lower than those found in the RSM scenario ($P < 0.05$), except for the ones improved by mass allocation ($P > 0.05$).

Discussion

Reference allocation framework

To our knowledge, no studies are available about equine milk *sensu lato* and donkey milk *sensu stricto*. On the other hand, Aguilera et al. (2019) studied the impact of mechanisation in Spanish agriculture and compared bovine and equine carbon footprints. They found a lower impact from equines in comparison with bovines (expressed as kg CO_2 eq KW^{-1} $year^{-1}$), and highlighted that horses showed the lowest values (lower than donkeys and mules). The capability of bovines to feed on roughages and their consequently higher methane emissions, lower power capacity per unit live weight and lower number of working days (207–212 $year^{-1}$ of bovines vs. 247–251 $year^{-1}$ of mules and donkeys) explained this trend. Similarly, Cerutti et al. (2014) investigated GWP of draught equids, estimating85 g CO_2 eq generated in a donkey working hour. Almost 60% of these emissions are from feed sources, followed by equipment, veterinary care and housing. No contribution of enteric/manure emissions was reported by the authors. Our results, despite focusing on a different declared functional unit,

Table 8
Life cycle assessment (LCA) analysis results for donkey milk production. Different superscripts in the same line indicate a significant difference ($P < 0.05$).

Impact category	RSM RA	RSM MA	RSM EA	IMPM RA	IMPM MA	IMPM EA
GWP kg CO_2	43.7[a]	8.5[c]	23.6[b]	5.8[d]	3.8[e]	5.3[d]
ACP g SO_2	258[a]	50[c]	140[b]	34[c]	22[c]	31[c]
EUP g PO_4^{3-}	86[a]	17[c]	46[b]	11[c]	7[c]	10[c]

Abbreviations: RSM = Real Scenario Model; IMPM = Improved Milk Production Model; RA = Reference Allocation; MA = Mass Allocation; EA = Economic Allocation; GWP = Global Warming Potential (kg CO_2 equivalents); ACP = Acidification Potential (g SO_2 equivalents); EUP = Eutrophication Potential (g PO_4^{3-} equivalents).

found animal methane emissions to contribute only minimally to the overall CO_2 equivalents, in agreement with Cerutti et al. (2014). Energy sources, mainly fossil fuels and their emissions, contributed to carbon footprint by more than 50% (Fig. 2, RMS and IMPM framework both), followed by feed (14%) supplied to the greatest number of donkeys (foals, young animals, no-lactating jennies, jacks). The larger requirements hypothesised for lactating jennies, in the IMPM scenario, slightly affected its contribution to GWP (Fig. 2). Fig. 2 highlights that methane enteric emissions contributed with a similar percentage, half of which was due to the lactating jennies (6.4%). The other significant share involved in GWP (>10%) is represented by buildings and utilised agricultural areas. N_2O, originating mainly from manure management, is thought to be 10 times more powerful than CH_4 as a GHG. Very low amounts of N_2O were found in this study, in agreement with Cerutti et al. (2014).

When we hypothesised an increased milk yield in the IMPM scenario (about 2 litres head^{-1} day^{-1}), significantly ($P < 0.05$) lower results were recorded (5.8 kg CO_2 eq). This result is a logical consequence of the larger DFU. Bava et al. (2014) and Gislon et al. (2020) carried out less exacerbated comparisons and found that higher milk yields improved almost all impact categories. Despite the unchanged profile in terms of buildings, utilised agricultural area and agrochemicals of IMPM compared to RSM, the increased yield model halved the contribution of these "services". This trend could be explained by the increased amount of feed supplied to lactating jennies to increase their milk production. Enteric emissions proportion differed in the two scenarios (6.4 and 8.2% in RSM and IMPM, respectively, Fig. 2), and this aspect needs to be clarified. In IMPM, the percentage of hay was not changed, however, a larger amount of market concentrates and grain oat was added to the diet. As shown in the enteric emissions section, a specific equation focusing on concentrates as cytoplasmic carbohydrate source (Martin-Rosset et al., 2012) is required for equids. A different approach is commonly used to assess methane emissions in ruminants, mainly focused on the metabolism of cellulose, provided by forages or roughages.

As far as concerns the CO_2 equivalents in IMPM, the estimates we obtained are comparable with those found in the literature for buffalo raw milk. Buffaloes require approximately the same inputs (e.g. feed) and produce three to four times less milk than cattle (Pirlo et al., 2014a and 2014b; Romano et al., 2021a). Jennies are less productive (2 kg milk head^{-1} day^{--1}), but require lower inputs (feed, fossil fuels) and produce less GHGs than buffaloes. These differences could explain the comparable emissions.

In the RSM scenario, the estimated ACP was 258 g SO_2 equivalents per kg of raw milk. Aguilera et al. (2019) studied the environmental impact of equids focusing on carbon footprint without considering ACP. Cerutti et al. (2014), estimated in donkeys an ACP of 0.34 g SO_2 eq. per working hour, however, they did not provide the breakdown into ACP components, therefore, no comparable data is available in donkeys. In cattle, Bava et al. (2014) reported a large range (8.6–21.7 g) of SO_2 equivalents per kg of Fat Protein Corrected Milk (FPCM). Similar values were observed also in other studies carried out under Mediterranean environmental conditions: 27.8 g (Noya et al., 2018) and 9.3–27.6 g (Romano et al., 2021b).

Vagnoni et al. (2017) assessed the sustainability of *Pecorino* sheep cheese in Sardinia and attributed to raw milk a mean of 38 g SO_2 equivalents. The value was comparable with those found by Romano et al., (2021a) and Bragaglio et al. (2022) for buffalo milk (39 g and 46.5 g, respectively). Slightly higher values (65 g) were found by Pirlo et al., (2014a). The cited studies on buffalo milk were carried out in Mediterranean climate. Although ACP is an impact category less mitigated than GWP by the size of the main product, livestock systems with a low degree of intensification and feed efficiency (as most donkey farms are) are rather penalised as concerns acidification (Guerci et al., 2013a; 2013b).

Baldini et al. (2018) carried out a LCA study on three dairy cattle farms and observed that, energy consumption gave a noticeable amount of pollutants involved in acidification, particularly in one farm. A similar share (5%) was attributed to sulphur dioxide by Bava et al. (2014). In dairy cattle systems, Bava et al. (2014) reported ammonia to account for almost 90% of the acidification category. Bragaglio et al. (2018) observed that in grazing beef systems, the largest share of SO_2 equivalents was due to ammonia from manure. In our pasture-based system, ammonia still contributed for more than 55%, however, a distinction between the two scenarios (RSM and IMPM) is required.

The IMPM scenario was found to be more sustainable (34 g SO_2 equivalents) compared to RSM (258 g, $P < 0.05$). Similarly to GWP, in both scenarios, the percentage contribution of energy sources was greater than those found by other authors (Bava et al., 2014; Baldini et al., 2018). Ammonia is the first cause of acidification (Guerci et al., 2013b; Sabia et al., 2018), and it is produced by emissions during manure storage, crops cultivation and, in pasture-based systems, dung, manure and urine deposited on the field. Our study, in agreement with the literature, showed a high share of ammonia, but it also showed significant percentages of sulphur dioxide (Fig. 3a and b). Sulphur dioxide emissions are almost exclusively due to fossil fuels (diesel), and this share is probably emphasised by the smaller ammonia emissions of equids compared to ruminants. The same amount of diesel fuel was computed in the two scenarios, whereas a different diet was hypothesised for lactating jennies in IMPM. This could explain the higher percentages of ammonia in IMPM than RSM, with a proportionally lower contribution of sulphur dioxide and nitrogen oxides (mainly released from diesel combustion) (Baldini et al., 2018).

For the impact category of eutrophication, IMPM was more sustainable than RSM ($P < 0.05$), with 11 and 86 g PO_4^{3-} equivalents, respectively. Nitrate leaching and volatilised ammonia are commonly recognised as the main contributors to eutrophication, which agrees with our findings (Fig. 4a and b). Battini et al. (2016) and Romano et al., (2021b) emphasised how legumes, by increasing nitrogen fixation, can reduce the EUP. Battini et al. (2016) observed that, in dairy cows, high milk yields decreased both eutrophication and climate change impact. Romano et al., (2021b) compared eutrophication in dairy cattle farms with and without pasture, and found the pasture-based farm to be less sustainable, even though it was organic. The farm investigated in the present study complies with organic regulations; thus, only

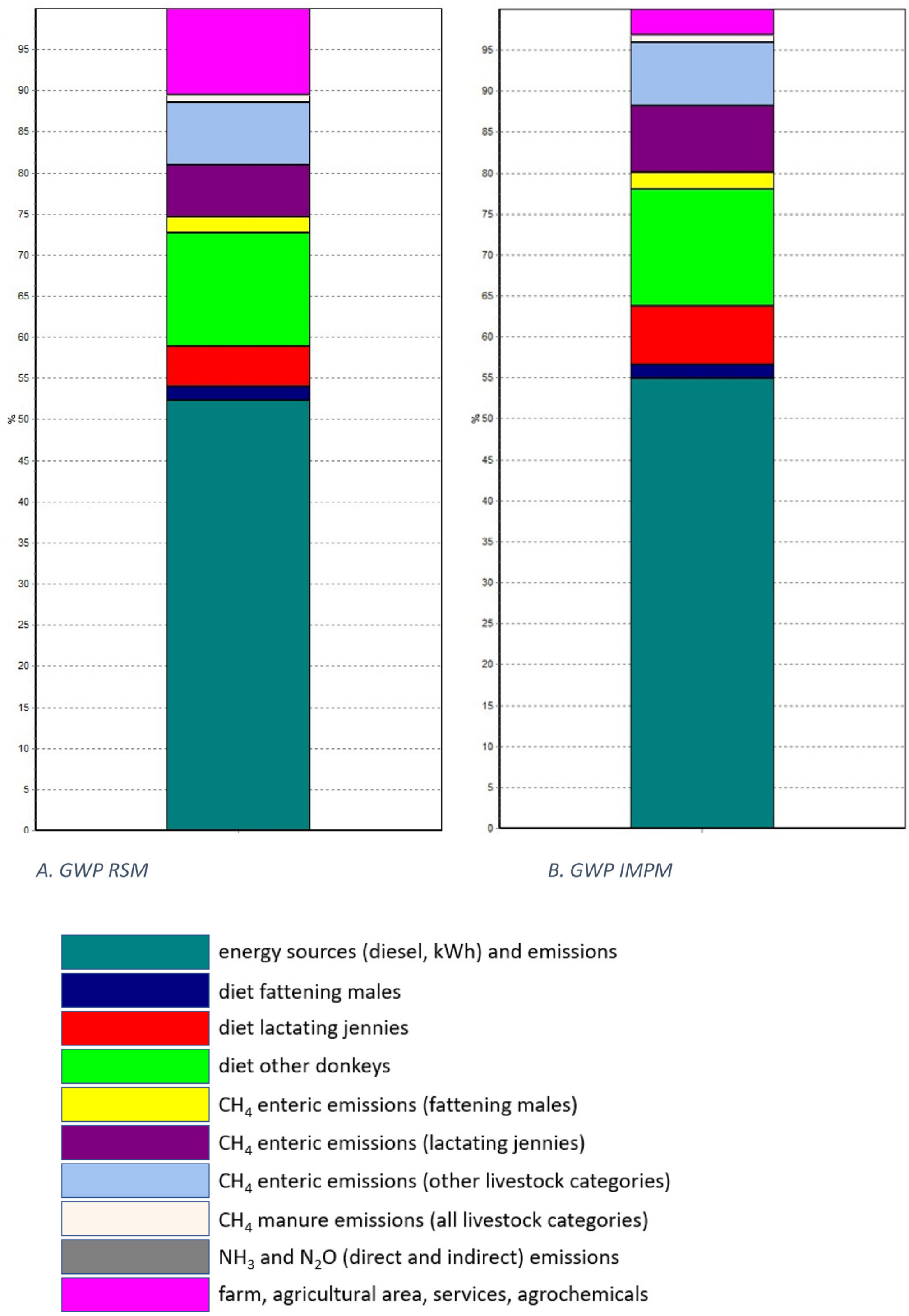

Fig. 2. Contributors to Global Warming Potential (GWP) in the two scenarios of the donkey farm; 2A = Real Scenario Model (RSM); 2B = Increased Milk Production Model (IMPM). Contributors (phases and substances) are shown in percentage, with Reference Allocation (RA).

organic fertilisers (Table 1) and manure from grazing donkeys are used as soil enrichment and were involved in EUP computation. This category is also affected by ammonia, N_2O and phosphorus from feed produced on farm and purchased (Pirlo and Lolli, 2019).Fig. 4a and b shows a little increase in the proportion of ammonia and nitrates in IMPM (71.3%) compared to RSM (68.3%), probably due to the larger use of purchased concentrate feed and their leaching (O'Brien et al., 2012). Overall, the two scenarios seem to affect the relative contribution of different substances more in the ACP than in the EUP impact category. In particular, RSM and IMPM had similar shares of phosphates and phosphorus, known as minor contributors to eutrophication (Bava et al., 2014).

The role of mass and economic allocations

Mass allocation (**MA**) significantly improved sustainability in GWP, ACP and EUP categories ($P < 0.05$). This criterion decreased CO_2 equivalents from 43.7 to 8.5 kg, and a similar trend was observed both for ACP and EUP. The values of acidification and

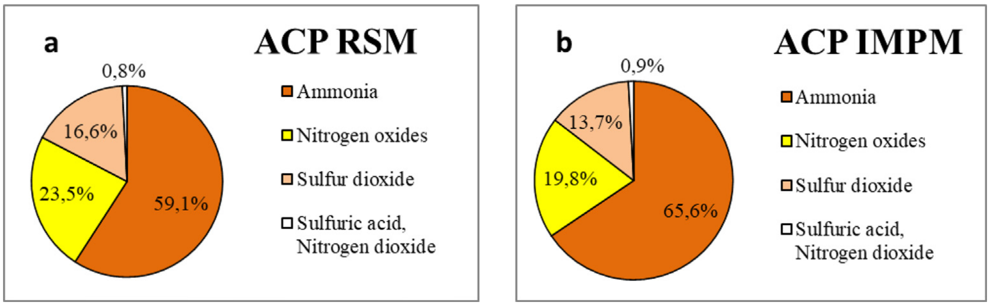

Fig. 3. Contributors to Acidification (ACP) in the two scenarios of the donkey farm; 3a = Real Scenario Model (RSM); 3b = Increased Milk Production Model (IMPM). Contributors (substances) are shown in percentage, with Reference Allocation (RA).

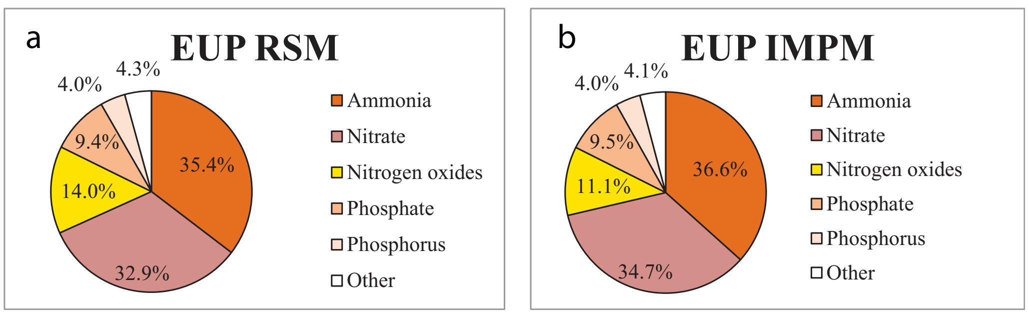

Fig. 4. Contributors to Eutrophication (EUP) in the two scenarios of the donkey farm; 4a = Real Scenario Model (RSM); 4b = Increased Milk Production Model (IMPM). Contributors (substances) are shown in percentage, with Reference Allocation (RA).

eutrophication with reference allocation were 258 and 86 g, respectively. After MA, acidification amounted to 50 g SO_2 eq. and eutrophication 17 g PO_4^{3-}.

The three impact categories (GWP; ACP and EUP) were all affected by EA, showing significantly lower amounts than RA, even though values were higher than those obtained with mass criterion ($P < 0.05$). After economic allocation (EA), the RSM showed 23.6 kg CO_2 eq., 140 g SO_2 eq. and 46 g PO_4^{3-}eq. for GWP, ACP and EUP, respectively.

As expected, MA led to larger decreases than EA, given the little milk yield in RSM. In this scenario, the amount (in tonnes) of by-products is comparable with that of the DFU (milk yield), thus, a significant proportion of pollutants was removed from the main product. Despite the similar masses of DFU and by-products, EA has been less effective than MA. This is explained by the price of milk (10 000 EUR t^{-1}), which is much higher than that of all other by-products (bread and durum wheat, fattened donkeys), i.e. 270, 320 and 5 500 EUR t^{-1}, respectively.

As stated above, MA had higher effectiveness than EA. In dairy systems, this result has been previously reported. In particular, Berlese et al. (2019) and Pirlo and Lolli (2019) found lower impacts after MA in buffalo and cattle farms. Kiefer et al. (2015), investigating the carbon footprint of cattle, attributed 1.70 kg CO_2 eq. per kg FPCM without allocation, 1.47 with economic allocation and 1.37 with mass allocation. When ecosystem services were included in the economic model, these authors estimated 1.35 kg CO_2 eq., not much lower compared to mass allocation. On the other hand, Pirlo et al., (2014a) used economic allocation only deeming it to be more representative of the social case for sustainability in the dairy buffalo system. In our study, IMPM sustainability was improved by the hypothesised increase in milk production. As concerns GWP, EA did not significantly affect CO_2 equivalents (reduced from 5.8 to 5.3 kg, $P > 0.05$) whereas MA improved it (3.8 kg CO_2 eq, $P < 0.05$). IMPM results showed values comparable to CO_2 equivalents estimated in less efficient ruminants (e.g., buffaloes). Our findings after MA (3.8 kg CO_2 eq.) are similar to the value reported by Vagnoni et al. (2017) for sheep milk (2.80–3.27 kg CO_2 eq.). Our results after reference allocation and economic allocation were similar to values reported in studies on buffaloes. Our values with EA and RA allocation (5.3–5.8 kg CO_2) can be compared with those found by Romano et al., (2021a) and Bragaglio et al. (2022) (5.05 and 5.15 kg, respectively). Pirlo et al., (2014a) also found a similar result (5.1 kg), whereas a higher value (6.4 kg) was recorded by Berlese et al. (2019).

In RSM, SO_2 equivalents decreased considerably after mass allocation and showed no significant differences with all IMPM values. As concerns acidification, the IMPM value after reference allocation (34 g SO_2, mainly due to ammonia) did not differ from values after mass and economic allocation (22 and 31 g SO_2 equivalents, respectively). These values are slightly higher than those obtained in conventional dairy cattle farming (19, 16 and 15 g with NA, EA and MA, respectively) (Pirlo and Lolli, 2019). Guerci et al., (2013b) found a similar range (between 15.2 and 25.6 g SO_2 eq per kg of Energy Corrected Milk). Interestingly, Pirlo and Lolli (2019) argued that milk yield did not improve ACP, whereas Guerci et al., (2013b) stated that ACP and EUP could be decreased by increasing milk yield. Guerci et al., (2013a) studied the effect of different dairy cattle farming strategies on sustainability, and observed that intensive systems reduced acidification and other impact categories.

Berlese et al. (2019) studied buffalo milk, obtaining results very similar to ours (37, 20 and 36 g SO_2 eq. with RA, MA and EA, respectively). Their allocations affected GWP (6.4, 3.4, 6.1 kg CO_2 eq., respectively), which is also in agreement with our findings. These results could be explained by the similar ratios between the main product (milk) and by-products in buffalo systems and in our donkey farm. Nunes et al. (2020) studied the sustainability of sheep milk using 1 kg of a typical Portuguese cheese as the functional unit. They found an ACP of almost 94 g SO_2 eq. and reported that raw milk had an overall contribution of 96%.

Overall, it can be stated that high ACP values are usually found in species having low productive performances. Nunes et al. (2020) recorded a satisfactory milk yield on average, nevertheless, the high input (i.e., feeding) for lactating ewes (1.2 kg head^{-1} day^{-1} of concentrates) could explain the large values of SO_2 and PO_4^{3-} equivalents they found.

With respect to eutrophication, it can be classified as marine and freshwater. In the present study, we chose to assess eutrophication *tout court*, identified with PO_4^{3-} emissions. Ammonia and nitrates contribute to EUP for about 70%, with RSM and IMPM showing a very similar share of these substances.

In the IMPM framework, there are no differences between results obtained after MA, EA and with RA. Moreover, values obtained with MA in RSM do not statistically differ from the results obtained in IMPM regardless of the allocation method. In both scenarios, crop fertilisation and nitrogen spread by livestock provided about 70% of the PO_4^{3-} equivalents. Guerci et al., (2013a) argued that, besides GWP, several LCA impact categories can be improved by adopting more intensive and efficient farming practices. Consequently, in IMPM, the EUP equivalents, despite being not affected by allocation, were significantly lower than in RSM due to the larger milk yield.

Conclusions

Our study compared a real scenario (based on data obtained from the farm) and a theoretical scenario (built assuming a higher milk yield size and increased inputs). In the real scenario, allocation (and in particular mass allocation) improved the farm sustainability, showing values comparable with those of the increased yield scenario. In the theoretical scenario, the increased milk yield (potentially achievable with a different milking frequency and foals management) plays a more relevant role than allocation in mitigating the emissions. In this high-yield scenario, the impacts per kg of milk are comparable to those obtained in less efficient ruminants such as buffaloes or sheep. Although donkey milk is not decisive in ensuring the economic sustainability of the studied farm, it represents an important peculiarity. This study was the first to assess the environmental sustainability (in terms of GWP, ACP and EUP) of donkey milk, and considered wheat-related inputs within the system boundaries. This choice was made because milk, in the absence of income from wheat, could not be produced.

As a future research, it would be interesting to compare this farm to at least another (ideally hosting Martina Franca donkeys): However, equally precise data would be needed, on animal care (e.g. livestock categories, feeding, milking routine).

Given the rarity of farms rearing donkeys for milk in large numbers, and having a milking parlour, this study represents a first attempt at studying donkey dairy systems. It is hoped that future studies will fill this knowledge gap and assess the sustainability, both in environmental and economic terms, of these peculiar systems, in order to raise awareness on the feasibility of this kind of farming.

Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.animal.2023.101057.

Ethics approval

Not applicable.

Data and model availability statement

The data that support the study findings are private and confidential.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) did not use any AI and AI-assisted technologies.

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Declaration of interest

None.

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