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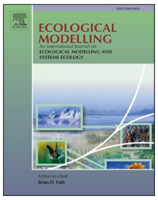

Environmental assessment of milk production from local to regional scales

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ABSTRACT

The environmental impact of livestock activities as Earth global warming is already well known. Therefore, the reuse of resources and products is addressed to reduce the damage caused by intensive livestock farming within a fossil fuel-based economy. Most studies related to sustainability correctly evaluate the processes' energy efficiency under human control but disregard the resources provided for free by nature. For these reasons, the Emergy Accounting (EMA) method is applied to evaluate the direct and indirect environmental support to milk production at regional (Campania Region, Italy) and local levels (buffalo farm within Campania Region), also comparing these results to available outcomes from scientific literature at different spatial scales. Therefore, this study aims to: (i) evaluate the resources consumption across scales from an environmental, donor–side perspective, (ii) suggest improvement options based on feedback use of resources, and (iii) test a calculation method to avoid double counting in complex systems. At the local level, a buffalo farm within Campania Region was evaluated from crop cultivation for feed purposes up to milk production according to three different scenarios for fodder production: (i) manure produced by livestock as fertilizer (closed-loop – circular model), (ii) manure purchased from the market with an integrative amount of chemical fertilizers (open loop), and (iii) chemical fertilizers only (linear model). EMA results applied to the regional level provide a Unit Emergy Value (with Labor & Service) of about 3.09E+07 sej g^{-1}, heavily affected by the emergy of feed production. The buffalo farm within Campania Region (local evaluation) proves to be the most efficient milk production system in terms of resource use; in contrast, the buffalo farm in Brazil is the most self-sufficient milk production system, compared to similar studies from Poland, Slovenia, and Northern Italy. The evaluation of the manure use scenarios (feedback within the system boundaries and purchase from the market) shows the importance of an appropriate assessment approach to overcome the methodological limitations of circularity evaluations. In conclusion, the transition to a sustainable future can be achieved by implementing circular patterns, which should be adequately evaluated to support the correct approach for public policies.

1. Introduction

Half of the global land use is agricultural land needed to provide food security for the growing population (IPCC, 2019). Agriculture (including forestry and other land uses) is responsible for 23% of the direct anthropogenic greenhouse gasses (GHG) emissions (IPCC, 2019). Pastures are 40% of the total agricultural land. Its environmental impact is related to the emission of GHG by ruminant activities, transportation, and processing. In addition to the effects directly generated by the livestock activities, the degradation of the forests by land conversion to feed production (causing the reduction of the biodiversity and the increment of desertification, erosion, pollution of water, and water scarcity) increase the total impact of pastures (Lipson and Reynolds, 2006; O'Mara, 2011). Even though meat and milk are an essential part of a balanced diet–providing essential amino acids for the metabolism and meeting the individual energy requirements for human nutrition (Joint WHO/FAO/UNU Expert Consultation 2007; WHO, 2018), recent studies have highlighted that reducing meat and milk consumption

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could be beneficial in terms of (i) GHG emissions reduction and water resources conservation, and (ii) human health: the excessive meat and milk consumption seems to be correlated to cardiovascular diseases, some forms of cancer and, when considering wild meat, some virus infections (González et al., 2020; Wang et al., 2020).

OECD and Food and Agriculture Organization of the United Nations (2020) foresee an increment of 1.6% of world milk production by 2029, with half of this increment in the number of herds, meaning a rise in cows' and buffalos' milk productivity (which have produced 96% of the total milk, in 2019). Therefore, higher productivity is also required to overcome the increment of land consumption - a substitution of (semi-) natural land cover by constructions (artificial coverings) - and the reduction of pasture areas caused by the abandonment of the non-profitable primary livestock activities (ARPA, 2020; EU, 2007; ISPRA, 2020, 2018).

From a Circular Economy (CE) perspective, the implementation of a bioeconomy strategy in the dairy sector would bring environmental benefits to conserve the ecosystem's functions provided by natural land cover, reducing the GHG emissions and fossil resources consumption with the desired productivity (COM(2018) 673, 2018). Furthermore, the application of sustainable practices in soil management and land occupation, with the support of production processes that reuse high amounts of resources to reduce the impact throughout the entire product's life cycle, support the transition from a linear to a circular paradigm (Almeida et al., 2020; D'Ovidio et al., 2016; Potting et al., 2017; Primavesi, 1985).

In Italy, livestock occupied 30% of the total agricultural area, in 2018; 7.55 million heads produced more than 12,744,000 tons of milk (FAOSTAT, 2020a). Nevertheless, their related emissions are two-thirds of the whole impact generated by the agricultural sector (FAOSTAT, 2020b). Although the livestock sector in Campania Region represents only 4% of the total milk produced in Italy, this region concentrates 74% of the buffalo heads of the country, being the first national buffalo milk producer (85% of buffalo milk produced in Italy) (CLAL.it, 2020a, 2020b; ISTAT, 2020a). The Campania Region dairy sector is characterized by different small companies, including family business management, low automation, and predominant craftsmanship in milk processing dairies (Sabia et al., 2018b).

The environmental impact of milk production is commonly assessed from the consumer side, which evaluates the emissions of GHG and other pollutants generated by processes under human control (Carè et al., 2012; Castanheira et al., 2010; Cederberg and Mattsson, 2000; Famiglietti et al., 2019; Guerci et al., 2013; Pirlo et al., 2014; Pirlo and Carè, 2013; Sabia et al., 2018a; Thomassen et al., 2008). Pieper et al. (2020) underlined how animal-based products, meat, in particular, is one of the most relevant contributors to GHG emissions among food products, with organic products performing slightly better than conventional ones. However, the assessment of processes outside human control requires a comprehensive evaluation, including also renewable resources consumption. Few authors analyzed milk production by applying the Emergy Accounting (EMA), a donor-side-oriented method that takes into appropriate accounting the ecosystem services and natural capital depletion (from the biosphere point of view) instead of only considering market valued fossil resources. In this context, Vigne et al. (2013) assessed a range of milk production farms from diverse locations, highlighting the benefits of multi-scale analyses. Jaklič et al. (2014) incorporated EMA into a multicriteria analysis of the Slovenian milk farms, integrating socioeconomic assessment methods to support decision-making. Kocjančič et al. (2018) aimed to investigate the impact of national policies by a multicriteria evaluation which included EMA as the environmental perspective to the decision-making model. Agostinho et al. (2019) sought to investigate the sustainability of clustered milk productive systems in Brazil, discussing the trade-offs between productivity and environmental burdens. Additionally, EMA was included in the "multicriteria multi-scale biophysical assessment method" proposed by Ghisellini et al. (2014a), comparing dairy farms from different Italian regions to a farm in Poland, discussing the impacts of different management options. Spagnolo et al. (2020) focused on the biogas generated using farms' by-products, proposing the expansion of the system boundaries and underlining the necessity of multi-scale analyses to provide a more profound comprehension. From an economic-ecological perspective, Dong et al. (2012) evaluated the sustainability of grasslands in northern China, using EMA to model the behavior of natural lands in different grazing scenarios. The proposed schemes highlighted that the small-scale grazing systems provided environmental benefits, even if they were still intensive models. EMA was also used to simulate the grassland's natural capital and its related ecosystem services. In order to decrease the grazing pressure on the natural grassland of North Xinjiang, Dong et al. (2012b) discussed the social reasons that prevent the conversion from intensive grazing to human-managed pastures. According to the available literature review, a complete EMA evaluation of resource cycling in dairy farms was not yet performed.

Therefore, this work aims to investigate the role of feedback processes of by–products within a CE perspective. From this point of view, the reuse of manure in fodder production, even if being a well-known ancient practice, is a perfect and straightforward example that complies with CE features of reuse (of by–products) and reduction (of new resources and raw materials) (Ellen MacArthur Foundation, 2012; European Commission, 2020). Moreover, this work assesses the environmental performance of milk production by applying EMA on (i) milk production at the regional level of Campania Region, Italy; (ii) the local milk production at a site-specific buffalo farm within Campania Region, and (iii) the comparison of local milk production to similar studies from literature at different spatial scales in Poland, Northern Italy (Emilia Romagna), Slovenia and Brazil (Ghisellini et al., 2014a; Kocjančič et al., 2018; Oliveira, 2018). The buffalo farm in Campania Region is based on primary data collection. For a suitable comparison with literature investigated farms, the different sizes (Total Emergy Use, U), the land constraints (Empower Density), the milk productivity (expressed by the Unit Emergy Value), and other EMA performance indicators of yield and environmental cost were considered.

The novelty, hence, is to: (1) understand the various environmental performances of the investigated livestock farming processes at different scales and identifying the main factors affecting such performances; (2) shed light on potential bio circular patterns within the investigated process (focusing in particular on manure) and, finally, (3) test the emergy approach and its recently suggested improvements in order to understand its ability to explore circular patterns, resource efficiency and savings of milk production systems at different spatial scales. These provide a clearer comprehension of the circular actions to support policymaking towards sustainability.

2. Materials and methods

This study is structured (**Fig. 1**) as an evaluation of the regional dairy livestock sector (Dairy Livestock in Campania Region), with a focus on a local dairy farm (Buffalo Farm within the Campania Region) and on some developed scenarios, which were evaluated considering different EMA procedures. Furthermore, innovation in emergy algebra is explored to ascertain its capability to account for circular patterns properly. This latter issue is based on three different scenarios of fodder production: (i) self-produced manure scenario, in which the manure produced by the livestock is cycled back as fertilizer (closed-loop- circular model); (ii) purchased manure scenario (open loop), a broader CE perspective through networking with various subsystems exchanging materials and energy, in which the fertilizers needed (manure and some chemical fertilizers) are imported from the market, and (iii) entirely chemical scenario, in which production is only based on chemical fertilizers (a typical linear fodder production in Italy). The only circular pattern considered for the evaluated scenarios of the Buffalo Farm within the Campania Region is the manure reused as fertilizer since the other by-

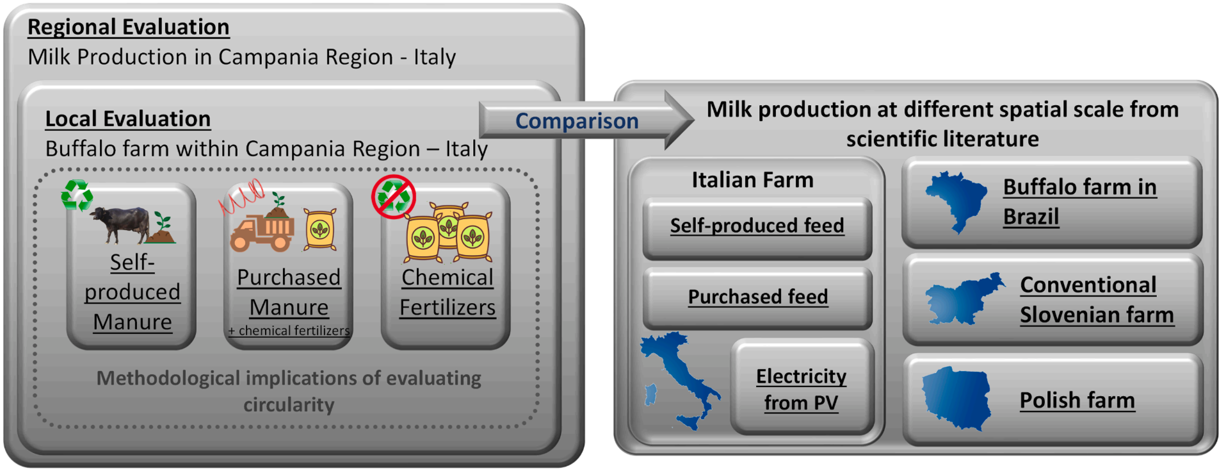

Fig. 1. An overview of the applied framework to evaluate the environmental sustainability of the milk production at: Regional evaluation, a site-specific evaluation-Local (including scenarios: self-produced manure represented by a recycle closed-loop symbol, purchase manure represented by spiral open-loop processes, and chemical fertilizers as the linear model – left side of the figure) and comparison with milk productions from updated scientific literature (right side of the figure).

product (carcasses) represents less than 5% of the total outputs generated annually. Thus, according to the literature review, other circular patterns are disregarded (Fahd et al., 2012; Ghisellini et al., 2014a; Santagata et al., 2019; Spagnolo et al., 2020; Wang, 2014). Additionally, a comparison with similar studies carried out in Italy, Poland, Slovenia, and Brazil is performed in order to test to what extent the EMA approach captures the different environmental performances and the capability of this methodology to support sustainable policies.

2.1. *Emergy accounting method*

Emergy Accounting (EMA) is a method to assess a systems' performance. This assessment accounts for the valuable resources provided by nature and their cumulative flows, supporting transformation processes from raw materials to complex natural and anthropogenic products. EMA is a donor-side (or supply-side) assessment method that focuses on the resource flows' convergence to the investigated system by expanding the time scale to include indirect and direct material and energy flows. EMA also assesses the space and time required for resource production, providing a quantitative evaluation of the renewability of resource flows and storage (Ulgiati, 2001). In other words, EMA highlights the overall environmental loading of a process by quantifying the use of nonrenewable resources versus renewables, suggesting a measure of a process' distance from environmental equilibrium (Brown and Ulgiati, 2004a; Santagata et al., 2019).

By definition, EMA accounts for all the available energy (exergy) used directly and indirectly to produce resources and then goods and services in the biosphere (Brown and Ulgiati, 2004b; Odum, 1996). It requires the knowledge and quantification of a system's flows and stocks: space or territory, infrastructure, economic and market aspects considering limits, components, interactions, upstream (input) and downstream (output) relationships, and internal assets. As primary resources are measured in different units, a standard unit (namely, available energy of one kind, generally solar) is defined to express the work of nature to produce them, characterized by different convergence and concentration. Solar equivalent energy (solar emergy) is therefore introduced (and measured as sej, solar emergy joule, hereafter solar emjoules), based on equivalency factors among different sources with reference to the solar one (Brown and Ulgiati, 2016; Odum, 1996). These factors are named UEVs (Unit Emergy Value, sej unit^{-1} of input flow) or Transformities (measured as unit flows of available energy, sej J^{-1}) to convert resources of different natures into solar emergy, expressing the efficiency of resource use (Santagata et al., 2019). Since all materials and energy flows can be expressed in terms of their available energy, these equivalency factors allow the comparison among all of them. By definition, the solar transformity value is 1 sej J^{-1} (Odum, 1996).

2.1.1. *Environmental performance indicators*

The Emergy approach provides a set of indicators capable of capturing different dimensions of investigated systems, projecting the local scales to the larger scale of the biosphere. This multidimensionality of EMA can be the basis for designing environmental and economic policies across scales. The main indicators can be identified as:

- Total Emergy (U), calculated by summing all the emergy inflows as $\Sigma U_i = e_i * UEV_i$, where e_i is the *i–th* inflow of available energy and UEV_i is the related Unit Emergy Value. The total emergy U expresses the size of the system at the scale of the biosphere, namely the amount of resources that makes the system's existence possible.
- UEV (Unit Emergy Value), the emergy invested per unit of output (sej/J, sej/g) – is a measure of the environmental efficiency of the conversion process. When specifically measured in the unit of available energy (J), it is named Transformity;
- ED (Empower Density), the emergy invested per unit area, reflecting the intensity of renewable and nonrenewable emergy resources due to land development and human activities (ED = U/Area);
- %REN (Percentage of Renewability), the fraction of emergy from renewable (R) sources (%REN = R/U);
- EYR (Emergy Yield Ratio), an indicator of the system's dependence on resources imported from outside, F, namely the benefit obtained by exploiting local resources (renewable –R and nonrenewable –N) by means of imported ones: $EYR = U/F = (R + N + F)/F$;
- ELR (Environmental Loading Ratio), an indicator of the pressure that system's activities exert on the local environment, $ELR = (N + F)/R$, pushing it far from environmental equilibrium (ELR = 0);
- ESI (Environmental Sustainability Index) indicates the relation between local benefit achieved and local environmental equilibrium affected (ESI = EYR/ELR).

All indicators can be calculated by also including (or not including) the emergy supporting direct and indirect labor (the latter, most often named "services"). Of course, processes cannot occur without Labor and Services (L&S; Ulgiati and Brown, 2014), which means that the actual emergy cost of a process – a city metabolism or a national economy – must include locally renewable, locally nonrenewable, and imported resources as well as L&S (direct and indirect labor, that makes processes and economies possible). Excluding L&S allows a closer look at resource flows, but L&S brings into the evaluation information, know-how, infrastructures that support a society, i.e., express to what extent resources are converted into a culture. Therefore, all indicators should be calculated with and without including L&S, and results can be interpreted in terms of tangible and intangible resources driving a society. Results without L&S also provide an assessment of raw resource use on a large scale, making the results of various studies comparable (Santagata et al., 2019; Zucaro et al., 2013).However, EMA faces critics as some aspects remain questioned by academics, considering the method challenging to be understood outside the academy boundaries (Patterson et al., 2017). The absence of (or little) reliance on EMA calculation relies on the lack of analyses regarding data uncertainties, quality, and sensitivity which are not present in the majority of the published EMA studies (Cleveland et al., 2000; Raugei et al., 2014). Thus, EMA still requires more accuracy and transparency to make the method more widespread, accepted, and understood by the general public, academics, and decision-makers (Marvuglia et al., 2017).

2.1.2. The algebra of emergy

Considering the systemic characteristics of the Emergy approach, specific algebra rules were defined to assess the contribution of stocks, flows, and processes to the system dynamics. These rules, initially detailed by Odum (1971), deriving from the equivalent-circuit theory and following standardization process, are summarized here:

a) If a process only generates one product, the total emergy U driving the process is assigned to the output product.
b) If the output flow splits into two or more flows having the same physicochemical properties, the driving emergy also splits according to each output flow's available energy (exergy).
c) If two or more products are simultaneously generated (co-products, having different physicochemical characteristics although generated together), the total emergy is entirely assigned to both co-products. This is because each of them cannot be produced without investing the whole emergy amount (e.g., electricity and hot water in a thermal power plant).
d) When co-products reunite, their emergy cannot be summed up to avoid double–counting (i.e., "creation" of emergy against the conservation laws of thermodynamics). Consequently: (d_1) emergy in upstream feedbacks should not be double-counted; (d_2) when co-products reunite downstream, only the emergy of the largest flow is considered.

The d_1 rule about feedbacks can also be interpreted differently: if by-products are fed back to previous steps of the system, they prevent the need for an equal amount of input emergy. The rule recognizes an implicit circularity benefit and dictates double-counting to be avoided. In practical terms, the feedback is not added again as an input. Instead, if the by-products are dispersed as undesired outflows and emissions, their quality decreases in proportion to the form and concentration changes relative to the environment. Therefore, Brown (2015) suggested evaluating diluted, low–quality by-products neither as splits nor co-products, but instead as emergy losses (an inefficiency of the process) that need to be quantified and subtracted from the emergy driving the main product; the amount of such losses is calculated by Brown as a fraction of the input emergy proportional to the mass of by-products, in so breaking the no–allocation (c) rule. Thus, by-products are treated as a different kind of low–quality, undesired outflows, introducing a slightly modified procedure into the emergy algebra from Odum (1996) to justify a partial allocation procedure. Building on such an innovative concept, Santagata et al. (2019) suggested that the allocation be proportional to the exergy fraction of by-products, instead of their mass, i.e., their residual ability to drive other ecosystems' processes (e.g., manure as fertilizer).

In this study, the process generates a main product (milk) characterized by a higher UEV than emergy inflows and several kinds of by-products (not waste), characterized by a lower UEV (e.g., manure, wastewater, carcasses). All of these by-products, however, offer transfer advantages to other processes and, as a consequence, circularity potential at different scales: manure as fertilizer of fodder in the farm, wastewater for biogas production at urban scale (Buonocore et al., 2018, 2012), carcasses as animal feed or substrates for electricity production at regional scale (Santagata et al., 2019). Therefore, a fraction of total U proportional to the exergy fraction of by-products over the total exergy of all outputs can be allocated to these by-products according to

$$U_{by-products} = U_{total} * \left(Exergy_{byproducts} \big/ Exergy_{total}\right) \tag{(1)}$$

as well as to the main product according to

$$U_{mainproduct} = U_{total} \tag{(2)}$$

(for a detailed explanation, see Santagata et al. (2019)).

In this study, we focus on manure as a typical by-product to show how scale affects the calculation of UEVs and the other environmental performance indicators. To overcome limits and avoid double-counting of considering manure input, the following procedures were addressed:

- For the **self-produced manure** scenario, a null UEV value is assigned to the manure;
- For the **purchased manure** scenario, the UEV of the manure is the value calculated in this work, according to the exergy of by-products calculation following Eq. (1) (for details, see Appendix C).

Additionally, in this study, every emergy value is calculated or updated (for data coming from literature) according to the 1.2E+25 seJ yr^{-1} Global Emergy Baseline (GEB), and all UEVs related to previous GEBs were converted accordingly (Brown et al., 2016). The EMA procedure for the investigated literature studies has been considered to calculate renewable flows, with "R" being the largest among free local environmental inputs, i.e., sun, wind, rainfall, and deep heat inputs. According to the current EMA procedure (Brown and Ulgiati, 2016), R is classified into three distinct groups: Primary Sources, Secondary and Tertiary Sources. The sun's energy, geothermal heat, and tidal compose the Primary Sources, which are summed up to yield the final value of this group. This is then compared to Secondary and Tertiary Sources' values, which include the kinetic energy of wind and waves, the chemical potential of rain, and the geopotential and chemical potential of runoff, i.e., the contributions of flows originated by the Primary Sources. The largest value between the sum of the Primary Sources and the highest value of Secondary and Tertiary Sources is established as the R value (indicating the availability and the convergence of biosphere work to the investigated system). Therefore, following to current EMA procedure, in this study, the scientific literature results were recalculated from the original data provided by the authors. All EMA calculations for milk production in Campania Region, buffalo Farm within Campania, and all investigated literature studies are reported in Appendix A and B.

2.2. Milk production in campania region

In Campania Region, pastures represent 20% of the regional agricultural land use, occupying 112,200 ha of area (Fig. 2. Land cover map of Campania Region (Corinne Land Cover, 2018)). The 697,446 animals (43% buffalos, 28% cows, 29% sheep, and 0.04% goats) produced around 393.000 ton of milk in 2018 (52.7% of cow's and 46.7% buffalo's milk) (ISTAT, 2020a). Campania Region concentrates 74% of Italy's buffalos. It is the most productive Region of this type of milk, reaching 85% of the national buffalo milk production (ISTAT, 2020a).

The regional territorial data were obtained from georeferenced systems (GIS) (Corinne Land Cover, 2018), and inputs from nature (sun, geothermal heat, tidal, and rain) were estimated from the Italian National Institute of Statistics (ISTAT, 2020b, 2018). The purchased goods were estimated from regional agricultural handbooks (Ribaudo, 2011). All input details are described in Table 1. Fig. 3 shows the investigated

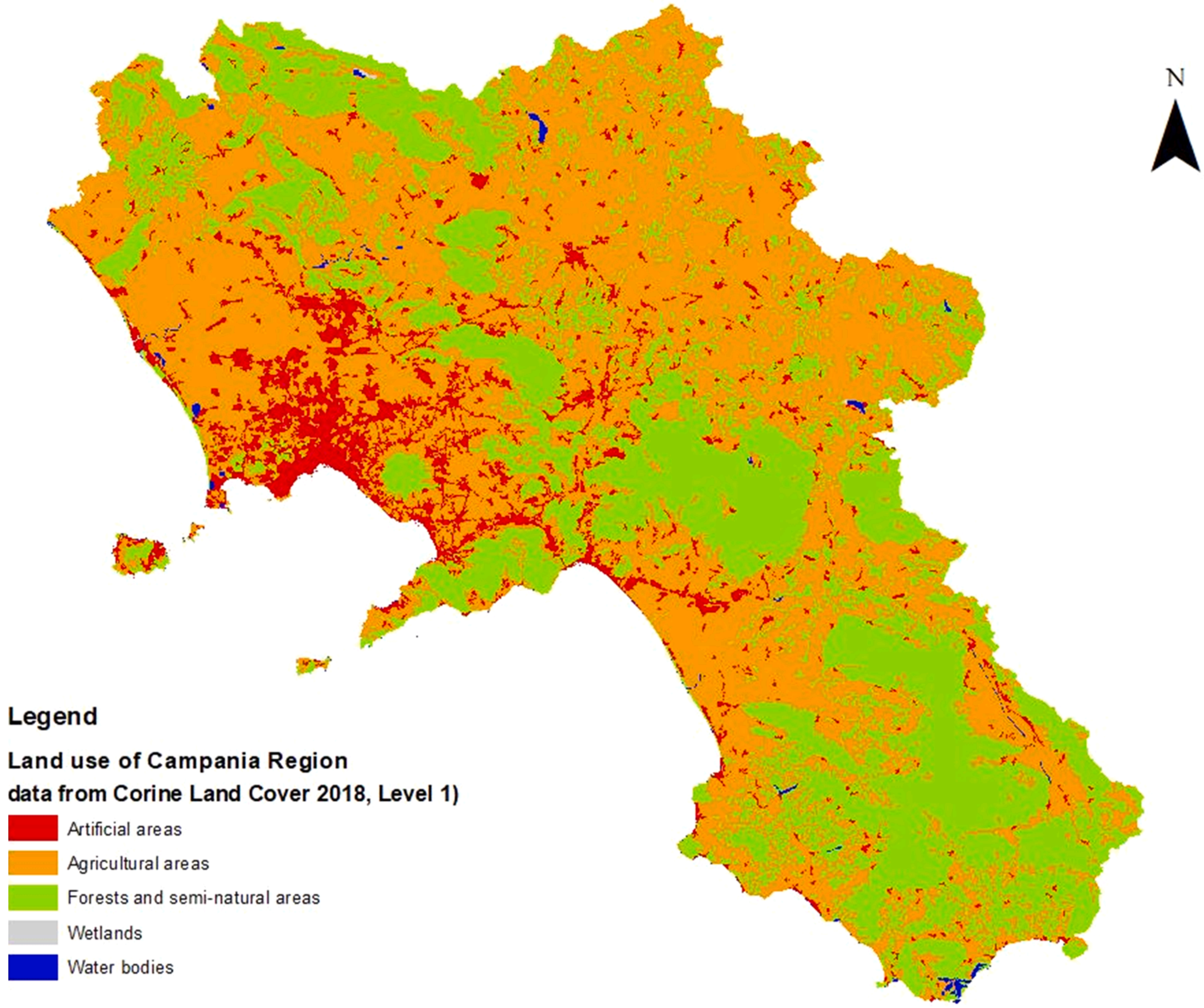

Fig. 2. Land cover map of Campania Region (Corinne Land Cover, 2018).

system boundary of the dairy livestock sector in the Campania Region, considering electricity, feed, machinery, medicines, diesel/heavy oil, and water as resources from the economy.

2.3. *Local milk production systems*

2.3.1. *Local buffalo farm within campania region*

The investigated conventional buffalo farm (Fig. 4), located in Caserta Province (Campania Region, Italy), is characterized by family management. The milk production stems from the fodder cultivation up to the milk sold to the market. The farm has 34 ha of crop area and produced 717.6 tons of biomass in 2018, divided into sorghum (176 tons in 8 ha), alfalfa (31 tons in 7 ha), corn (180 tons in 15 ha), and ryegrass (48 tons in 4 ha) to feed the 542 confined buffalos. The annual milk productivity is 975 tons yr^{-1}. In addition, the farm reuses all manure produced by the buffalos as fertilizer for fodder production. In Table 1, the local scale data are reported concerning the three above-described scenarios related to the fodder production practices: (i) **self-produced manure** scenario; (ii) **purchased manure** scenario, and (iii) fully **chemical fertilizers** scenario.

2.3.2. *The evaluated scenarios local buffalo farm within campania region*

The fodder production based on **self-produced manure** is the business-as-usual scenario. First, all manure produced by the livestock (2.200 tons in 2018) is dried and then used as fertilizer (130 tons of dried manure). In this scenario, the manure is stocked in the investigate system boundary (Fig. 4– orange line), waiting for a natural fermentation (Abbruzzese et al., 2021; Wang et al., 2021). After that, following the Italian regulations to prevent soil and water contamination (appropriate balance between carbon-nitrogen elements), the manure can be safely spread (Ministero Delle Politiche Agricole Alimentari E Forestali, 2016). Indeed, the management of manure is a common practice in European countries in which 80% (average value of the past 20 years (FAOSTAT, 2021a) of the total produced manure is used as fertilizer or for energy generation purposes (biogas production for heat and electricity generation).

The **purchased manure** scenario considers the manure coming from outside the system boundaries (imported inputs - F), according to the demand of nitrogen for each crop production (corn, alfalfa, sorghum, and ryegrass) reported in Ribaudo (2011). To keep unchanged the fodder productivity (717.6 ton year^{-1}), a balance between purchased manure (considering 2% of nitrogen in the buffalo's manure composition (Faugno et al., 2012)) and nitrogen fertilizer was estimated (Table 1).

The **chemical fertilizers** scenario considers the requirements of the fertilizer reported in a standard Italian agronomic handbook (Ribaudo, 2011) for the same productivity of corn, alfalfa, sorghum, and ryegrass. Chemical fertilizers are still commonly used in monocultures (Artuzo et al., 2021; Ghisellini et al., 2014b; Kocjančič et al., 2018; Willers et al., 2017): while in Europe, the tendency of the past 20 years is an annual reduction of 2% of fertilizer used in crops, in countries where environmental policies are not clearly imposed and controlled, the use of

Table 1
Input and output data for the livestock sector in Campania Region and local Buffalo Farm within Campania Region, per hectare.

Items	Unit (ha^{-1} yr^{-1})	Livestock Campania Region	Buffalo Farm Campania Region		
			Self-produced Manure	Purchased Manure	Chemical Fertilizers
Inputs from Nature					
Sun insolation	J	3.1E+13	3.1E + 13	3.1E + 13	3.1E + 13
Geothermal heat	J	9.0E + 08	9.0E + 08	9.0E + 08	9.0E + 08
Tidal energy	J	3.3E + 09	–	–	–
Wind	J	9.5E + 10	9.5E + 10	9.5E + 10	9.5E + 10
Wave energy	J	2.2E + 12	–	–	–
Rain, chemical potential	J	4.7E + 10	4.7E + 10	4.7E + 10	4.7E + 10
Runoff, geopotential	J	1.2E + 09	1.2E + 09	1.2E + 09	1.2E + 09
Runoff, chemical potential	J	3.3E + 07	3.3E + 07	3.3E + 07	3.3E + 07
Loss of topsoil	kg	1.2E + 04	7.5E + 02	7.5E + 02	7.5E + 02
Inputs from Economy					
Diesel and heavy fuel	J	5.8E + 09	4.9E + 09	5.6E + 09	5.6E + 09
Oil - lubricants	J	1.3E + 08	–	–	–
Electricity	J	5.6E + 09	6.6E + 09	6.6E + 09	6.6E + 09
Water (from aqueduct)	m^3	7.8E + 01	9.9E + 02	9.9E + 02	9.9E + 02
Seeds	kg	–	4.3E + 01	4.3E + 01	4.3E + 01
Fertilizers					
Chemical Mix	kg	–	–	–	1.3E + 02
Nitrogen	kg	–	–	5.4E + 01	1.4E + 02
Manure (dry)	kg	–	1.3E + 04	5.4E + 03	–
Feed					
Average Mix	kg	4.5E + 04	–	–	–
Straw	kg	–	1.3E + 02	1.3E + 02	1.3E + 02
Mineral Feed	kg	–	4.3E + 00	4.3E + 00	4.3E + 00
Chemicals					
Pesticides /Herbicides	kg	–	2.2E-01	2.2E-01	2.2E-01
Detergents	kg	–	2.6E + 02	2.6E + 02	2.6E + 02
Disinfectants	kg	–	1.6E-01	1.6E-01	1.6E-01
Machinery					
steel and iron	kg	1.1E-01	2.7E + 00	2.7E + 00	2.7E + 00
aluminum	kg	1.8E-02	4.7E-01	4.7E-01	4.7E-01
rubber and plastic	kg	1.3E-03	3.3E-02	3.3E-02	3.3E-02
copper	kg	3.9E-03	1.0E-01	1.0E-01	1.0E-01
Medicines	kg	3.8E + 01	–	–	–
Human Labor	person	1.7E-01	1.5E + 00	1.5E + 00	1.5E + 00
Services	€	1.8E + 04	1.7E + 04	1.7E + 04	1.7E + 04
Output	**Unit (yr^{-1})**				
Milk	kg head^{-1}	5.6E+02	1.8E + 03	1.8E + 03	1.8E + 03
Manure (total, 34 ha)	kg		2.2E + 06	2.2E + 06	2.2E + 06
Carcasses (total, 34 ha)	kg		1.0E + 05	1.0E + 05	1.0E + 05

chemical fertilizers increased 80% during the same period (FAOSTAT, 2021b).

2.3.3. *Comparison with milk farms from literature*

A comparison among the results of local **buffalo farm within Campania Region** considering the business-as-usual scenario (self-produced manure) and the results provided from previous literature case studies was performed. For a suitable comparison, previous EMA evaluations were updated, adjusting all data to the same Global Emergy Baseline (Brown et al., 2016), the same UEVs for each input and the same updated calculation procedures (Brown and Ulgiati, 2016), in the following studies:

- Milk farm in Italy: an Italian Farm located in the Emilia Romagna Region with 1850 herds, producing 66 tons of milk per year (Ghisellini et al., 2014a). The farm comprises 23 ha of pastures and 380 ha of conventional feed production divided into alfalfa, ryegrass, and maize crops. Three different hypothetical scenarios investigated for this farm were considered: (a) partially **self-produced feed** – producing 39% of the total feed consumed and purchasing the remaining fraction, (b) all needed **feed purchased from the market**, and (c) in addition to self–production of food as in (a), also **electricity generated from photovoltaic panels** to produce the energy consumed in substitution of the conventional electricity from the Italian national grid;
- Milk farm in Poland: the **Polish farm** located in the south-western of the country. The 1810 herds produce 2200 tons of milk per year. The 950 ha of organic cultivation produces rape, grass, green maize, corn, barley wheat, sugar beets as feed for the cattle (Ghisellini et al., 2014a);
- Brazilianbuffalofarm: the family-managed **buffalo farm in Brazil** has 3 ha of pasture and is located in Joanópolis municipality, southeast of São Paulo State, in Brazil. The milking of 12 herds is manual, obtaining 5.2 tons year^{-1} of milk. A lack of investment and management characterizes the farm. Only the essential inputs to produce milk for family subsistence and self-consumption are purchased (Oliveira, 2018);
- Milk Farm in Slovenia: the **conventional Slovenian farm** has 17 ha with 37% of this area for feed production. The productivity was 110 tons of milk per year produced by 20 dairy cows (Kocjančič et al., 2018).

Table 2 shows the input flows and the amounts of milk produced within the buffalo farm in Brazil and cow farms in Emilia Romagna (Italy), Poland, and Slovenia:

3. Results

3.1. *Dairy livestock sector in campania region*

EMA indicators for the milk produced by the average livestock activity in Campania Region (Table 3) highlight the high dependency on nonrenewable and imported goods. L&S represents about 35% of the total Emergy (Fig. 5 and Table 4). Nevertheless, the highest percentage

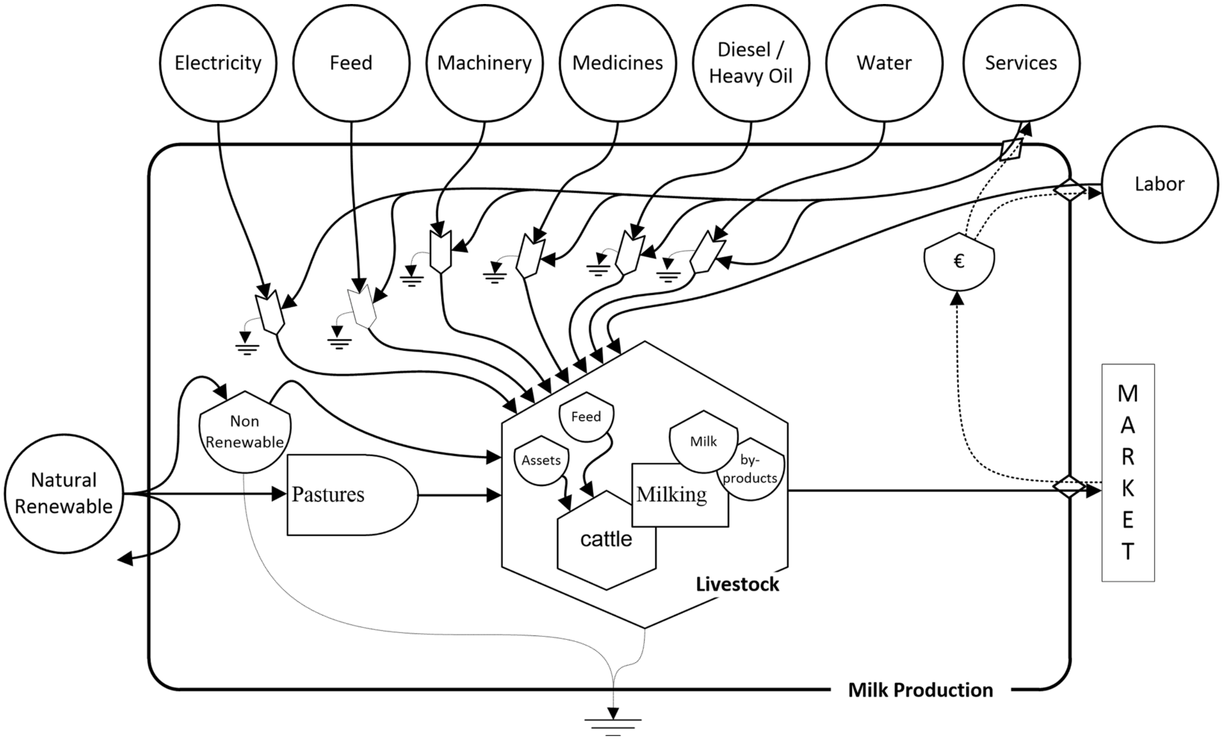

Fig. 3. System Diagram of Dairy Livestock Sector in Campania Region, Italy. Natural Renewable Inputs represent the solar insolation, geothermal heat, tidal energy, wind, wave energy, and rain; Nonrenewable Local Inputs, loss of topsoil – erosion; Pastures are represented as a producer while livestock, as a consumer (Odum, 1996).

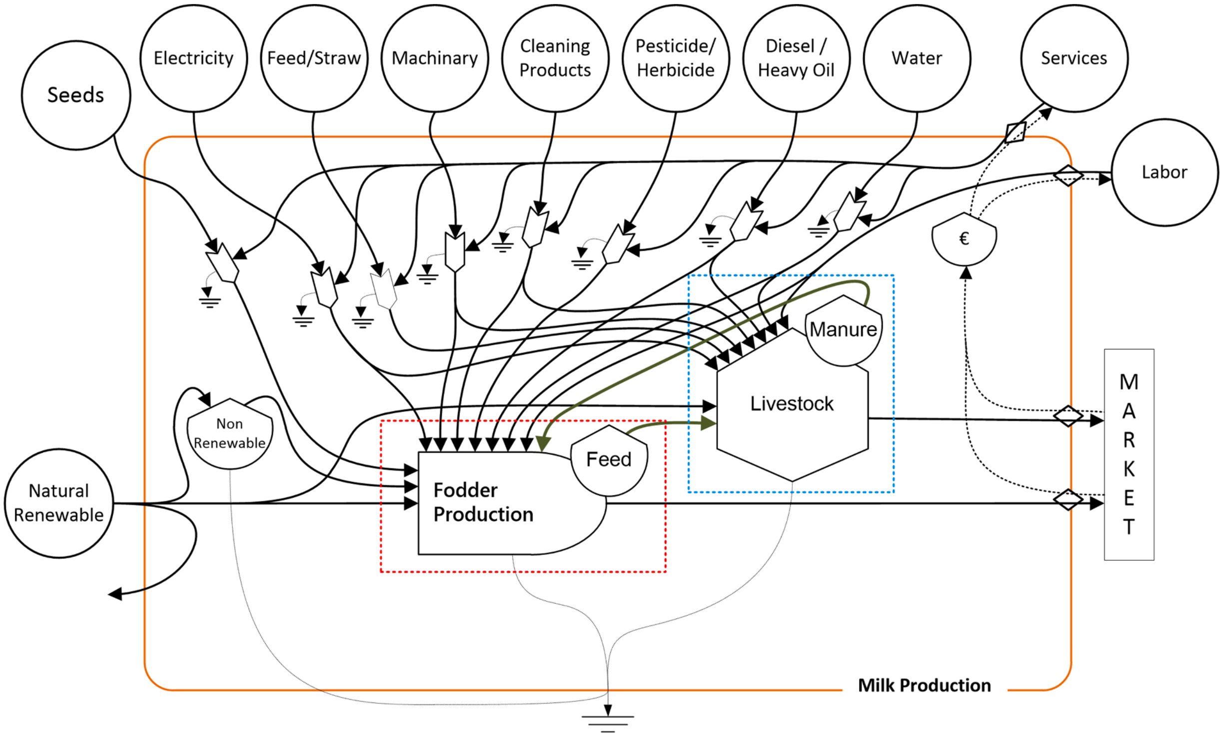

Fig. 4. General System Diagram of the milk production in the local buffalo farm within the Campania Region represents its business-as-usual – self-produced manure scenario. (Symbols from Odum, 1996); where Natural Renewable represents local inputs as sun insolation, geothermal heat, tidal energy, wind, wave energy, and rain; Nonrenewable, erosion; Fodder Production is represented as a producer, Livestock as a consumer, and Feed and Manure as stocks. The dashed areas are subsystems – fodder production in red and Livestock in blue - from which outputs cycling within the system boundaries (delimited by the orange line) can be observed as bold green arrows - feed as input for Livestock and Manure, for Fodder Production.

Table 2
Input and output data from literature case studies per hectare. (*).

Items	Unit (ha^{-1} yr^{-1})	Buffalo Farm Brazil	Emilia Romagna Farm			Polish Farm	Conventional Slovenian Farm
			Self-Produced Feed	Purchased Feed	Electricity from PV		
Inputs from Nature							
Sun insolation	J	7.1E+13	4.1E+13	4.1E+13	4.1E+13	3.3E+13	3.7E+13
Geothermal heat	J	1.6E+09	1.7E+10	1.7E+10	1.7E+10	2.4E+10	1.6E+10
Wind	J	–	–	–	–	–	–
Rain, chemical potential	J	1.2E+10	1.0E+11	1.0E+11	1.0E+11	1.8E+11	8.0E+09
Runoff, geopotential	J	–	–	–	–	–	–
Runoff, chemical potential	J	6.4E+10	2.6E+10	2.6E+10	2.6E+10	1.3E+10	4.1E+10
Loss of topsoil	kg	3.7E+09	1.4E+09	1.4E+09	1.4E+09	7.1E+08	2.2E+09
Inputs from Economy							
Diesel and heavy fuel	J	–	4.6E+05	1.4E+10	4.6E+05	2.0E+05	5.6E+09
Oil - lubricants	J	–	3.1E+07	–	3.1E+07	1.5E+07	–
Electricity	J	4.9E+09	3.5E+09	3.5E+09	–	3.1E+09	1.4E+09
Electricity from PV	J	–	–	–	3.5E+09	–	–
Water (from aqueduct)	m^3	–	3.5E+02	2.9E+02	3.5E+02	7.6E+01	3.5E+01
Seeds	kg	–	2.6E+00	–	2.6E+00	–	–
Fertilizers							
Chemical Mix	kg	–	8.7E+00	0.0E+00	8.7E+00	–	6.5E+01
Manure (dry)	kg	–	–	–	–	6.7E+02	–
Feed							
Average Mix	kg	1.7E+03	1.4E+04	2.2E+04	1.4E+04	2.8E+03	9.5E+02
Chemicals							
Pesticides /Herbicides	kg	–	3.8E-01	–	3.8E-01	1.3E+00	4.9E-01
Machinery							
steel and iron	kg	–	7.2E+00	4.3E+00	4.3E+00	2.3E+00	2.2E+01
aluminum	kg	–	1.2E+00	7.3E-01	7.3E-01	4.0E-01	3.8E+00
rubber and plastic	kg	–	8.7E-02	5.2E-02	5.2E-02	2.9E-02	2.7E-01
copper	kg	–	2.6E-01	1.6E-01	1.6E-01	8.6E-02	8.2E-01
Human Labor	person		3.3E-01	3.5E-02	3.0E-02	3.5E-02	5.3E-02
Services	€	–	7.8E+01	5.9E+03	8.6E+03	5.9E+03	1.5E+03
Output	***Unit (yr^{-1})***						
Milk	kg $head^{-1}$	4.3E+02	3.6E+01	3.6E+01	3.6E+01	1.2E+03	5.5E+03

*Data from Oliveira (2018), Ghisellini et al. (2014a), and Kocjančič et al. (2018).

Table 3
Indicators related to the milk produced in Campania Region (for details, see Appendix A.1).

	Unit	with L&S	without L&S
U	sej yr^{-1}	1.22E+22	7.89E+21
Transformity	sej J^{-1}	1.27E+10	8.25E+09
UEV	sej g^{-1}	3.09E+07	2.01E+07
Empower Density	sej ha^{-1}	1.08E+17	7.03E+16
Indicators			
% Ren		10.5%	12.9%
EYR		1.14	1.18
ELR		8.53	6.74
ESI		0.13	0.18

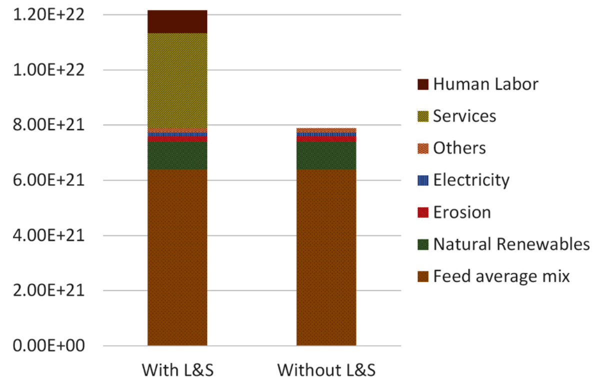

Fig. 5. Emergy inputs (sej $year^{-1}$) by percentage of contribution to milk production by average livestock activity in the Campania Region.

Table 4
Emergy inputs percentage - milk production by average livestock activity in the Campania Region.

Inputs	With L&S	Without L&S
Human Labor	6.8%	–
Services	28.3%	–
Feed - Average Mix	52.5%	80.9%
Natural Renewables	8.4%	12.9%
Erosion	1.6%	2.5%
Others	1.3%	2.0%
Electricity	1.1%	1.7%

of resource consumption is due to the feed purchased from the market, representing 52.5% and 80.9% of total emergy, with and without L&S, respectively. Statistical data, on which Table 3 is based, only refer to purchased feed and do not help distinguish between manure or chemical fertilizers usage. Results also show renewable resources are 10.5% and 12.9%, with and without L&S, respectively, also accounting for calculating the index%REN–the renewable fraction embodied in L&S (Viglia et al., 2018).

3.2. Local buffalo farm within campania region - a case study

The local buffalo farm within Campania Region was evaluated considering the manure produced by the buffaloes used as fertilizer for fodder production, namely (i) **self-produced manure** scenario. Moreover, as mentioned in the Methods section, two other scenarios were analyzed: (ii) **purchased manure** scenario (manure produced outside of the system boundaries), and (iii) fodder cultivation with **chemical fertilizers**. To preventing double-counting, the manure recycled in–farm is assigned a UEV= 0, agreeing with the third rule of emergy algebra. In contrast, the UEV of manure was calculated according to the emergy allocation described in Eq. (1) in the purchased manure scenario. EMA indicators are calculated accordingly. The results are shown in Table 5, Table 6**Error! Reference source not found.** and Fig. 6.

For the **self-produced manure** scenario, Table 5 shows a%REN of 6.0% and 6.4%, with and without L&S, respectively, the lowest value of ELR, and the highest of EYR due to the reduced imported inputs (Fig. 6.a. and Table 5**Error! Reference source not found.**). Results without L&S highlight that water, detergents, and electricity for cleaning and milking processes together with water for irrigation of crop productions represent 73.3% of U (Fig. 6.a. and Table 6). Instead, L&S – when included – accounts for 94.7% of total U (Fig. 6.a. and **Error! Reference source not found.**). In other words, the emergy to produce milk is mainly embodied in human labor (50 workers) since fertilizers come from self–produced manure. Comparing the three scenarios (**self-produced manure, purchased manure,** and **chemical fertilizer),** the U values, with L&S, of manure are about 50% of the values from chemicals, namely 3.31E+18, 3.68E+18, and 7.05E+18, respectively. EMA indicators of **reused manure** scenario show higher renewability and low UEV, the **chemical fertilizer** scenario shows the lowest%REN and higher UEV. When focusing on the **purchased manure** scenario (Fig. 6.b. and **Error! Reference source not found.**), results show that 85.4% of U is related to L&S (percentage slightly decreased due to the accounting of manure from outside). Without L&S, the imported manure represents 62% of total U while the impact of fertilizer, in this scenario only nitrogen, accounts for 4.8% of U (Fig. 6.b. and **Error! Reference source not found.**). The%REN in the **purchased manure** approach is 5.4% and 2.1%, with and without L&S, respectively, mainly related to the amount of rain (**Error! Reference source not found.**5). For the **chemical fertilizer** scenario (Fig. 6.c. and **Error! Reference source not found.**), L&S represents about 44.5% of the U, followed by 52.0% of U coming from the chemical mix of fertilizers (mix of nitrogen (N), phosphorus (P), and potassium (K) elements). If L&S is not considered, 95.5% of the total U comes from fertilizers.

3.3. *Worldwide dairy farms from literature*

The updated literature evaluations of milk production are shown and compared in Table 7, Table 8 and Fig. 7. In detail:

- The milk produced within a farm in the Emilia Romagna region (Italy), based on the **purchased feed** scenario (Fig. 7.a. and Table 8), among the compared literature farms, has the highest U value (1.9E+19 sej yr^{-1} with L&S and 1.3E+19 sej yr^{-1} without L&S), UEV (1.2E+11 sej J^{-1} and 7.9E+10 sej J^{-1}, with and without L&S specifically), and Empower Density (2.9E+08 and 1.9E+08 sej ha^{-1}, with and without L&S, respectively). The high ELR value of 175.8 (without L&S) explains the low ESI value (0.01);
- Results for both **self-produced feed** and **electricity from PV** scenarios of the Italian farm in the Emilia Romagna region are pretty similar (Fig. 7.a. and Table 8). The environmental performance of the productive milk system using electricity from renewable sources is slightly better than the **self-produced feed** scenario without renewable electricity. For both scenarios, the most impacting input is the feed imported from the market, ranging from 46.5% with L&S and 67.7% without L&S (Table 7);
- The productive milk system of the dairy **Polish Farm** presents U values of 9.9E+18 sej yr^{-1} with L&S and 5.5E+18 sej yr^{-1} without L&S (Fig. 7.b. and Table 8). L&S is 44.9%, while the most impacting inputs without L&S are: manure (20.9%) and purchased feed (61.7%) (Table 7);
- The **buffalo farm in Brazil** has the lowest U (7.2E+16 sej yr^{-1} and 2.8E+16 sej yr^{-1}, with and without L&S, respectively). This farm shows great environmental performance, among the compared farms, with the highest EYR (1.41 and 2.93 with and without L&S, respectively) and the highest value of ESI (0.149 without L&S) (Fig. 7.c. and Table 8). The ELR indicator is highly affected by the percentage of nonrenewable input (erosion - represents 23.7% and 61.1% of U with and without L&S, respectively). Moreover, human labor represents 60.7% of the U value with L&S) (Table 7);
- The milk produced by the **conventional Slovenian farm** has an intermediate U value among the compared literature farms (Fig. 7.d. and Table 8), mainly impacted by the fertilizers used for feed crop production (92.8% of U value without L&S) (Table 7).

4. Discussion

The milk produced in Campania Region is dependent on resources imported from the market. Therefore, statistical data used do not explicitly include self-production of feed using inside-farm manure. However, to overcome the lack of specific data at Regional scale (due to the heterogeneity of milk productive farms within the Region: regarding size, management, mechanization, and productivity), the support of GIS would be advisable to individualize best practices, quality, and availability of natural resources, and intrinsic social characteristics, besides the restrict use for geographical and spatial territory's data (United Nations Division for Sustainable Development, 1992). Additionally, GIS allows a more precise estimate of natural resources data, resulting in an improved Emergy analyses' results (Agostinho et al., 2010). The regional assessment results of the livestock sector at the regional level translated its business model: local production, short supply chains, and significant productivity allied to the availability of natural renewable resources. Similar results were found in Ghisellini et al. (2014b), pointing out the critical role of fertilizer for both: (i) regional intensive agricultural production and (ii) the regional milk production, in which the feed (average mix) is highly dependent on the use of fossil-based fertilizers.

From the methodological perspective, the local dairy farm (buffalo farm within Campania Region) was based on primary data collected by ad hoc questionaries during the field visits. However, further investigation cannot disregard rigorous statistical treatment of data uncertainty to provide a more reliable assessment. Indeed, the EMA is one of only a handful of methods that captures the impact of natural resource exploitation. Therefore, a complementary evaluation joining EMA with

Table 5

Results of milk production in the Buffalo Farm within Campania Region under different scenarios of crops fertilization (for details, see Appendix A.2).

	Unit	Self-producedManure with L&S	 without L&S	PurchasedManure with L&S	 without L&S	ChemicalFertilizers with L&S	 without L&S
U	sej yr^{-1}	3.31E+18	1.75E+17	3.68E+18	5.38E+17	7.05E+18	3.91E+18
Transformity	sej J^{-1}	1.39E+09	7.37E+07	1.11E+10	1.62E+09	2.12E+10	1.18E+10
UEV	sej g^{-1}	3.39E+06	1.80E+05	2.70E+07	3.94E+06	5.17E+07	2.87E+07
Empower density	sej ha^{-1}	9.73E+16	5.15E+15	1.08E+17	1.58E+16	2.07E+17	1.15E+17
Indicators							
% Ren		6.0%	6.4%	5.4%	2.1%	2.8%	0.3%
EYR		1.07	1.09	0.34	0.07	1.03	1.00
ELR		15.60	14.53	54.26	699.78	34.33	346.24
ESI		0.07	0.08	0.0063	0.0001	0.030	0.003

Table 6
Emergy inputs percentage - Buffalo farm within Campania Region and different scenarios of crops fertilization.

Inputs	Self-produced Manure With L&S	 Without L&S	PurchasedManure with L&S	 Without L&S	ChemicalFertilizer with L&S	 Without L&S
Human Labor	65.7%	–	59.1%	–	30.8%	–
Services	29.0%	–	26.3%	–	13.7%	–
Water	1.6%	29.7%	1.4%	9.7%	–	–
Electricity	1.4%	27.3%	1.3%	8.9%	–	–
Detergents	0.9%	16.3%	0.8%	5.3%	–	–
Diesel and heavy fuel	0.7%	13.5%	0.7%	5.1%	–	–
Natural Renewables	0.3%	6.4%	–	–	–	–
Others	0.2%	4.7%	0.6%	4.3%	2.5%	4.6%
Erosion	0.1%	2.1%	–	–	–	–
Manure	–	–	9.1%	62.0%	–	–
Fertilizer - Chemical Mix	–	–	0.0%	0.0%	52.0%	93.8%
Fertilizer Nitrogen	–	–	0.7%	4.8%	0.9%	1.7%

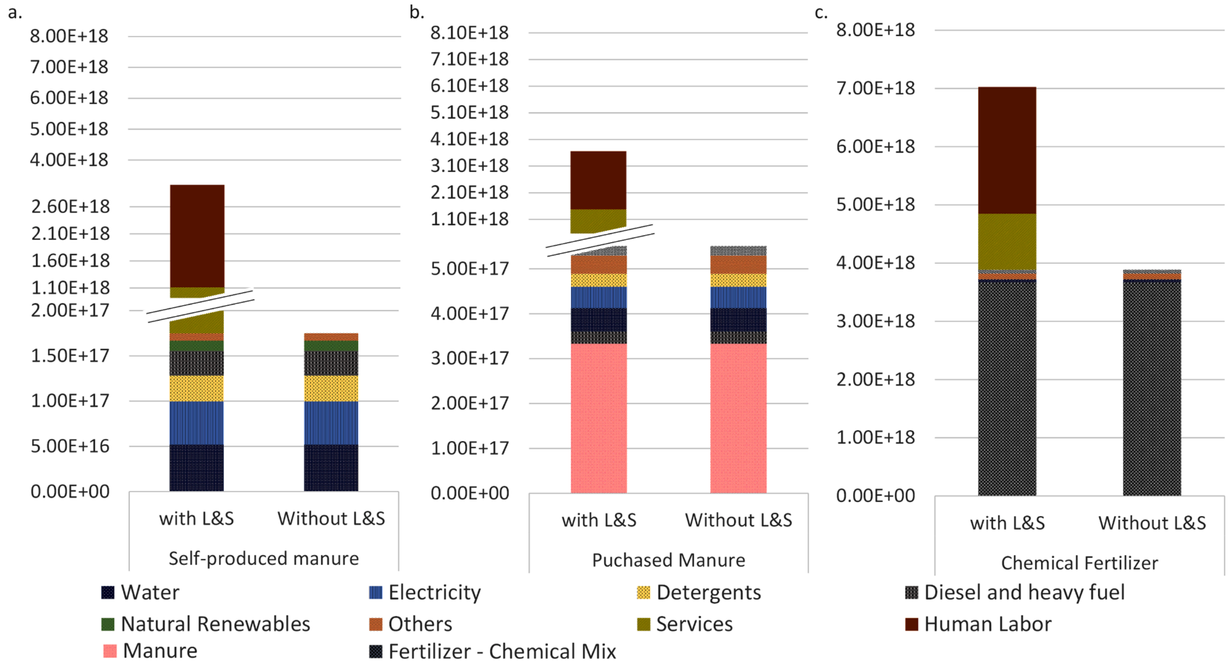

Fig. 6. Emergy inputs (sej year^{-1}) by percentage of composition - Buffalo farm within Campania Region and different scenarios of crops fertilization.

Table 7
Emergy inputs percentage - milk production in selected farms.

Inputs	Emilia Romagna Farm (Italy) PurchasedFeed with L&S	 without L&S	 Self-Produced Feed with L&S	 without L&S	 Electricity from PV with L&S	 without L&S	Polish Farm with L&S	 without L&S	Buffalo Farm Brazil with L&S	 without L&S	Conventional Slovenian Farm with L&S	 without L&S
Human Labor	2.7%	–	4.1%	–	4.1%	–	21.9%	–	60.7%	–	6.0%	–
Services	30.1%	–	26.2%	–	26.5%	–	23.0%	–	0.5%	–	4.6%	–
Erosion	–	–	–	–	–	–	–	–	23.7%	61.1%	2.2%	2.4%
Feed - Average Mix	60.0%	89.3%	46.5%	66.7%	47.0%	67.7%	34.0%	61.7%	8.8%	22.8%	1.9%	2.1%
Electricity	1.6%	2.4%	2.0%	2.9%	–	–	6.3%	11.5%	4.4%	11.3%	–	–
Natural Renewables	–	–	–	–	–	–	1.4%	2.6%	1.9%	4.8%	–	–
Fertilizer - Chemical Mix	–	–	19.1%	27.4%	19.3%	27.8%	–	–	–	–	82.9%	92.8%
Others	1.4%	2.0%	2.2%	3.1%	2.2%	3.1%	1.8%	3.3%	–	–	2.4%	2.7%
Water	–	–	–	–	–	–	–	–	–	–	–	–
Manure	–	–	–	–	–	–	11.5%	20.9%	–	–	–	–
Electricity from PV			–	–	0.9%	1.4%	–	–	–	–	–	–
Diesel and heavy fuel	4.2%	6.3%	–	–	–	–	–	–	–	–	–	–

another well-known method, namely Life Cycle Assessment (LCA), is recommended in order to overcome the limits of a single method evaluation (Oliveira et al., 2021). Nevertheless, the results of the local evaluation within Campania Region, comparing the **reused manure** and **purchased manure** scenarios (Fig. 6.a., Fig. 6.b. and Table 6) with the **chemical fertilizers** scenario, underline the advantage of exploiting the nature's support embodied in the manure (and in another by-product such as carcasses) by implementing circular patterns at local

Table 8
Comparison of milk production in selected farms (for details, see Appendix A.3).

Indicators	Unit	Emilia Romagna Farm (Italy)						Polish Farm		Buffalo Farm Brazil		Conventional Slovenian Farm	
		PurchasedFeed		Self-Produced Feed		Electricity from PV							
		with L&S	without L&S	with L&S	without L&S	with L&S	without L&S	with L&S	without L&S	with L&S	without L&S	with L&S	without L&S
U	sej yr^{-1}	1.9E+19	1.3E+19	1.5E+19	1.0E+19	1.5E+19	1.0E+19	9.9E+18	5.5E+18	7.2E+16	2.8E+16	1.1E+18	9.6E+17
Transformity	sej J^{-1}	1.2E+11	7.9E+10	9.3E+10	6.5E+10	9.2E+10	6.4E+10	1.8E+09	1.0E+09	5.7E+09	2.2E+09	4.0E+09	3.6E+09
UEV	sej g^{-1}	2.9E+08	1.9E+08	2.3E+08	1.6E+08	2.3E+08	1.6E+08	4.5E+06	2.5E+06	1.4E+07	5.3E+06	9.8E+06	8.8E+06
Empower density	sej ha^{-1}	4.7E+16	3.2E+16	3.7E+16	2.6E+16	3.7E+16	2.6E+16	1.0E+16	5.8E+15	2.4E+16	9.3E+15	6.3E+16	5.7E+16
Indicators													
% Ren		2.4%	0.6%	2.3%	0.7%	2.3%	0.7%	4.1%	2.6%	5.5%	4.8%	1.1%	0.5%
EYR		1.02	1.01	1.02	1.01	1.03	1.01	1.05	1.04	1.41	2.93	1.03	1.03
ELR		41.50	175.83	42.58	144.32	42.11	142.05	23.26	37.60	17.03	19.69	90.29	195.76
ESI		0.02	0.01	0.024	0.007	0.024	0.007	0.05	0.03	0.08	0.149	0.011	0.005

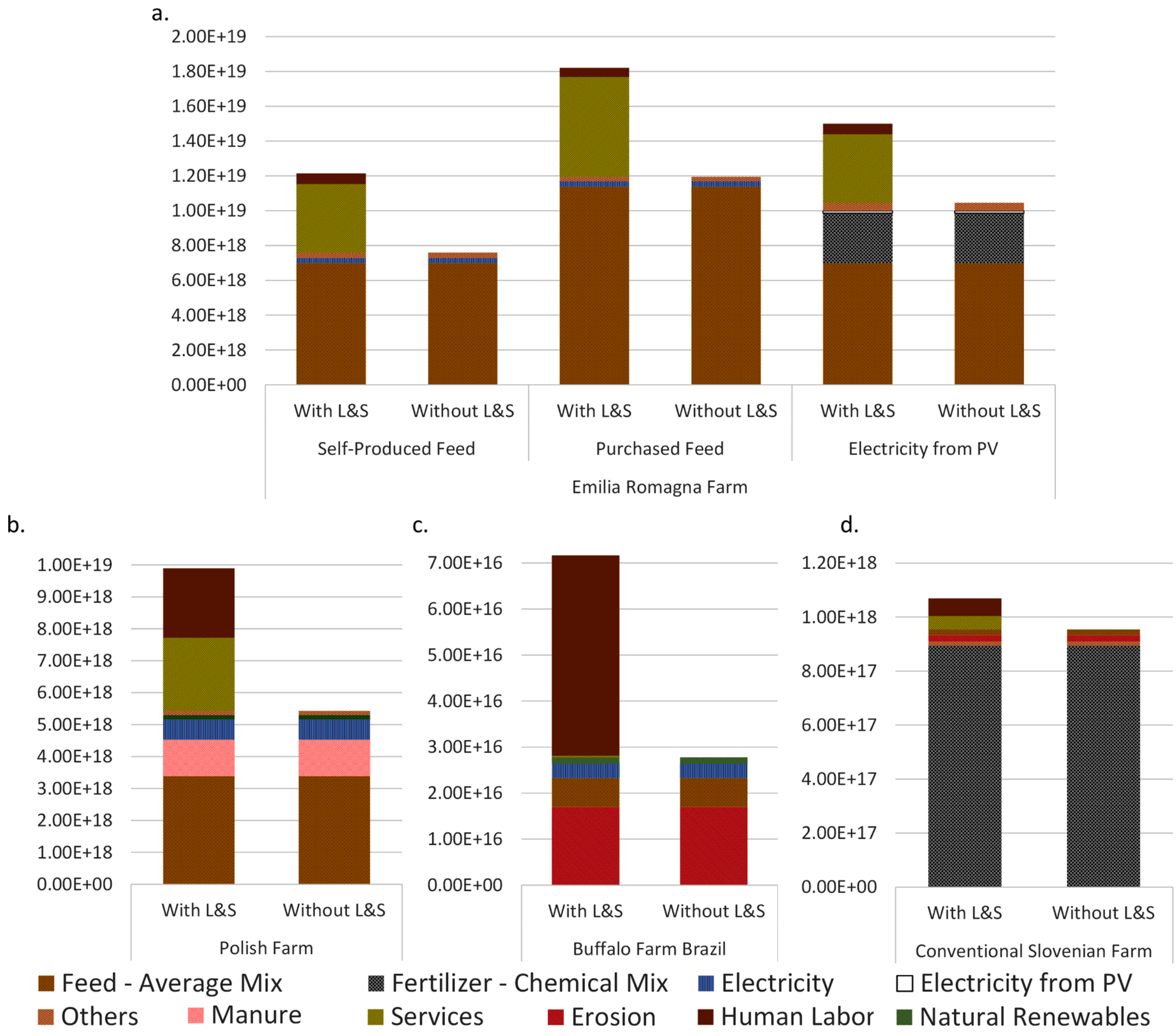

Fig. 7. Emergy inputs (sej $year^{-1}$) by percentage of milk composition produced in a. Emilia Romagna Italian farm and scenarios, b. Polish Farm, c. Buffalo farm in Brazil, and d. Conventional Slovenian Farm, highlighting the percentage of the main inputs.

or larger scales (using purchased manure means reuse at a larger scale – open loop). Indeed, when used as fertilizer, the manure produces positive environmental feedbacks. Instead, if the manure is considered only for energy valorization (biogas production), part of its potential exergy is lost and cannot be reused. The present study overcomes the limits of circularity assessment often disregarded in literature studies due to the invisibility of closed loops of materials when evaluated by linear designed methods. As expected, from the environmental perspective, the **chemical fertilizers** scenario is the worst productive system, for which dispiriting policies are needed.

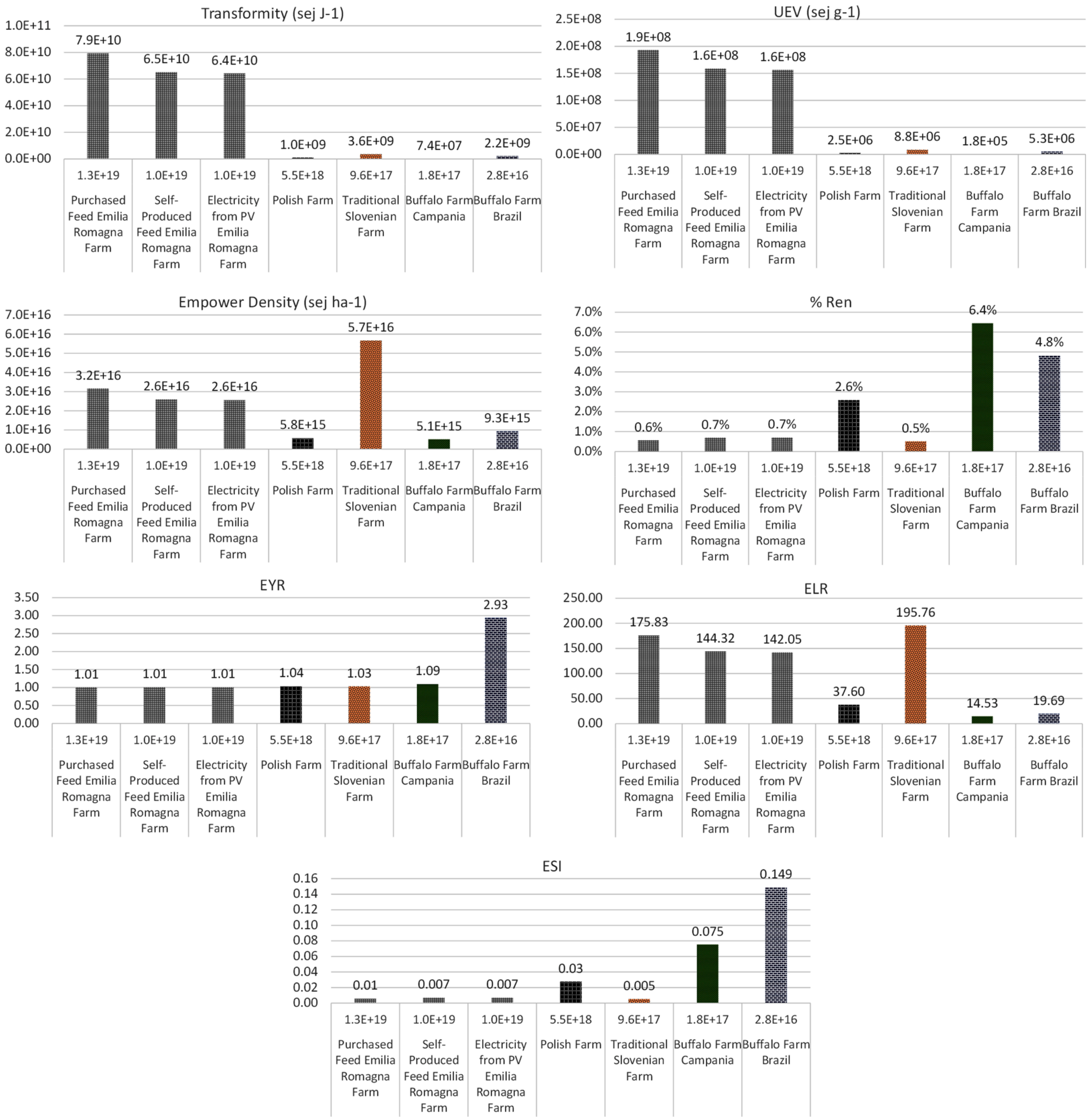

Fig. 8. Emergy indicators of the milk produced in the evaluated farms, organized in decreasing value of U (without L&S).

Fig. 8 shows the comparison among all investigated milk farms only without L&S following the decreasing order of U value. The results without L&S allow the comparison of studies located at different countries/regions, avoiding the local impact of currency exchange, product prices, local labor regulations, and the investigated time period, specific for each studied system.

Among all evaluated farms, the milk produced by the buffalo farm within Campania Region (analyzed in Fig. 8 only as business-as-usual scenario – **self-produced manure**) has the lowest UEV and highest renewability among all evaluated case studies, indicating that fewer natural resources are requested per each kg of milk produced, even if most of the processes involved are still based on fossil resources and imported goods (low EYR values). Thus, results show that the buffalo farm within Campania Region is the most efficient milk system producer, even if it still depends on fossil resources (imported inputs from the economy).

The milk produced by the **buffalo farm in Brazil** presents the best EYR value due to the low import of resources from the main economy and lower reliance on fossil fuel-based processes (Fig. 8 and Table 8). The ELR indicator of the milk produced by this farm is affected by the erosion of pastures (nonrenewable resource - N) due to the soil stress caused by the exclusive buffalo grazing in the absence of pastures management (only free grazing). Buffalo farm in Brazil represents a self-sufficient model, which respects the ecosystem's natural cycling processes and meets the energy requirements for production within its boundaries, instead of forcing productivity seeking profits (Ripoll-Bosch et al., 2014).

The **Polish Farm** also presents good environmental performance due to organic fodder cultivation, which uses manure instead of chemical fertilizers, with sufficient land (pastures) to provide natural resources needed for milk production. However, environmental load (ELR) is 158% higher than the buffalo farm within Campania Region (**self-produced manure** scenario) due to the erosion of pastures and the need for purchased feed mix to complement the cattle diet, demanded to support the highest milk productivity per animal. On the other hand, the **conventional Slovenian Farm** is an intensive dairy farm without sufficient area to supply its demands for natural resources (highest Empower Density and Environmental Load).

The comparison (Fig. 8) highlights the worst performance in natural resources consumption for the milk produced by the Emilia Romagna Farm, Italy (Ghisellini et al., 2014a). On the other hand, the **electricity from PV** scenario presented slightly better results due to higher renewability (%REN) and less dependence on fossil fuels (ESI). However, the difference between the latest and the **self-produced feed** scenario cannot be noted except after the second decimal digit. From the environmental point of view, none of the three scenarios of the Emilia Romagna farm proved to be effectively sustainable. However, the overall results showed that material and energy efficiency improvements need careful evaluation. Thus, from the environmental perspective, the suggested improvements are not effectively related to sustainability.

5. Conclusions

This study firstly evaluates the natural resource consumption of Campania Region dairy livestock farms by applying the Emergy Accounting (EMA) method to average statistical data. EMA is then applied to a local dairy system, a buffalo Farm within Campania Region, based on primary data and different in–farm fertilization scenarios. Finally, results are compared to other national and international studies from the scientific literature to identify the best-performing systems and understand potential environmental improvements. In particular, the focus was placed on the avoided load generated by the reuse of by-products (manure) as fertilizer instead of relying on chemical fertilizers from a circular economy perspective.

The regional assessment of milk production shows feed as the most impacting input flow, due to the embodied energy of fertilizers, still intensively used in fodder production in Italy, while the buffalo farm in Campania Region under the **self-produced manure** scenario appears to be the most efficient milk production system from a donor side perspective (less resource use per unit of product). Due to free pasture grazing, the buffalo farm in Brazil shows the environmental benefits of the self-sufficiency model of production.

These results clearly show the potential of EMA in becoming a management tool for public policies, supporting the stakeholder's decision to promote sustainable processes. Sustainability cannot be only based on economic profitability (intensive production systems), disregarding social and environmental perspectives in line with circular principles, as highlighted by the investigated system of the buffalo farm in Campania Region (self-produced manure). Considering sustainability as preserving ecosystems for future generations and reducing the impacts of climate change, the self-sufficient production model (buffalo farm in Brazil) shows more significant results. Thus, the public policy's priority should encourage the implementation of circular economy practices (such as reuse, recycling, and reduction) and ecological management to preserve the environment. The environmental assessment method (EMA) should not be disregarded because it can capture quality differences in the driving flows. The detailed analyses of the three scenarios for the Campania Region buffalo farm shed light on the enormous impacts generated by a milk production system based on linear intensive production pattern (chemical fertilizers scenario) and the much better performance of the two circular manure-based patterns at different models (use of self-produced manure scenario and open-loop purchased manure scenario). Although the EMA approach was applied only to the circular pathway of manure, the procedure can be applied to all circular patterns and flows with expected similar results. The updated emergy algebra procedure used in this study allows an appropriate evaluation of circularity by avoiding double-counting of input flows and correctly allocating driving resources to by-products. However, future studies are needed to continually assess the implications of assumptions and estimates required for the emergy calculations linked to local primary data collection (renewable and nonrenewable) and the UEVs (used to transform useful energy from inputs and its stocks), enabling greater transparency in the calculation of indicators and, consequently, greater dissemination of the EMA method.

CRediT authorship contribution statement

M. Oliveira: Formal analysis, Investigation, Validation, Writing – review & editing. **A. Zucaro:** Formal analysis, Investigation, Validation, Writing – review & editing. **R. Santagata:** Formal analysis, Investigation, Validation, Writing – review & editing. **S. Ulgiati:** Conceptualization, Project administration, Funding acquisition, Validation, Writing – review & editing.

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.To the best of our knowledge, no conflict of interest, financial or other, exists. We have included acknowledgements and funding sources after the conclusion.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ecolmodel.2021.109795.

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