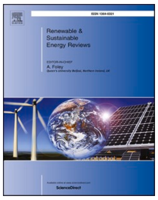
Renewable and Sustainable Energy Reviews 148 (2021) 111314

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser



Circular economy in the agro-industry: Integrated environmental assessment of dairy products

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ARTICLE INFO

Keywords:
Environmental assessment
Life cycle assessment
Emergy accounting
Urban systems
Dairy products
Circular economy
Integrated framework
LEAF

ABSTRACT

Bio-circular strategies to improve production and consumption can be the answer to decrease the current environmental pressure of the dairy sector. Environmental impacts are related to the extensive fodder production with intense use of fertilizers, greenhouse gasses emission from cattle and fossil fuels. To understand and measure the burdens of a dairy production chain (particularly buffalo mozzarella cheese, a specialty of the Campania Region, Italy), the Life Cycle Assessment and Emergy accounting Applied Framework (LEAF) was applied. Many studies evaluated dairy systems using single methods, which are unable to capture all sustainable perspectives. The LEAF evaluation encompasses an Ex-ante LCA (Life Cycle Assessment) to identify the hotspots and suggest feasible improved scenarios of the investigated case study. Followed by EMA (EMergy Accounting) and Ex-post LCA applications, LEAF assures the feasibility of the proposed solutions and verifies the reduction of the environmental burdens towards increased sustainability. Two different scenarios were built based on the identified hotspots (cleaning products and electricity): (i) a technological improvement (dealing with cleaning processes methods), (ii) an eco-efficiency perspective (fossil energy replaced with renewable alternatives). Additionally, viewpoint shifting scenarios based on (iii) different allocation procedures were proposed to discuss crucial methodological issues. Results showed that technological improvements provide the best environmental performance, with lower emissions and better Emergy indicators, and better work conditions. However, the use of a more renewable electricity mix can deliver similar environmental gains. The change of perspective in the last scenario highlighted that multi-output issues should be carefully treated to avoid misleading results.

1. Introduction

In 2018 more than 50% of the world's population lived in urban areas. Estimations pointed out increasing urban concentrations due to the exponential growth of world population combined with the migration from rural to urban areas and the low percentage of increment of the rural inhabitants in the last decades [1–3]. By 2050, cities will be responsible for consuming 80% of the food produced worldwide [4]. However, more than 30% of all food produced is wasted and lost [5]. The food chain, at the retail and consumer levels, leads these statistics with 40% of wasted and lost food - for the dairy sector, this percentage achieves 60% at consumption level [6–8].

1.1. Towards more resilient cities

The current challenge towards more resilient cities consists of closing open links between resources and demand. Due to the complex metabolism of urban systems, the potential of resources is most often ignored. For this reason, urban systems require an integrated analysis of multiple aspects [9,10], from energy and materials flows, information, consumption of resources, and all interactions between humans and non-human components, over the entire production process. Only an integrated assessment can adequately evaluate the consumption of resources, emissions, and waste pathways on a broader scale, as well as potential cycling and recovery [11–14].

The opportunities that holistic assessments of urban systems can

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https://doi.org/10.1016/j.rser.2021.111314
Received 6 October 2020; Received in revised form 27 May 2021; Accepted 5 June 2021

List of abbreviations including units and nomenclature:

%REN	Percentage of Renewability
€	Euro
BAU	Business As Usual
CIP	Cleaning-in-Place
DOP	Protected Designation of Origin (Denominazione d'Origine Protetta – Italy)
ELR	Environmental Loading Ratio
EMA	Emergy Accounting
ESI	Environmental Sustainability Index
EYR	Emergy Yield Ratio
EU	European Union
F	Imported nonrenewable inputs
FEP	Freshwater eutrophication potential
FETP	Freshwater ecotoxicity potential
FSP	Fossil resource scarcity potential
g/kg	Grams/Kilograms
GWP	Global warming potential
HCTP	Human carcinogenic toxicity potential
HNTP	Human non-carcinogenic toxicity potential
IGP	Indication of Geographic Protection (Indicazione Geografica Protetta – Italy)
ILCD	International Reference Life Cycle Data
IRP	Ionizing radiation potential
ISO	International Organization for Standardization
J	Joules
kWh	kilowatt-hour
L	Liter
L&S	Labor and Services
LCA	Life Cycle Assessment
LEAF	Life Cycle Assessment & Emergy Accounting Applied Framework
LUP	Land use potential
m/s	Meters per second
m^2	Square meters
m^3–	Cubic meters
MEP	Marine eutrophication potential
METP	Marine ecotoxicity potential
MSP	Mineral resource scarcity potential
N	Nonrenewable inputs
ODP	Stratospheric ozone depletion potential
OFHP	Ozone formation, Human health potential
OFTP	Ozone formation, Terrestrial ecosystems potential
PMFP	Fine particulate matter formation potential
Prod.	Production
R	Renewables inputs
ReCiPe	life cycle impact assessment method
ReTraCE	Releasing the Transition towards the Circular Economy
sej	solar emjoules
T	Tones
TAP	Terrestrial acidification potential
TETP	Terrestrial ecotoxicity potential
U	Total Emergy
UEV	Unit Emergy Value
WCP	Water consumption potential
yr	year

identify may promote the achievement of several Sustainable Development Goals, among which: achieve food security, which means to guarantee food to all population, through the promotion of sustainable agriculture (SDG 2); sustainable and inclusive industrialization (SDG 9); and finally sustainable consumption and production patterns (SDG 12), to build resilient infrastructures and ensure wellbeing (SDG 3) [15].

Cities are connected to, and are dependent on, the surrounding rural environment and influence the market and the industrial food processes [16]. To meet the increasing demand for food from the rising world population, industries focused on increasing productivity during the past decades, using harmful methods to human health and the environment. The latter risk is related, for example, to the massive use of chemicals on extensive monocultures, carbon emissions, and water consumption associated with the industrialized products. These patterns replace natural ingredients for cheaper options, producing the so-called ultra-processed food, usually rich in calories, added sugar, sodium, and unhealthy fats, and deficient of micronutrients as fibers, proteins, and vitamins, in disagreement with the recommended intake for a balanced and healthy diet [4,17,18].

In this sense, the food production chain is a sensitive subject for the potential application of the bio-circular economy principles towards the sustainability challenge of integrating social, economic and environmental perspectives through the efficient use of resources. In order to diminish unprecedented pressure on the environment and resource consumption and reduce the impact on climate change, biodiversity, water and land availability, and finally, pollution levels, waste generated by production patterns are recognized as potential secondary raw materials. Circular Economy (CE) emerged as a restorative and regenerative production system to replace the linear industrial processes, extending the lifetime of resources, materials and products flows to integrate the bioeconomy concept [19–23].

1.2. *Exploring potential benefits of bio–circular economy*

This work captures the opportunities of bio-circular economy strategies by using Life Cycle Assessment (LCA) [24–26] and Emergy Accounting (EMA) [27] evaluation methods, from anthropocentric and biosphere perspectives, respectively. The proposed framework procedure integrates LCA and EMA in the LEAF approach (LCA & EMA Applied Framework) [28], yielding different conclusions through the simultaneous and sequential application of these two assessment methods. LCA evaluates the resources under human control, while EMA expands the time scale, considering the biosphere work needed for resource generation. LCA results highlight the burdens on the environment caused by human activities, while EMA accounts for ecosystem services across space and time scales, as well as societal dynamics (know–how, information, education) and infrastructures (transportation, health, power, governance) embedded in direct and indirect labor [24,28,29].

Some bio-circular strategies in the agro-industry are ancient practices, as the reuse of manure as fertilizer and the reuse of whey from the cheese production as a supplement for cattle feeding [30–32], widely investigated in this work. The proposed assessment methods, LCA and EMA, have been largely used to evaluate dairy products. However, a proper evaluation of the dairy supply chain is still required to overcome the limits of single method approaches and explore multiple sustainable perspectives consistent with the complexity of the investigated system [14].

From an anthropocentric perspective (processes under human control), LCA was applied in several studies highlighting Greenhouse Gases (GHG) emissions and other pollutants generation during dairy production [33–41]. Compared to other food categories, livestock-based products have been recognized among the most relevant contributors to GHG emissions, with organic procedures performing slightly better than conventional ones [42]. From a biosphere perspective (EMA), several studies focused on multicriteria analyses were performed

[44–50]. The benefits of multi-scale analysis have been pointed out in several assessments dealing with dairy systems in Mali (the western African savannah), Reunion Island (a French territory in the Indian Ocean), and Poitou-Charentes and Bretagne (both west France Regions) [43]; dairy farms from different Italian regions have been compared each other and with a farm in Poland, discussing the impacts of diverse management options, by means of a "multicriteria multi-scale biophysical assessment method" [44]; the performance of Slovenian dairy sector characterized by different farm size and intensity has been investigated by means of integrated socio-economic and environmental assessment (EMA) methods [45]; sustainable and resilient dairy farms in Slovenia were also analyzed by integrating EMA into conventional decision-making approaches [46]. In Brazil, trade-offs between productivity and environmental burdens have been discussed by means of EMA evaluation of clustered milk productive systems [47]. Different grazing scenarios were modeled to assess the behavior of natural lands and evaluate the sustainability of grasslands in China [48], highlighting that the small-scale grazing systems provide more environmental benefits. Still in China, the social reasons that prevent the conversion from intensive grazing to human-managed pastures were discussed, supported by EMA indicators [49]. The most recent study calls for a multi-scale analysis to deeply understand the environmental performance of biogas generation from farms' byproducts in Italy [50]. The first attempts to integrate EMA and LCA methods were around 2013. For the first time, the necessity to evaluate processes and products from the resource's consumption perspective, accounting for the work of nature to produce them, was discussed [29,51]. LCA and EMA share similarities in their evaluation procedures, based on inventory data, calculation of indicators, and results interpretation. The integration faced criticism due to the EMA uncertainty of data used and its lack of standardization. However, EMA improves LCA assessments by quantifying the work of nature needed to drive the evaluated process or product. The integration is symbiotic, as LCA inventories can improve EMA calculations [29]. Further, in order to integrate the Life Cycle Inventories database in the EMA calculations procedure, SCALEM software was developed [51,52]. Recently, a special type of paper, which is produced in a traditional factory in Amalfi (Campania Region, Italy), was evaluated by giving rise to the sequential application of LCA and EMA methods (LEAF, as previously mentioned). LEAF is, through the synergic calculation, evaluation and analysis of results, a useful tool to focus on energy, materials, and environmental improvement options [28].

1.3. Main goals of the present study

In this work, the LEAF procedure is applied to evaluate the agro-industry productive sector in the Campania Region (Italy) by assessing the buffalo mozzarella production and cheese coproducts. Italian dairy products are known worldwide for their high quality and variety, leading to protected and regulated denominations of origin (e.g., DOP, IGP) and production protocols. The dairy sector is a significant example of a complex system, differentiated primarily on demand and supply segments, and increasingly integrated with the European Union (EU) and international markets. In the Campania Region, dairy production is an important part of the agri-food economy in terms of economic value generated on national and international markets [53] and related to the quality and variety of products. Moreover, Italian production and consumption patterns, grounded on the Mediterranean diet, provide opportunities to understand sustainable local food systems that also safeguard traditional knowledge of food and culture [54].

Therefore, the novelty of this work is to improve the integration between LCA and EMA within the LEAF procedure through bio-circular economy strategies to evaluate the agro-industry in a multi-dimensional perspective suggesting viable solutions towards sustainability. In the present study, typical dairy products (in Campania Region, Italy) are evaluated through the sequential application of LCA and EMA (LEAF) in a two-fold perspective: (1) evaluating the environmental performance of the production chain and (2) suggesting a methodological improvement for the integration of LCA and EMA in LEAF procedure. The evaluation is carried out considering the current business as usual dairy production and suggesting three different scenarios, characterized by: (i) technological improvements (on cleaning processes); (ii) eco-efficiency perspective (fossil energy sources replaced with renewable alternatives); and finally (iii) viewpoint shifting scenario (changing the allocation procedure). Since the management and planning of the production lead to an actual transition towards a Circular Economy [55,56], this study defines possible improvements into the buffalo dairy production chain and provides insights into the development of the sustainable agro-industry [57].

2. Materials and methods

2.1. Description of the dairy process under study

The investigated company, an average size dairy farm, is located in the Campania Region, Caserta Province, Italy. It is a family-managed factory, started in 1991 to produce cheese from purchased milk. Then, in 1995, the family expanded its activity to the entire productive chain by acquiring a dairy farm, becoming responsible for the whole process, from fodder production to milk processing into dairy products (Fig. 1).

The data were collected through field visits and interviews with the company owners. Background and missing data have been assumed based on scientific literature and specific databases, as shown in Table 1.

2.1.1. Fodder production

The 34 ha cultivated area produces around 720 tons per year of fodder mix that is the basis of buffalo feed: corn (24%), ryegrass (7%), alfalfa (25%), and sorghum (44%). The main fodder production phases are soil preparation, seeding, irrigation, mowing, and harvesting. The company self-supplies fertilizers, seeds, water for irrigation, and machinery data (Table 1). Manure, from the livestock phase, is used as fertilizer, and the amount was calculated using the average annual value of manure produced by buffalos (Table 1).

2.1.2. Livestock

The intensive breeding of 540 heads - 357 female buffaloes, without grazing, produces 2700 L of milk per day. A correct nutritional balance of feed nutrients is necessary to produce milk with the required fat and protein rates and maintain the productivity to deliver the buffalo mozzarella and other coproducts. Supplementary nutrition is provided, based on straw and additional feed, to achieve the mineral nutritional requirements. The quantity and frequency of feed and water supplied depend on both the growth livestock phases and the lactation period. The buffaloes are milked through a mechanical herringbone milking machine twice a day, and the milk is stored in stainless-steel refrigerated tanks with controlled temperature. The produced manure is partially reused as fertilized in the fodder production (less than 4%), and the most significant part is discarded.

2.1.3. Cheese-making

The milk is filtered and undergoes a series of processing steps to produce the buffalo mozzarella and also medium and high seasoned cheeses, ricotta, butter, yogurt, and cream. Whey is a coproduct of buffalo mozzarella; the most considerable part is disposed of, and only a tiny amount is used back to feed the buffaloes (less than 4%).

Fig. 2 details the buffalo dairy production, highlighting the current circular pattern among the phases.

2.2. Assessment methods2.2.1 Life Cycle Assessment (LCA)

LCA is a worldwide standardized method for the environmental assessment of human-dominated processes, defined by ISO standards and the ILCD handbook [24–26] and focusing on the entire products' life

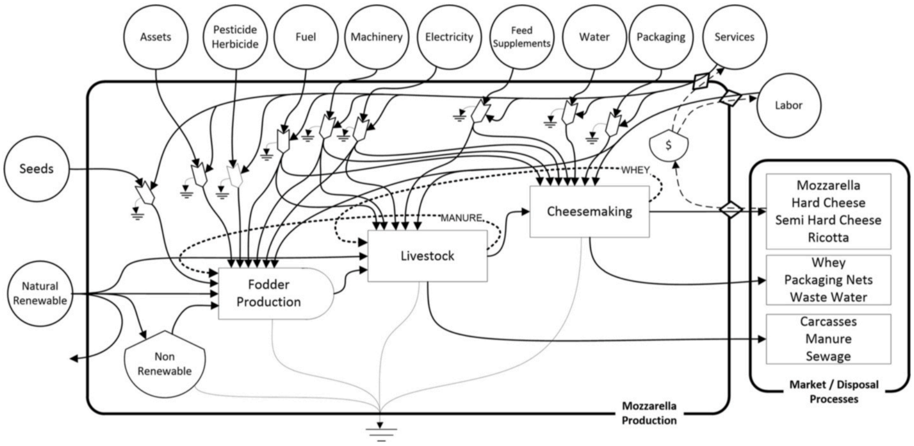

Fig. 1. System diagram of the studied buffalo dairy production: inputs, outputs, and flows are shown as the current production model, highlighting with dashed arrows the circular patterns already integrated into the production chain. The company encompasses fodder production, livestock, and the cheese-making phase (symbols based on system diagrams developed by H.T. Odum [58]).

cycle of products and functions, from resources extraction up to the final disposal in cradle-to-grave perspective. However, when recovery and recycling are included, LCA might present cradle-to-cradle perspective. LCA assesses the potential environmental impacts from the consumer-side perspective, analyzing the raw materials acquisition, airborne, water and soil emissions, and other environmental exchanges, including the effects on the ecosystems and human health through all life cycle stages. LCA indicators are provided for different impact categories, such as climate change, resources depletion, toxicity, and eutrophication defined by the implemented assessment method [72]. LCA is designed to be performed through four different phases: (1) goal and scope definition, (2) life cycle inventory, (3) life cycle impact assessment, and (4) interpretation of results [24,25]. The present work was performed by using the SimaPro software v.9.0.0.49 (https://network.simapro.com/rg) to set up the LCA model of the investigated process and implement the impact assessment calculations.

Regarding the data quality, multiple sources of input/output flows were used. Personal interviews (primary data) were integrated with bibliographic sources (secondary data). In detail, primary and site-specific data obtained from tailored questionnaires during field visits were used as foreground information. Moreover, background data (data related to energy generation, auxiliary material, extraction, and treatment of raw materials, manufacturing processes and impacts of waste management) were retrieved from the Ecoinvent database v.3.5 [73]. Obviously, LCA databases have pros and cons since they provide background data essential to perform a proper evaluation but sometimes data are not site specific. In order to overcome the limits of a professional dataset, an Italian national database is under development (Project Arcadia - https://www.arcadia.enea.it). The ReCiPe Midpoint (H) v.1.03 method [74] was used for the impact assessment, as it provides choices of different impact categories with the proper unit and the related characterization factors (Table 2).

This work focused on the main product of the evaluated company, the buffalo mozzarella cheese. Therefore, the LCA and EMA assessments were based on the buffalo mozzarella production. The selected functional unit was the annual mozzarella cheese production (1.2×10^{05} kg/yr). The investigated system boundary was based on cradle-to-gate approach, including all inputs and outputs to produce the 1.2×10^{05} kg of mozzarella cheese (Fig. 1).

2.2.1. Emergy Accounting (EMA)

EMA is an environmental accounting method to measure systems' performance considering the support of the natural ecosystem in delivering services or products. Total Emergy (U) is defined as the available energy (most often expressed in terms of solar energy) directly and indirectly needed to generate a product or a service and provided to a process as local and non-local, renewable and nonrenewable sources, goods, information, know-how, direct and indirect labor, the latter expressed as L&S (Labor and Services) [27,75]. A different hierarchical quality characterizes every accounted flow expressed through a coherent conversion factor (the UEV, Unit Emergy Value), converting all mass and energy items into Emergy flows, measured as sej (solar emjoules). The unit of the UEVs is sej/unit-of-flow. When a UEV is measured as sej/J, it is named transformity [27], equal to 1 by definition for the one related to solar radiation. The calculated Emergy flows are then summed up to obtain the total Emergy U driving the investigated system. The UEV of an output service/product is obtained dividing U by the related yield. Every transformation step reduces the available energy transferred for further transformations but increases its quality in terms of concentration of biosphere work per unit of the final product. Every Emergy value is related to a Global Emergy Baseline (GEB), representing the total annual renewable Emergy driving the biosphere. Emergy calculations in this work refer to the most recent 12.0×10^{24} seJ/yr GEB [76]; all UEVs related to other GEBs were updated accordingly.

Grouping resources used by transformations as locally available renewable (R) and nonrenewable (N), imported nonrenewable (F), labor and services (L&S) makes possible the calculation of several indicators, among which:

- Percentage of Renewability: $\%REN = R+(L_R + S_R)/U$, the fraction of Emergy from renewable sources, where L_R and S_R are the renewable fractions of L&S.
- Emergy Yield Ratio: $EYR = U/(F + S_N + L_N)$, expresses the amount of local resources made available by an external investment, where L_N and S_N are the nonrenewable fractions of L&S. The lowest value is 1 when all the Emergy driving a system is from the outside.
- Environmental Loading Ratio: $ELR = (N + F + L_N + S_N)/(R + L_R + S_R)$, indicating the load on the environment as the ratio of nonrenewable and imported resources to renewable ones available locally.
- Environmental Sustainability Index: $ESI = EYR/ELR$, a composite indicator of the self-reliance of a system (numerator) and the environmental loading.

2.2.2. LEAF: an integration of LCA and EMA frameworks

LEAF is an integrated procedure that provides a multi-perspective analysis system through the sequential application of LCA and EMA evaluation methods [28]. The sequential integrated approach aims to achieve a holistic perspective through the joint application of the LCA consumer-side perspective and the EMA donor-side perspective: LCA boundaries include what is under human control, while EMA expands

Table 1
Inventory.

Item	Unit	Value	Type of data[a]	Reference
Inputs				
Renewable				
Sun insolation	$J/m^2/yr$	6.10×10^{09}	ED	[59]
Geothermal heat	$J/m^2/yr$	1.61×10^{05}	ED	[59]
Wind velocity	m/s	2.60×10^{00}	ED	[59]
Rainfall	m/yr	1.18×10^{00}	ED	[60]
Evapotranspiration water	%	0.40×10^{00}	ED	[60]
Crops Land Use area	ha	3.40×10^{05}	MD	
Erosion rate	$g/m^2/yr$	2.50×10^{03}	ED	[61]
Materials				
Diesel and heavy fuel	kg/yr	5.87×10^{04}	MD	
Diesel price	€/L	0.78×10^{00}	ED	[62]
Electricity	kWh/yr	1.83×10^{05}	MD	
Electricity price	€/kWh	0.19×10^{00}	ED	[63]
Electricity from PVP price	€/kWh	5.20×10^{-02}	ED	[64]
Natural Gas	m^3/yr	6.06×10^{04}	MD	
Natural Gas Price	€/m^3	5.70×10^{-02}	ED	[64]
Water (from aqueduct)	m^3/yr	3.74×10^{04}	MD	
Water price	€/m^3	2.16×10^{00}	ED	[65]
Seeds	kg/yr	1.47×10^{03}	MD	
Seeds Price	€/kg	8.16×10^{-01}	ED	[66]
Fertilizers				
Nitrogen	kg/yr	9.18×10^{02}	MD	
Nitrogen Fertilizer Price	€/kg	1.85×10^{-01}	ED	[67]
Urea	kg/yr	9.20×10^{02}	MD	
Urea Price	€/kg	3.70×20^{-01}	ED	[67]
Straw	kg/yr	4.53×10^{03}	MD	
Straw Price	€/kg	8.50×10^{01}	ED	[62]
Mineral Feed	kg/yr	1.46×10^{02}	MD	
Mineral Feed Price	€/kg	3.10×10^{01}	ED	[68]
Pesticides/Herbicides	kg/yr	7.50×10^{00}	MD	
Pesticides Price	€/kg	6.71×10^{00}	ED	[69]
Detergents	kg/yr	9.00×10^{04}	MD	
Detergents Price	€/kg	1.54×10^{00}	ED	[69]
Disinfectants	kg/yr	5.40×10^{01}	MD	
Disinfectants Price	€/kg	2.99×10^{00}	ED	[69]
Nitric Acid	kg/yr	3.60×10^{01}	MD	
Nitric Acid Price	€/kg	6.80×10^{00}	ED	[69]
Machinery	kg/yr	2.19×10^{02}	MD	
Machinery Price	€/kg	1.17×10^{01}	ED	[70]
Human Labor		person/yr	1.00×10^{02}	MD
Output				
Intermediate Fodder Production				
Corn	kg/yr	1.80×10^{05}	MD	
Alfalfa	kg/yr	3.14×10^{05}	MD	
Sorghum	kg/yr	4.80×10^{04}	MD	
Ryegrass	kg/yr	3.14×10^{05}	MD	
Intermediate Livestock Production				
Carcasses	kg/yr	1.00×10^{05}	MD	
Manure	kg/yr	2.22×10^{06}	ED	[71]
Raw milk	kg/yr	9.65×10^{05}	MD	
Cheese-making Production				
Buffalo mozzarella	kg/yr	1.21×10^{05}	MD	
Hard cheese	kg/yr	2.95×10^{03}	MD	
Ricotta	kg/yr	3.42×10^{04}	MD	
Butter	kg/yr	6.79×10^{02}	MD	
Semi-hard cheese	kg/yr	3.65×10^{03}	MD	
Whey	kg/yr	1.00×10^{06}	MD	

[a] MD (measured data): primary data from tailored questionnaires collected during field visits; ED (estimated data): secondary data collected from scientific literature, Ecoinvent database v.3.5 and specialized websites.

boundaries over biosphere-wise space and time scales, acknowledging the generation of resources and services from ecosystems and societal processes through human labor and services [29,77,78]. The LEAF integrated procedure is performed in three steps (Fig. 3):

a. Ex-ante LCA, to investigate the environmental burdens of the system and recognize the hotspots to be addressed.
b. EMA scenarios to explore the environmental performance of different proposed solutions modeled around the selected hotspots to understand the environmental viability of solutions.
c. Ex-post LCAs of the proposed scenarios to assess whether the hotspots have been removed thanks to the proposed solutions and the overall burdens have been reduced.

LEAF investigates several improvement scenarios to compare the feasibility, process performances, and environmental burdens. Scenarios are built on several improvement hypotheses: for instance, better management in the process as it is; resource optimization perspective, where improvement is achieved through the best available technologies; and an eco-efficiency perspective, where nonrenewable resources are dropped in favor of renewable ones. However, LEAF scenarios can be chosen according to the needs of the investigated process and the audience for which the study is intended. Anyhow, the sequential multi-perspective application of the two methods provides a deeper understanding of the investigated system by offering a feasible environment-friendly solution to be achieved.

In order to solve the multi-outputs issue and assign the environmental load to each identified coproduct of the buffalo dairy production, this work applied the exergy allocation to LCA assessment [79,80] (Table 3).

A higher exergy value indicates a higher work potential. Commonly within the LCA method, the largest allocation fraction is assigned to the main function or product, recognizing the reason for which a process is conducted. This represents a very anthropocentric point of view [81]. Coproducts generated in the investigated system, even if showing low or no economic value, can play an essential role as feedback in the same system (fertilizer or animal feed) or as input for another supply chain (pharmaceuticals, newborn nutrition, athlete supplements, and food ingredients). Therefore, a careful evaluation is needed to deal with a complex system also characterized by different co-products.

Briefly, the LEAF analysis consists of selecting the main hotspots based on the Ex-ante LCA, focusing on those items (inventory inflows) that affect the largest number of impact categories to the largest average extent (%). Solutions/scenarios are, then, proposed and evaluated via EMA and Ex-post LCA, applied to all identified scenarios. EMA evaluations are expected to point out which suggested improvements have the best (and most affordable) environmental performance in terms of resource demand. At the same time, the Ex-post LCAs may verify if the identified hotspots/impacts have actually been removed or reduced. At the end of the Discussion session in this study, a comparison between the EMA and LCA scenarios is presented to contribute to the decision-making process.

3. Results

The main product of the investigated dairy company is the buffalo mozzarella cheese. Therefore, as highlighted in the Material and Methods section, the results of the LEAF procedure were showed and discussed concerning the main product (buffalo mozzarella cheese).

3.1. The ex-ante LCA

The Ex-ante LCA were carried out for the dairy production chain in the Campania Region (raw milk and mozzarella cheese production inventories related to the ex-ante LCA are shown in Tables A1 and A2 in Appendix). The total impacts linked to the annual buffalo mozzarella

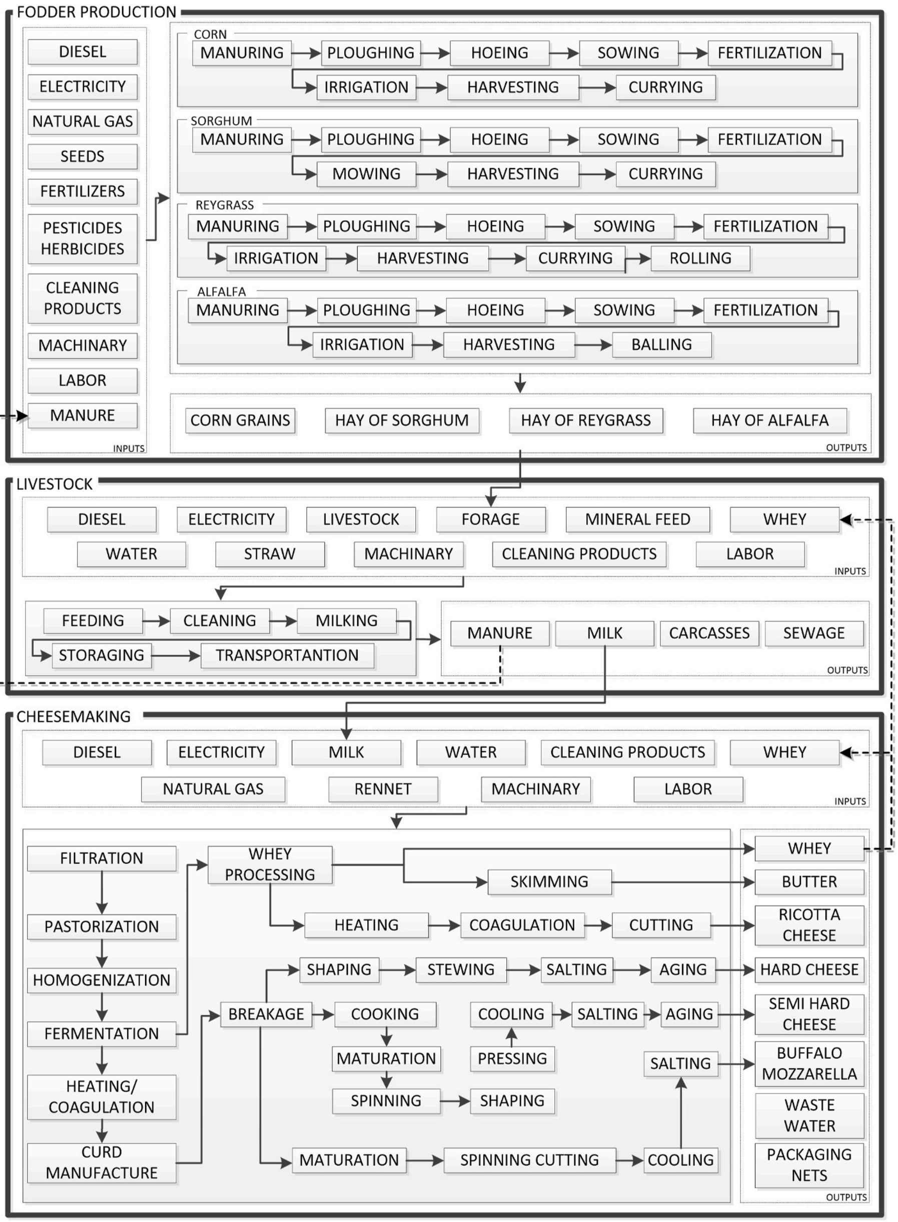

Fig. 2. Buffalo dairy production - from the fodder production until the final products, highlighting the circular patterns in dashed arrows.

cheese (Table 4) and the relative share from the different inputs (Fig. 4) allowed to identify the main hotspots of the investigated system.

Fig. 4 displays the percentage contributions of inputs to the characterized results. The main hotspots for all investigated impact categories are represented by the detergent used in the cheese-making process (43%: Sodium hydroxide 25% and Nitric Acid 18%). In this regard, the sodium hydroxide markedly contributed to FEP (51%), while Nitric acid results to be the main drivers of MSP (46%). The minimum contributions are respectively within ODP (1%) and MEP (2%). The raw buffalo milk, carrying the burdens of the fodder production and livestock steps, shows an average contribution of 24% across the investigated impact categories. The electricity from the Italian grid represents another significant contribution (20%). The local emissions, citric acid for cheese-making, natural gas, water, and machinery, all together, generated a relatively small average impact of about 13%, for the investigated impact categories.

Raw milk, the livestock phase's main output, is identified as a relevant hotspot due to a significant impact on the entire system's burdens. Fig. 5 shows the percentage contributions to the total environmental loads related to the livestock phase showing a significant contribution to fodder production (used as buffalos feed) and electricity consumption. The negative contribution to the HNTP impact category is related to the significant absorption of metals (mostly zinc, cadmium, and lead) from the soil due to the chemical fertilizers in oat production, purchased from the market to correct buffalo's nutrition balance. According to the company's management staff, changes in the buffalo feed mix could not be easily implemented to maintain milk productivity. Therefore, no adjustment has been modeled for buffalo feedstuff. Instead, an improvement to the raw milk production phase was considered by replacing fossil with renewable electricity mix (eco-efficiency perspective Scenario, also named Scenario 2) as electricity is also a hotspot in this analysis.

Based on the results achieved from the Ex-ante LCA analyses and considering the needs of the investigated buffalo mozzarella cheese factory, two scenarios were built based on selected hotspots, followed by a third scenario related to methodological issues:

Table 2
Recipe Midpoint (H) impact categories.

Impact category	Abbreviation	Unit
Global warming potential	GWP	kg CO_2 eq
Stratospheric ozone depletion potential	ODP	kg CFC11 eq
Ionizing radiation potential	IRP	kBq Co-60 eq
Ozone formation, Human health potential	OFHP	kg NO_x eq
Fine particulate matter formation potential	PMFP	kg PM2.5 eq
Ozone formation, Terrestrial ecosystems potential	OFTP	kg NO_x eq
Terrestrial acidification potential	TAP	kg SO_2 eq
Freshwater eutrophication potential	FEP	kg P eq
Marine eutrophication potential	MEP	kg N eq
Terrestrial ecotoxicity potential	TETP	kg 1.4-DCB
Freshwater ecotoxicity potential	FETP	kg 1.4-DCB
Marine ecotoxicity potential	METP	kg 1.4-DCB
Human carcinogenic toxicity potential	HCTP	kg 1.4-DCB
Human non-carcinogenic toxicity potential	HNTP	kg 1.4-DCB
Land use potential	LUP	m^2a crop eq
Mineral resource scarcity potential	MSP	kg Cu eq
Fossil resource scarcity potential	FSP	kg oil eq
Water consumption potential	WCP	m^3

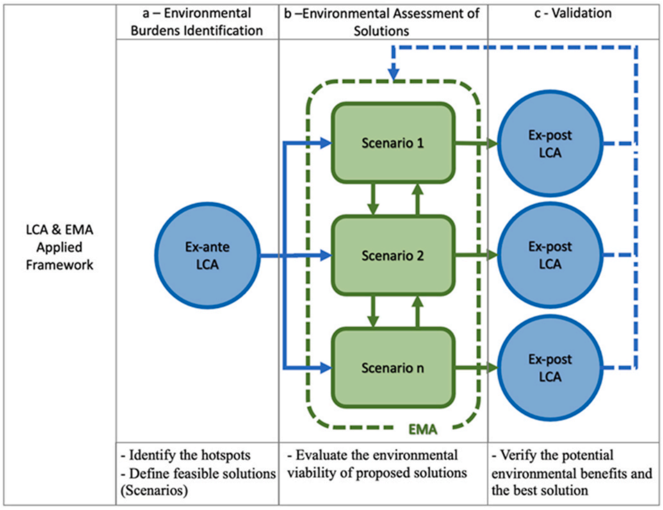

Fig. 3. Proposed LEAF Framework based on the integration of Life Cycle Assessment (LCA) and Emergy Accounting (EMA) methods.

Table 3
Exergy allocation of coproducts.

Allocation livestock phase	Mass (t)	Exergy content (J)	Allocation (%)
Raw buffalo milk	965	5.4×10^{12}	30%
Dead animals for meat	100	1.1×10^{12}	6%
Manure	2223	1.2×10^{13}	64%
Allocation Cheese-making phase			
Buffalo mozzarella	120.7	1.6×10^{12}	48%
Hard cheese	2.95	4.2×10^{10}	1%
Ricotta	34.19	3.6×10^{11}	11%
Butter	0.68	2.4×10^{10}	1%
Semi-hard cheese	3.65	6.8×10^{10}	2%
Whey	1000	1.2×10^{12}	37%

(i) Scenario 1: technological improvement scenario. Cleaning-in-Place (CIP)[1] process was considered to improve the cleaning efficiency by automated processing.

(ii) Scenario 2: eco-efficiency improvement scenario. The common Italian electricity mix is replaced by a 100% renewable electricity mix available in Italy[2]: hydropower (about 50%), geothermal power (about 24%), wind power (about 24%), and photovoltaic power (about 2%).

(iii) Scenario 3: viewpoint shifting scenario. This is a conceptual scenario starting from the usual Emergy algebra (no allocation to coproducts) and the most common procedure in LCA (economic allocation; physical allocation, such as energy, mass, or exergy). This scenario aims to test the validity of the above procedures by applying the LCA allocation procedures to EMA calculations, keeping the inventory unchanged. Therefore, we compare three sub-scenarios:
- BAU scenario: follows the Emergy algebra rules (no allocation procedure) and LCA standard allocation procedures.
- Economic allocation also to EMA - based on the monetary value of the different coproducts, as sometimes applied in LCA.
- Exergy allocation also to EMA – the total Emergy is assigned to each output flow according to its exergy content, as sometimes applied in LCA.

In scenario three, LEAF is not applied to investigate an improvement hypothesis but instead to account for methodological issues (results affected by different allocation procedures), pointing out the added value of the LEAF integrated framework. According to the LEAF procedures [28], after identifying the hotspots and defining the scenarios, the EMA evaluation was performed for each identified solution.

3.2. *The scenario 1*

Scenario 1 was built on the environmental burdens associated with the cheese-making cleaning facilities, mainly related to the heavy use of detergents and water. Thus, Scenario 1 suggested a technological improvement compared to the business-as-usual perspective. The alternative solution is the cleaning process automation, known as Cleaning-in-Place (CIP), which reduces up to 70% of the water and chemicals consumed in a cheese factory [82,83]. Inventories of Scenario 1 raw milk and mozzarella cheese production are shown in Appendix in Table A3 and Table A4, respectively.

EMA results for Scenario 1 (Fig. 6) show that 58% of U value is represented by direct human labor while 29% by indirect labor (L&S). The contribution (Fig. 6, left side) related to the other input flows, mainly related to the agricultural phase, appeared circumscribed (EMA results are reported in Table B1 in Appendix).

When L&S is not accounted for, the residual emergy is considered as 100% (right side of Fig. 6), highlighting the percentages of the other inflows (diesel, heavy fuels, and natural gas) that reach 64% of total U without L&S. Straw (consumed in the livestock phase as supplementary nutrition) and electricity strongly affect the U without L&S (18% and 15%, respectively), also due to the use of fossil resources (chemical

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[1] Cleaning phase is critical to the dairy industry, and to all food industries, in general. Cleaning-in-place technology is a well-known solution to optimize this process [94,95]. In one hand, due to the development of cleaning products and better knowledge about the optimal process parameters (temperature, chemicals concentration, flow rate) during the past decade, the CIP is recognized as an effective and cost effectively solution to assure the compliance to local regulations, increase products' safety and shelf life, and save resources. On the other hand, investments in infrastructure are needed, as well as the correct destination of the wastewater generated [96,97].

[2] According to NWG Report: http://www.nwgenergia.it/documenti/Relazione-Benefit-2018-Nwg.pdf.

Table 4
Characterized results related to the annual buffalo mozzarella cheese -Ex-ante LCA.

Impact category	Total	Local Emissions	Citric acid	Natural gas	Water	Machi-nery	Sodium hydroxide	Nitric acid	Raw Milk	Electricity
GWP	2.6×10^5	6.1×10^4	1.7×10^3	1.9×10^4	6.4×10^1	5.4×10^2	3.6×10^4	5.5×10^4	6.1×10^4	2.8×10^4
ODP	3.5×10^0	2.4×10^{-3}	5.4×10^{-3}	2.3×10^{-2}	3.1×10^{-7}	2.5×10^{-4}	3.8×10^{-2}	1.6×10^0	1.8×10^0	2.2×10^{-2}
IRP	1.0×10^4	0.0×10^0	2.3×10^2	1.2×10^2	2.1×10^{-1}	4.5×10^1	4.2×10^3	5.2×10^2	7.7×10^2	4.4×10^3
OFHP	5.3×10^2	9.3×10^1	3.2×10^0	3.6×10^1	1.5×10^3	1.4×10^0	9.0×10^1	9.9×10^1	1.5×10^2	5.8×10^1
PMFP	2.5×10^2	1.0×10^1	2.9×10^0	1.5×10^1	1.1×10^3	1.5×10^0	8.2×10^1	4.4×10^1	5.2×10^1	4.3×10^1
OFTP	5.4×10^2	9.3×10^1	3.3×10^0	3.8×10^1	1.6×10^{-3}	1.5×10^0	9.1×10^1	9.9×10^1	1.5×10^2	5.9×10^1
TAP	8.2×10^2	3.4×10^1	9.9×10^0	4.5×10^1	2.6×10^{-3}	2.9×10^0	1.4×10^2	1.9×10^2	2.7×10^2	1.3×10^2
FEP	4.0×10^1	0.0×10^0	7.6×10^{-1}	6.9×10^{-1}	4.8×10^{-4}	6.5×10^{-1}	2.1×10^1	4.3×10^0	2.7×10^0	1.1×10^1
MEP	1.3×10^1	0.0×10^0	1.0×10^0	4.8×10^{-2}	3.8×10^{-5}	3.5×10^{-2}	1.9×10^0	2.1×10^1	9.3×10^0	9.4×10^{-1}
TETP	2.9×10^5	0.0×10^0	3.6×10^3	3.8×10^3	1.6×10^0	1.0×10^4	1.1×10^5	8.7×10^4	1.9×10^4	6.5×10^4
FETP	4.6×10^3	0.0×10^0	4.4×10^1	5.6×10^1	2.6×10^{-2}	1.1×10^2	1.3×10^3	6.6×10^2	3.3×10^2	2.2×10^3
METP	6.2×10^3	0.0×10^0	5.9×10^1	1.1×10^2	3.6×10^{-2}	1.6×10^2	1.8×10^3	9.7×10^2	4.3×10^2	2.7×10^3
HCTP	4.2×10^3	0.0×10^0	6.0×10^1	2.5×10^2	2.1×10^{-1}	2.8×10^2	1.7×10^3	4.1×10^2	5.0×10^2	9.9×10^2
HNTP	9.0×10^4	0.0×10^0	1.1×10^3	1.5×10^3	5.8×10^{-1}	3.4×10^3	3.6×10^4	2.3×10^4	4.1×10^3	2.0×10^4
LUP	8.3×10^3	0.0×10^0	6.1×10^2	3.3×10^1	2.1×10^{-2}	1.6×10^1	7.4×10^2	2.0×10^2	5.4×10^3	1.3×10^3
MSP	4.7×10^2	0.0×10^0	4.8×10^0	2.2×10^1	6.7×10^{-3}	2.3×10^1	1.0×10^2	2.2×10^2	4.0×10^1	6.3×10^1
FSP	5.5×10^4	0.0×10^0	4.5×10^2	2.9×10^4	1.6×10^{-1}	1.1×10^2	9.0×10^3	4.8×10^3	3.6×10^3	8.1×10^3
WCP	3.6×10^3	0.0×10^0	1.4×10^2	-1.7×10^1	1.8×10^0	4.5×10^0	9.1×10^2	3.1×10^2	1.8×10^3	5.5×10^2

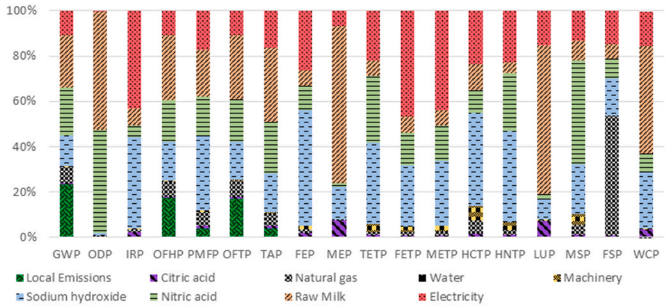

Fig. 4. Ex-ante LCA - characterized contributions of each input to the total impact. of the buffalo mozzarella production.

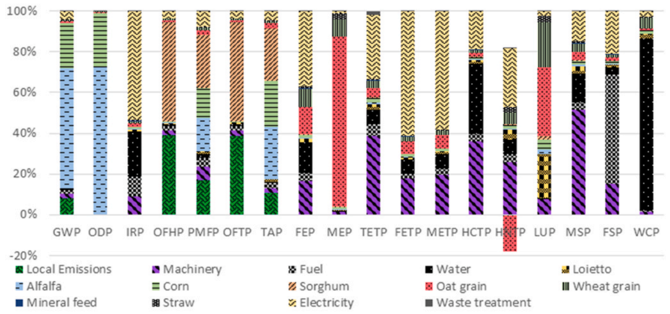

Fig. 5. Ex-ante LCA - Characterized results for the production of raw buffalo milk.

fertilizer, oil, coal, etc.). The EMA indicators (Table 5) show an EYR value very near to 1 highlighting how the process relies almost entirely on outside non-renewable resources (F), also confirmed by the high ELR value.

Table 6 shows the Ex–post LCA (characterized results) related to Scenario 1. Compared to the Ex-ante LCA, this scenario reduces the overall burdens in all investigated impact categories, with the largest decrease within MSP (45%) and smallest within LUP (8%) impact categories.

Fig. 7 shows the percentage contributions of each input flow to highlight the environmental burdens of Scenario 1. The raw buffalo milk still represents a major driver of the overall impacts (32%), with more marked contribution in MEP (77%), due to the fertilizers used at the fodder production and electricity consumption. Water and detergents add up to an average contribution of about 21%, underlining a reduction of 50% of the impacts compared to the Ex-ante BAU Scenario. On the whole, the environmental load of the other inputs (machinery, natural gas, citric acid, local emission) covered about 18% of the total impact (as averaged values for all impact categories), with more marked contribution from natural gas (8%).

3.3. *The scenario 2*

Scenario 2 is established based on an eco-efficiency perspective, through the substitution of the usual Italian electricity mix with a 100% renewable electricity mix provided at no additional cost upon request, and composed by: 50% hydropower, 24% geothermal, 24% wind, and 24% photovoltaic (in Appendix, Table A5 shows the LCA inventory of buffalo raw milk production and Table A6 reports the inventory of mozzarella cheese production for Scenario 2).

EMA results for Scenario 2 (Fig. 8) show 47% of U value represented by human labor and 44% by indirect labor, i.e., services (L&S) plus other minor inputs (see Appendix Table B2 for the EMA calculation procedure).

Although the %REN is slightly higher (5.8%), due to the use of renewable resources to produce the electricity mix, the investigated production is still heavily dependent on imported flows, as demonstrated by the ELR indicator (16.41) (Table 7).

When L&S is not considered, the residual emergy is considered as 100% (right side of Fig. 8) and the fossil-based resources, diesel, heavy fuels, and natural gas, reach 73%. The ESI (0.01) indicates that the investigated system is still far from achieving a balance with natural system (Table 7).

When the focus is placed on LCA (Ex-post LCA), the characterized results for Scenario 2, listed in Table 8 and Fig. 9, show that the prevailing hotspots are the cleaning agents (sodium hydroxide and nitric acid) and buffalo milk production. In comparison with the Ex-ante LCA, Scenario 2 shows less impact in all investigated categories scoring from about 1% (for ODP) up to about 45% (for IRP). The contributions to the different impact categories (Fig. 9) highlight how the cleaning agents used within the cheese-making highly affect the overall burden. The sodium hydroxide shows an average contribution of 33% across all impact categories, with a minimum of 1% in ODP and a maximum of 73% in IRP, while the nitric acid shows a minimum in MEP (2%) and a maximum in MSP (50%), with an average equal to 22% across all categories. Another significant impacting element is represented by the raw buffalo milk from the livestock phase (25% as average value for all impact categories), which was also improved in this scenario using the renewable electricity mix. The less impacting renewable electricity mix consumed in Scenario 2 affects the environmental burdens with an overall contribution of 4% with the highest impact in WCP (24%). The

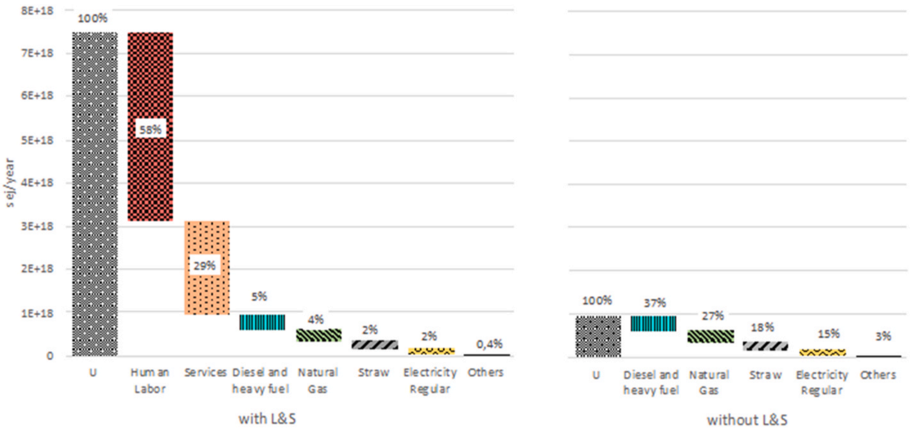

Fig. 6. Percentage contribution of the inputs on total Emergy (U) results from the buffalo mozzarella production - Scenario 1.

Table 5
Emergy Indicators for the buffalo mozzarella production - Scenario 1.

Indicator	Unit	with L&S	without L&S
U	sej/yr	7.48×10^{18}	9.68×10^{17}
UEV	sej/J	1.24×10^{07}	1.60×10^{06}
EYR		1.06	1.01
ELR		17.61	85.74
ESI		0.06	0.01
%REN		5.4%	1.2%

natural gas used present a 7% average contribution to the total impacts, local emissions account for an average 4%, while citric acid and machinery both adds up to an average 2%. Water contribution to impacts is really negligible, being almost equal to 0%.

3.4. The scenario 3

This scenario is based on a viewpoint shifting in order to test the methodological issue instead of improvement options. Based on the values shown in Table 9, an economic allocation is applied (LCA inventories of the livestock and cheese-making phase are shown in Appendix Table A7 and Table A8, respectively). The economic allocation is also introduced in EMA, unlike the commonly adopted procedure, that assigns the total Emergy U to each of the produced coproducts (i.e., to outputs with different physicochemical nature) [27].

Supposing that, the investigated coproducts present the exact physicochemical nature, the Emergy algebra rules prescribe to treat the coproducts as splits, assigning them a fraction of total U based on identified properties [48,49]. Adopting a broader view, all the coproducts presented in this work are essentially different mixtures of proteins, carbohydrates, fat, and water, with a different economic value that was the basis for assigning them different fractions of U. For the sake of clarity, EMA evaluation of Scenario 3 compared three different options: Scenario 3-BAU (according to the EMA procedure, any allocation is considered), Scenario 3-Economic Allocation, and Scenario 3-Exergy Allocation.

Scenario 3 – BAU: the different contribution of each input flows to the total Emergy (U) is shown in Fig. 10, while the EMA indicators are presented in Table 10.

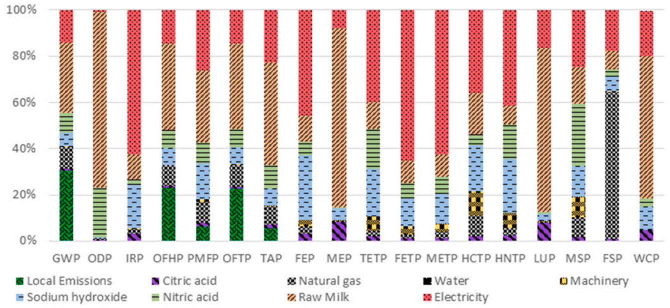

Fig. 7. Ex-post LCA - characterized contributions of each input to the total impact of the buffalo mozzarella production - Scenario 1.

Table 6
Ex-post LCA - Characterized impacts related to the buffalo mozzarella production - Scenario 1.

Impact category	Total	Local Emissions	Citric acid	Natural gas	Water	Machinery	Sodium hydroxide	Nitric acid	Raw Milk	Electricity
GWP	2.6×10^{5}	6.1×10^{4}	1.7×10^{3}	1.9×10^{4}	2.0×10^{-1}	5.4×10^{2}	1.1×10^{4}	1.8×10^{4}	6.1×10^{4}	2.8×10^{4}
ODP	3.5×10^{0}	2.4×10^{-3}	5.4×10^{-3}	2.3×10^{-2}	9.8×10^{-8}	2.5×10^{-4}	1.2×10^{-2}	5.1×10^{-1}	1.8×10^{0}	2.2×10^{-2}
IRP	1.0×10^{4}	0.0×10^{0}	2.3×10^{2}	1.2×10^{2}	6.6×10^{-2}	4.5×10^{1}	1.3×10^{3}	1.7×10^{2}	7.7×10^{2}	4.4×10^{3}
OFHP	5.3×10^{2}	9.3×10^{1}	3.2×10^{0}	3.6×10^{1}	4.9×10^{-4}	1.4×10^{0}	2.9×10^{1}	3.2×10^{1}	1.5×10^{2}	5.8×10^{1}
PMFP	2.5×10^{2}	1.0×10^{1}	2.9×10^{0}	1.5×10^{1}	3.6×10^{-4}	1.5×10^{0}	2.6×10^{1}	1.4×10^{1}	5.2×10^{1}	4.3×10^{1}
OFTP	5.4×10^{2}	9.3×10^{1}	3.3×10^{0}	3.8×10^{1}	5.0×10^{-4}	1.5×10^{0}	2.9×10^{1}	3.2×10^{1}	1.5×10^{2}	5.9×10^{1}
TAP	8.2×10^{2}	3.4×10^{1}	9.9×10^{0}	4.5×10^{1}	8.4×10^{-4}	2.9×10^{0}	4.4×10^{1}	5.9×10^{1}	2.7×10^{2}	1.3×10^{2}
FEP	4.0×10^{1}	0.0×10^{0}	7.6×10^{-1}	6.9×10^{-1}	1.5×10^{-4}	6.5×10^{-1}	6.6×10^{0}	1.4×10^{0}	2.7×10^{0}	1.1×10^{1}
MEP	1.3×10^{1}	0.0×10^{0}	1.0×10^{0}	4.8×10^{-2}	1.2×10^{-5}	3.5×10^{-2}	6.1×10^{-1}	6.6×10^{-2}	9.3×10^{0}	9.4×10^{-1}
TETP	2.9×10^{5}	0.0×10^{0}	3.6×10^{3}	3.8×10^{3}	5.2×10^{-1}	1.0×10^{4}	3.4×10^{4}	2.8×10^{4}	1.9×10^{4}	6.5×10^{4}
FETP	4.6×10^{3}	0.0×10^{0}	4.4×10^{1}	5.6×10^{1}	8.3×10^{-3}	1.1×10^{2}	4.0×10^{2}	2.1×10^{2}	3.3×10^{2}	2.2×10^{3}
METP	6.2×10^{3}	0.0×10^{0}	5.9×10^{1}	1.1×10^{2}	1.2×10^{-2}	1.6×10^{2}	5.7×10^{2}	3.1×10^{2}	4.3×10^{2}	2.7×10^{3}
HCTP	4.2×10^{3}	0.0×10^{0}	6.0×10^{1}	2.5×10^{2}	6.6×10^{-2}	2.8×10^{2}	5.5×10^{2}	1.3×10^{2}	5.0×10^{2}	9.9×10^{2}
HNTP	9.0×10^{4}	0.0×10^{0}	1.1×10^{3}	1.5×10^{3}	1.8×10^{-1}	3.4×10^{3}	1.2×10^{4}	7.3×10^{3}	4.1×10^{3}	2.0×10^{4}
LUP	8.3×10^{3}	0.0×10^{0}	6.1×10^{2}	3.3×10^{1}	6.7×10^{-3}	1.6×10^{1}	2.4×10^{2}	6.4×10^{1}	5.4×10^{3}	1.3×10^{3}
MSP	4.7×10^{2}	0.0×10^{0}	4.8×10^{0}	2.2×10^{1}	2.1×10^{-3}	2.3×10^{1}	3.3×10^{1}	6.9×10^{1}	4.0×10^{1}	6.3×10^{1}
FSP	5.5×10^{4}	0.0×10^{0}	4.5×10^{2}	2.9×10^{4}	5.1×10^{-2}	1.1×10^{2}	2.9×10^{3}	1.5×10^{3}	3.6×10^{3}	8.1×10^{3}
WCP	3.6×10^{3}	0.0×10^{0}	1.4×10^{2}	-1.7×10^{1}	5.6×10^{-1}	4.5×10^{0}	2.9×10^{2}	9.8×10^{1}	1.8×10^{3}	5.5×10^{2}

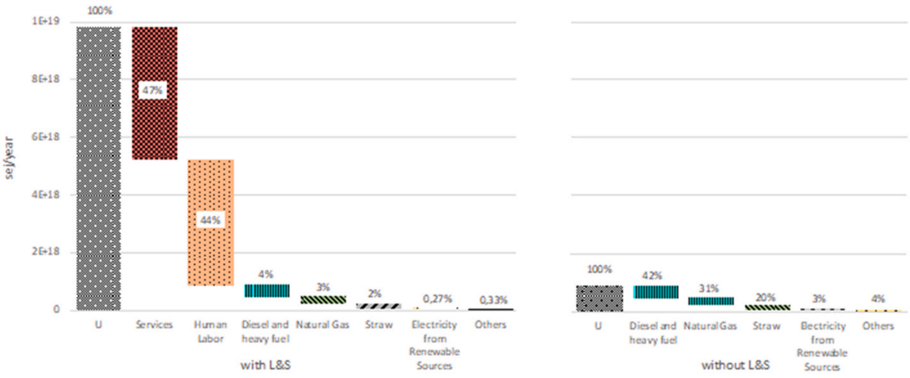

Fig. 8. Percentage contribution of the inputs on total Emergy (U) results of the buffalo mozzarella production -Scenario 2.

Table 7
Emergy Indicators for the buffalo mozzarella production - Scenario 2.

Indicator	Unit	with L&S	without L&S
U	sej/yr	9.83×10^{18}	8.58×10^{17}
UEV	sej/J	1.63×10^{07}	1.42×10^{06}
EYR		1.06	0.98
ELR		16.41	78.42
ESI		0.06	0.01
%REN		5.8%	1.3%

Labor represents 46% of the total U and Services, 44%. When L&S is not taken into account, the residual emergy is considered as 100% (right side of Fig. 10), showing the greatest share of diesel and heavy fuel (37%), followed by natural gas (27%), straw as animal supplementary nutrition (18%) and electricity (14%) consumption (common Italian electricity mix). The EMA indicators, for both Scenario 3-BAU with and without L&S, underline, once again, the significant influence of fossil-based products throughout the buffalo mozzarella production and the low sustainability (ESI) of the investigated process as a ratio between its dependence from outside sources (EYR) and from non-renewable (ELR) ones (EMA results for Scenario 3-BAU are reported in the Appendix, Table B3).

Table 8
Ex-post LCA - Characterized results related to the buffalo mozzarella production - Scenario 2.

Impact category	Total	Local Emissions	Citric acid	Natural gas	Water	Machinery	Sodium hydroxide	Nitric acid	Raw Milk	Electricity (Renewable Mix)
GWP	2.3×10^{5}	6.1×10^{4}	1.7×10^{3}	1.9×10^{4}	6.4×10^{-1}	5.4×10^{2}	3.6×10^{4}	5.5×10^{4}	5.9×10^{4}	1.9×10^{3}
ODP	3.5×10^{0}	2.4×10^{-3}	$5.x10^{-3}$	2.3×10^{-2}	3.1×10^{-7}	2.5×10^{-4}	3.8×10^{-2}	1.6×10^{0}	1.8×10^{0}	7.2×10^{-4}
IRP	5.7×10^{3}	0.0×10^{0}	2.3×10^{2}	1.2×10^{2}	2.1×10^{-1}	4.5×10^{1}	4.2×10^{3}	5.2×10^{2}	3.8×10^{2}	2.1×10^{2}
OFHP	4.7×10^{2}	9.3×10^{1}	3.2×10^{0}	3.6×10^{1}	1.5×10^{-3}	1.4×10^{0}	9.0×10^{1}	9.9×10^{1}	1.5×10^{2}	4.6×10^{0}
PMFP	2.1×10^{2}	1.0×10^{1}	2.9×10^{0}	1.5×10^{1}	1.1×10^{-3}	1.5×10^{0}	8.2×10^{1}	4.4×10^{1}	4.8×10^{1}	3.7×10^{0}
OFTP	4.8×10^{2}	9.3×10^{1}	3.3×10^{0}	3.8×10^{1}	1.6×10^{-3}	1.5×10^{0}	9.1×10^{1}	9.9×10^{1}	1.5×10^{2}	4.7×10^{0}
TAP	6.8×10^{2}	3.4×10^{1}	9.9×10^{0}	4.5×10^{1}	2.6×10^{-3}	2.9×10^{0}	1.4×10^{2}	1.9×10^{2}	2.6×10^{2}	6.4×10^{0}
FEP	3.0×10^{1}	0.0×10^{0}	7.6×10^{-1}	6.9×10^{-1}	4.8×10^{-4}	6.5×10^{-1}	2.1×10^{1}	4.3×10^{0}	1.8×10^{0}	9.8×10^{1}
MEP	1.3×10^{1}	0.0×10^{0}	1.0×10^{0}	4.8×10^{-2}	3.8×10^{-5}	3.5×10^{-2}	1.9×10^{0}	2.1×10^{-1}	9.2×10^{0}	6.9×10^{-2}
TETP	2.3×10^{5}	0.0×10^{0}	3.6×10^{3}	3.8×10^{3}	1.6×10^{0}	1.0×10^{4}	1.1×10^{5}	8.7×10^{4}	1.4×10^{4}	8.5×10^{3}
FETP	2.5×10^{3}	0.0×10^{0}	4.4×10^{1}	5.6×10^{1}	2.6×10^{-2}	1.1×10^{2}	1.3×10^{3}	6.6×10^{2}	1.4×10^{2}	1.8×10^{2}
METP	3.5×10^{3}	0.0×10^{0}	5.9×10^{1}	1.1×10^{2}	3.6×10^{-2}	1.6×10^{2}	1.8×10^{3}	9.7×10^{2}	2.0×10^{2}	2.3×10^{2}
HCTP	3.4×10^{3}	0.0×10^{0}	6.0×10^{1}	2.5×10^{2}	2.1×10^{-1}	2.8×10^{2}	1.7×10^{3}	4.1×10^{2}	4.3×10^{2}	2.7×10^{2}
HNTP	7.0×10^{4}	0.0×10^{0}	1.1×10^{3}	1.5×10^{3}	5.8×10^{-1}	3.4×10^{3}	3.6×10^{4}	2.3×10^{4}	2.5×10^{3}	2.5×10^{3}
LUP	7.0×10^{3}	0.0×10^{0}	6.1×10^{2}	3.3×10^{1}	2.1×10^{-2}	1.6×10^{1}	7.4×10^{2}	2.0×10^{2}	5.3×10^{3}	8.8×10^{1}
MSP	4.3×10^{2}	0.0×10^{0}	4.8×10^{0}	2.2×10^{1}	6.7×10^{-3}	2.3×10^{1}	1.0×10^{2}	2.2×10^{2}	3.6×10^{1}	2.3×10^{1}
FSP	4.7×10^{4}	0.0×10^{0}	4.5×10^{2}	2.9×10^{4}	1.6×10^{-1}	1.1×10^{2}	9.0×10^{3}	4.8×10^{3}	2.9×10^{3}	4.3×10^{2}
WCP	4.1×10^{3}	0.0×10^{0}	1.4×10^{2}	-1.7×10^{1}	1.8×10^{0}	4.5×10^{0}	9.1×10^{2}	3.1×10^{2}	1.8×10^{3}	1.0×10^{3}

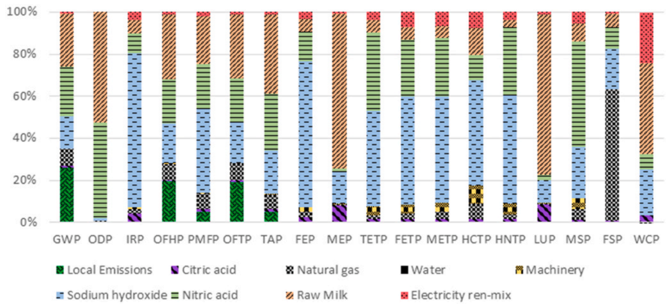

Fig. 9. Ex-post LCA - characterized contributions of each input to the total impact of the buffalo mozzarella production - Scenario 2.

Scenario 3-Economic Allocation: the monetary market value (primary data from tailored questionnaires during field visits) of the buffalo mozzarella, other cheeses and butter is taken into account (Table 9). On the other hand, whey, carcasses, and manure are considered waste, since only a discharged cost can be detected in literature.

Scenario 3-Exergy Allocation: the exergy embodied in each output of the studied dairy system is accounted for (Table 9). Table 11 shows the total Emergy for the three different options investigated in Scenario 3. Scenario 3-BAU displays the same value of U assigned to all outputs because they are considered as coproducts of the same evaluated system [86]. The results for Scenario 3, for both economic and exergy allocation, show the U values for each product. For the buffalo mozzarella cheese, the main product, the exergy allocation shows a U value 90% less than the U value calculated for Scenario 3-BAU. On the other hand, Scenario 3 - economic allocation displays a U value for the buffalo mozzarella 88% higher than the exergy allocation and 21% less than Scenario 3-BAU.

The highest U value in exergy allocation is the manure, which is entirely ignored by the economic allocation. In fact, economic allocation does not take into proper account the biosphere support for coproducts that cannot be sold on the market. Output flows that presently have no or small value to the eyes of humans may have more value for other species (e.g., plants and soil detritivores). Finally, value is presently determined by the cost of fossil fuels. When fossil fuels availability decline or environmental concerns arise, the economic cost may no longer be the main driving factor. It may be integrated by environmental cost (EMA) and ability to do work (exergy).

The same occurs when the UEV values are calculated, dividing U by the energy content of each product (Table 12): whey and manure show the highest UEV value among all coproducts under exergy allocation.

Table 13 lists the Ex-post LCA results for Scenario 3 for the buffalo mozzarella. Due to the larger allocation fraction assigned to the main products of the livestock and cheese-making steps (i.e., raw buffalo milk and buffalo mozzarella), the impact for all investigated impact categories appeared markedly higher, with values amounting from a minimum 79% increase to a maximum of 308% increase to HNTP and MEP impact categories, respectively.

Percentage contributions to the impact categories in Scenario 3 – Economic Allocation (Fig. 11) confirm the raw buffalo milk as the main hotspot of the buffalo mozzarella production, with an overall

Table 10
Emergy Indicators for the buffalo mozzarella production - Scenario 3-BAU.

Indicator	Unit	with L&S	without L&S
U	sej/yr	9.98×10^{18}	9.72×10^{17}
UEV	sej/J	1.65×10^{7}	1.61×10^{6}
EYR		1.06	1.02
ELR		17.09	85.22
ESI		0.06	0.01
%REN		5.5%	1.2%

Table 9
Allocation used in Scenario 3.

Output	Production (kg/yr)	Scenario 3-Economic Allocation				Scenario 3-Exergy Allocation	
		Price (€/kg)	Value Prod. (€/yr)	Income/Cost	%	Exergy (J/kg)	%
Buffalo mozzarella	1.21×10^{5}	14	1.69×10^{6}	Income	79	1.56×10^{12}	9.80
Hard cheese	2.95×10^{3}	7	2.07×10^{4}	Income	0.96	4.20×10^{10}	0.26
Ricotta	3.42×10^{4}	11.7	4.00×10^{5}	Income	18.59	3.64×10^{11}	2.29
Butter	6.79×10^{2}	12.45	8.45×10^{3}	Income	0.39	2.40×10^{10}	0.15
Semi-hard cheese	3.65×10^{3}	9	3.29×10^{4}	Income	1.53	6.84×10^{10}	0.43
Whey	1.00×10^{6}	0.015	1.50×10^{4}	Cost		1.21×10^{12}	7.58
Carcasses	1.00×10^{5}	0.2	2.00×10^{4}	Cost		1.11×10^{12}	7.01
Manure	2.22×10^{6}	0.022	4.89×10^{4}	Cost		1.15×10^{13}	72.49

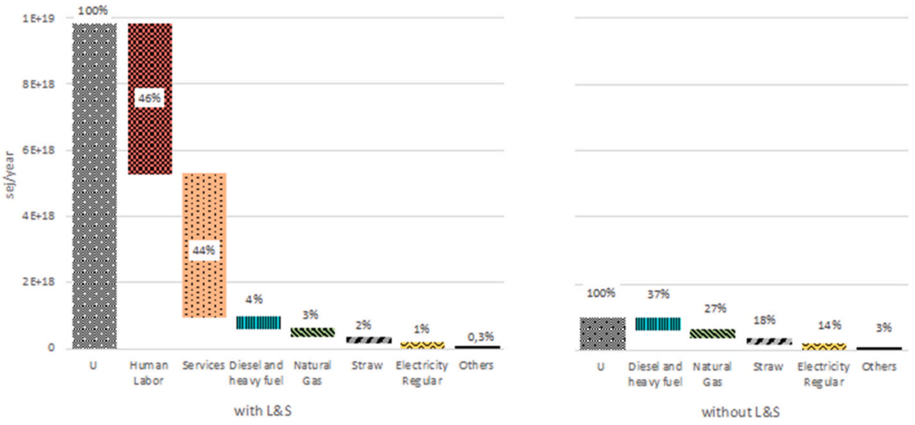

Fig. 10. Percentage contribution of the inputs on total Emergy (U) results of the buffalo mozzarella production - Scenario 3-BAU.

Table 11
Total Emergy by Outputs with allocation in Scenario 3.

Outputs	U - Total Emergy (sej)					
	Scenario 3-BAU		Scenario 3-Economic Allocation		Scenario 3-Exergy Allocation	
	with L&S	without L&S	with L&S	without L&S	with L&S	without L&S
Buffalo mozzarella	9.98×10^{18}	9.72×10^{17}	7.84×10^{18}	7.63×10^{17}	9.78×10^{17}	9.52×10^{16}
Hard cheese			9.59×10^{16}	9.32×10^{15}	2.63×10^{16}	2.56×10^{15}
Ricotta			1.86×10^{18}	1.81×10^{17}	2.28×10^{17}	2.22×10^{16}
Butter			3.92×10^{16}	3.82×10^{15}	1.51×10^{16}	1.47×10^{15}
Semi-hard cheese			1.52×10^{17}	1.48×10^{16}	4.29×10^{16}	4.18×10^{15}
Whey					7.57×10^{17}	7.36×10^{16}
Carcasses					7.00×10^{17}	6.81×10^{16}
Manure					7.24×10^{18}	7.04×10^{17}

Table 12
UEVs of each output in Scenario 3.

Outputs	UEV (sej/J)					
	Scenario 3-BAU		Scenario 3-Economic Allocation		Scenario 3-Exergy Allocation	
	with L&S	Without L&S	with L&S	Without L&S	with L&S	Without L&S
Buffalo mozzarella	1.65×10^{07}	1.61×10^{06}	1.30×10^{07}	1.27×10^{06}	1.62×10^{06}	1.58×10^{05}
Hard cheese	5.61×10^{08}	5.46×10^{07}	5.39×10^{06}	5.24×10^{05}	1.48×10^{06}	1.44×10^{05}
Ricotta	8.40×10^{07}	8.17×10^{06}	1.56×10^{07}	1.52×10^{06}	1.92×10^{06}	1.87×10^{05}
Butter	4.84×10^{08}	4.71×10^{07}	1.90×10^{06}	1.85×10^{05}	7.31×10^{05}	7.11×10^{04}
Semi-hard cheese	2.54×10^{08}	2.47×10^{07}	3.87×10^{06}	3.77×10^{05}	1.09×10^{06}	1.06×10^{05}
Whey	1.18×10^{08}	1.15×10^{07}			8.97×10^{06}	8.73×10^{05}
Carcasses	2.30×10^{07}	2.24×10^{06}			1.61×10^{06}	1.57×10^{05}
Manure	4.44×10^{06}	4.32×10^{05}			3.22×10^{06}	3.13×10^{05}

Table 13
Ex-post LCA - characterized results related to Scenario 3 of the buffalo mozzarella production.

Impact category	Total	Local Emissions	Citric acid	Natural gas	Water	Machinery	Sodium hydroxide	Nitric acid	Raw Milk	Electricity
GWP	6.4×10^{5}	9.9×10^{4}	2.7×10^{3}	3.1×10^{4}	1.0×10^{0}	8.8×10^{2}	5.8×10^{4}	8.9×10^{4}	3.2×10^{5}	4.6×10^{4}
ODP	1.2×10^{1}	3.8×10^{-3}	8.9×10^{-3}	3.8×10^{-2}	5.0×10^{-7}	4.1×10^{-4}	6.2×10^{-2}	2.6×10^{0}	9.5×10^{0}	3.6×10^{-2}
IRP	1.9×10^{4}	0.0×10^{0}	3.8×10^{2}	2.0×102	3.3×10^{-1}	7.4×10^{1}	6.8×10^{3}	8.4×10^{2}	4.0×10^{3}	7.2×10^{3}
OFHP	1.4×10^{3}	1.5×10^{2}	5.2×10^{0}	5.8×10^{1}	2.5×10^{-3}	2.3×10^{0}	1.5×10^{2}	1.6×10^{2}	7.8×10^{2}	9.4×10^{1}
PMFP	5.9×10^{2}	1.7×10^{1}	4.6×10^{0}	2.4×10^{1}	1.8×10^{-3}	2.4×10^{0}	1.3×10^{2}	7.2×10^{1}	2.7×10^{2}	7.0×10^{1}
OFTP	1.4×10^{3}	1.5×10^{2}	5.3×10^{0}	6.2×10^{1}	2.5×10^{-3}	2.4×10^{0}	1.5×10^{2}	1.6×10^{2}	7.9×10^{2}	9.5×10^{1}
TAP	2.3×10^{3}	5.5×10^{1}	1.6×10^{1}	7.4×10^{1}	4.3×10^{-3}	4.7×10^{0}	2.3×10^{2}	3.0×10^{2}	1.4×10^{3}	2.2×10^{2}
FEP	7.5×10^{1}	0.0×10^{0}	1.2×10^{0}	1.1×10^{0}	7.8×10^{-4}	1.1×10^{0}	3.4×10^{1}	7.0×10^{0}	1.4×10^{1}	1.7×10^{1}
MEP	5.5×10^{1}	0.0×10^{0}	1.6×10^{0}	7.8×10^{-2}	6.1×10^{-5}	5.7×10^{-2}	3.1×10^{0}	3.4×10^{-1}	4.8×10^{1}	1.5×10^{0}
TETP	5.5×10^{5}	0.0×10^{0}	5.9×10^{3}	6.1×10^{3}	2.6×10^{0}	1.6×10^{4}	1.7×10^{5}	1.4×10^{5}	9.9×10^{4}	1.1×10^{5}
FETP	8.6×10^{3}	0.0×10^{0}	7.1×10^{1}	9.1×10^{1}	4.2×10^{-2}	1.8×10^{2}	2.0×10^{3}	1.1×10^{3}	1.7×10^{3}	3.5×10^{3}
METP	1.2×10^{4}	0.0×10^{0}	9.7×10^{1}	1.9×10^{2}	5.9×10^{-2}	2.6×10^{2}	2.9×10^{3}	1.6×10^{3}	2.2×10^{3}	4.4×10^{3}
HCTP	8.6×10^{3}	0.0×10^{0}	9.7×10^{1}	4.1×10^{2}	3.3×10^{-1}	4.6×10^{2}	2.8×10^{3}	6.7×10^{2}	2.6×10^{3}	1.6×10^{3}
HNTP	1.6×10^{5}	0.0×10^{0}	1.9×10^{3}	2.5×10^{3}	9.4×10^{-1}	5.6×10^{3}	5.9×10^{4}	3.7×10^{4}	2.1×10^{4}	3.3×10^{4}
LUP	3.3×10^{4}	0.0×10^{0}	9.9×10^{2}	5.3×10^{1}	3.4×10^{-2}	2.6×10^{1}	1.2×10^{3}	3.3×10^{2}	2.8×10^{4}	2.1×10^{3}
MSP	9.1×10^{2}	0.0×10^{0}	7.7×10^{0}	3.5×10^{1}	1.1×10^{-2}	3.7×10^{1}	1.7×10^{2}	3.5×10^{2}	2.1×10^{2}	1.0×10^{2}
FSP	1.0×10^{5}	0.0×10^{0}	7.4×10^{2}	4.7×10^{4}	2.6×10^{-1}	1.8×10^{2}	1.5×10^{4}	7.8×10^{3}	1.9×10^{4}	1.3×10^{4}
WCP	1.2×10^{4}	0.0×10^{0}	2.2×10^{2}	-2.8×10^{1}	2.9×10^{0}	7.4×10^{0}	1.5×10^{3}	5.0×10^{2}	9.1×10^{3}	9.0×10^{2}

contribution of 43% (scoring from about 13% for HNTP, up to about 88% for MEP). It was followed by the detergents contributing together for 32% (19% sodium hydroxide and 13% nitric acid), electricity (16%), and for a similar extent by local emissions, citric acid, natural gas, water, and machinery (impacting together less than 10%).

4. Discussion

The presented LEAF results were displayed mixing improvement hypotheses for the suggested Scenarios 1 and 2, and methodological assumptions for Scenario 3, which aims to investigate common allocation procedures to LCA method using EMA. For Scenario 3, the results were showed as: (1) the EMA evaluation of the three sub-scenarios (BAU, economic allocation and exergy allocation), followed by (2) the Ex-post LCA for Scenario 3 – economic allocation, since the exergy allocation was considered as default procedure for the Ex-ante LCA,

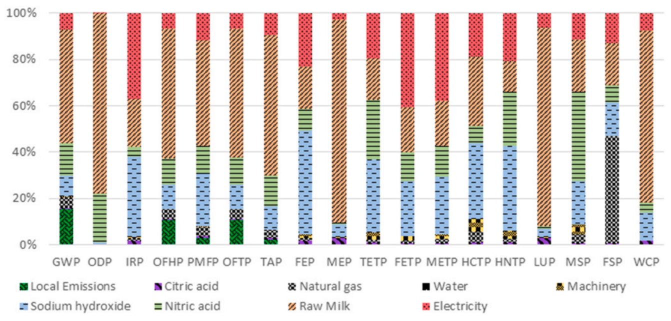

Fig. 11. Ex-post LCA - characterized contributions of each input to the total impact of the buffalo mozzarella production - Scenario 3 –Economic Allocation.

whilst the Scenario 3 - BAU is related only to the common adopted EMA procedure (no allocation).

The comparison between the EMA results with and without L&S of the two improving scenarios (Scenario 1 and Scenario 2) and the methodological shifting scenario (Scenario 3 with three sub-scenarios) show the same trend. Therefore, Fig. 12 and Table 14 show only the EMA results with L&S, highlighting that Scenario 1 has the best performance, due to reducing water consumption and cleaning products, for both total amount of Emergy (U) and UEV values.

However, Scenario 2 also presents EMA positive indicators: the highest renewability (%REN) and sustainability index (ESI), together with the lowest need for outside fossil resources (ELR).

Instead, Scenario 3, from the EMA point of view, shows considerable differences among the results of allocation options even if the buffalo mozzarella production chain is always the same, as well as the biosphere support to the production. The point is that allocating total emergy according to the economic value ignores the importance of byproducts for other species and allocating total Emergy according to the ability to do work (exergy) disregards that some products cannot be produced without the others.

Hence, applying different allocation procedures (based on energy, exergy, mass, or economic criteria) appraises different and sometimes misleading results. The split of total Emergy among coproducts should be strongly discouraged not to compromise the final results to consider the quality and the environmental loading of each output product. Indeed, as thoroughly discussed by Brown (2015) [84] and Santagata et al. (2019) [87], all coproducts have the same importance in the EMA procedure when the focus is placed on the natural support demand and the real dynamics of production processes.

Shifting to the LCA results, Fig. 13 displays the comparison among the Ex-ante LCA, Scenarios 1 and 2 and Scenario 3 – Economic allocation, showing for the Scenario 1 and 2 better performances than the Ex-ante LCA results. Scenario 1 shows the major overall improvement (-29% over the entire set of impact categories) proving that the burdens were effectively reduced for the technological optimization of the cleaning activity. Scenario 3 – Economic allocation has the highest contribution in all impact categories, due to the different allocation perspective, that do not change the total impact but only changes the share assigned to buffalo mozzarella cheese (since the impacts are theoretically the same but are distributed differently).

In summary, Scenario 1 and Scenario 2 provide technical improvements in the production chain resulting in better environmental performance due to better management of resources (Scenario 1) or more feasible energy sources (Scenario 2). Scenario 3 aims at testing the LEAF with more methodological choices, in this particular case, testing LEAF with different allocation methods. Thus, Scenario 3 shows how EMA results and LCA impacts change when changing perspectives and, more importantly, how this could also affect results with the larger scale dynamics. Therefore, the LEAF results highlight and reinforce how the allocation is a practice to assign burdens and performances to various products from different perspectives. However, the outcomes should be managed and interpreted very carefully since the allocation procedures impact the obtained results without real improvements within systems' functioning.

Indeed, this study addresses two different subjects. First of all, the dairy system was investigated to assess the environmental burdens and suggest possible improved solutions towards more sustainable production options (Scenario 1 and 2). Moreover, according to the LEAF procedure, the feasibility of the proposed scenarios was checked, and the potential environmental improvements obtained were verified (LCA Ex-post). On the other hand, in Scenario 3, the methodological issues related to the allocation procedures in LCA evaluations (following the standardized procedures [24–26]) were pointed out, and through the EMA application were checked and discussed in order to improve the interaction between evaluation methods and get a suitable integrated framework. Allocation, therefore, appears a virtual assignment of inputs and impacts to output flows, i.e., a more pragmatic (not necessarily useless) approach that ignores the real process at the larger biosphere scale. The main result and take-home lesson end up being that allocation should possibly be avoided, as dictated by both EMA and LCA rules, to prevent misleading or partial results.

5. Conclusions

The proposed LEAF allows a deep multi-method and multi-perspective evaluation of complex systems delivering a suitable set of indicators combining environmental burdens and performances. Moreover, this methodological framework overcomes the limits of single method evaluation bringing together the anthropocentric perspective (LCA) and the biosphere perspective (EMA), which are essential for a comprehensive environmental assessment of complex systems towards sustainability.

In this work, the LEAF procedure was applied to a site-specific dairy production in Campania Region (Italy) in order to (i) identify the main hotspots (Ex-ante LCA) and suggest improvement scenarios, (ii) investigated the environmental performance of the suggested processes (EMA), and (iii) verify the feasibility and the impact of the proposed solutions (Ex-post LCA) towards sustainability. The two proposed improvement scenarios were based on the cleaning products and electricity consumption identified as the most significant contributors to the total environmental burdens (Ex-ante LCA). Scenario 1 presented the best environmental performance, since it provides water and cleaning products savings. Moreover, the automation of the cleaning process provides new knowledge in a traditional dairy factory coupled up to better labor conditions due to the avoided chemical manipulation. Scenario 2 should also be considered a successful option, indeed, the use of renewable resources, instead of fossil-based products, reduces the total impacts. In Scenario 3, a methodological discussion was performed to underline the restraint of a single method appraising complex systems with multiple outputs and allow users to better and comprehensively understand how the allocation options can profoundly affect results and how assumptions can bring different outcomes when applied to diverse

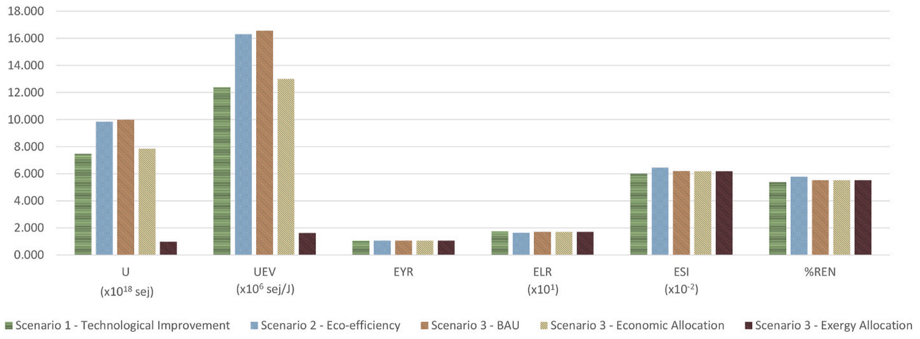

Fig. 12. The comparison of Emergy results with labor and services (L&S) among the three investigated scenarios.

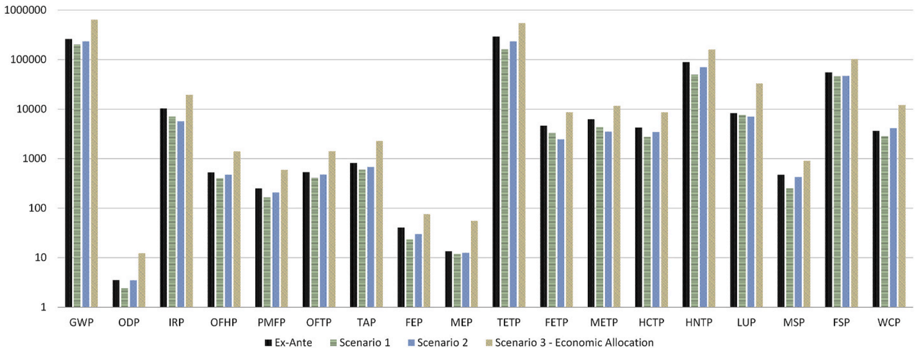

Fig. 13. Characterized results comparing buffalo mozzarella's current production (Ex-Ante LCA) with the proposed scenarios.

Table 14
Emergy results (with L&S) of the three scenarios related to buffalo mozzarella production.

	Scenario 1	Scenario 2	Scenario 3		
	Technological Improvement	Eco-efficiency	BAU	Economic Allocation	Exergy Allocation
U ($x10^{18}$ sej)	7.48	9.83	9.98	7.84	0.98
UEV ($x10^{7}$ sej/J)	1.24	1.63	1.66	1.30	0.16
EYR	1.06	1.06	1.06	1.06	1.06
ELR	17.61	16.41	17.10	17.10	17.10
ESI ($x10^{-2}$)	6.0	6.4	6.2	6.2	6.2
%REN	5.4	5.8	5.5	5.5	5.5

methods.

Credit author statement

Mariana Oliveira: Formal analysis, Investigation, Validation, Writing - Reviewing & Editing; Annalisa Cocozza: Formal analysis, Investigation; Amalia Zucaro: Formal analysis, Investigation, Validation, Writing - Reviewing & Editing. Remo Santagata: Formal analysis, Investigation, Validation, Writing - Reviewing & Editing and Sergio Ulgiati: Conceptualization, Project administration, Funding acquisition; Validation, Writing - Reviewing & 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.

Acknowledgments

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie Innovative Training Networks (H2020-MSCA-ITN-2018) scheme, grant agreement number 814247 (ReTraCE).

Supplementary data - Appendix A and B

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2021.111314.

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