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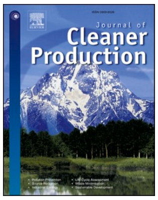

Integrating circularity as an essential pillar of dairy farm sustainability

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ABSTRACT

Given the complex and often negative interactions between humanity and nature, methodologies and frameworks for assessing the concepts of circularity (C) and sustainability (S) have become the focus of many studies in the last decade. However, C and S have developed partially independently, impairing the interpretation of their intricate relationships. In this context, there is still no regulatory framework on how to assess them in an integrated manner through simple but robust indicators. To fill this gap, this study proposes an evaluation framework that allows the holistic integration of C and S indicators (integration of CIrcularity and SUstainable indicators – CISU methodology) taking the dairy sector as a case study. For this purpose, 50 Spanish dairy farms have been selected to estimate a Composite Dairy Farm index (CDFi) as a result of the integration of 9 C indicators and 21 S indicators. The results obtained showed a relative homogeneity among dairy farms as well as some room for improvement, with the CDFi (scores from 0 to 100) varying from 36 to 64 points. The results indicate that minimising reliance on external cow feed, use of own-produced fodders, and suitable field management are essential to achieve a circular and sustainable milk production system. This manuscript contributes with the proposal of a novel framework that can be adapted to different companies and products to assess the implementation of CE principles to achieve sustainable development. However, the integration of additional aspects, such as industrial symbiosis, or its applicability at meso level appear as challenges in order to implement sustainable development throughout the supply chain.

1. Introduction

Currently, the definition of circular economy (CE) adopts numerous options which implies that uncertainty and subjectivity can be reflected in each circularity (C) assessment study (Niero and Kalbar, 2019). Moreover, it is common to find studies with different units of measurement (e.g. mass, energy or monetary) for quantification, which can pose difficulties when making direct comparisons between products or processes with similar characteristics (Linder et al., 2017). Under the premise of commitment to CE, different policies and regulations are being developed around the world. At the international level, ISO 59004 covers all its aspects related to CE, including public procurement, production or distribution, as well as broader areas such as changing consumer behavior (Gosh, 2020). At the European level, the Circular Economy Action Plan identifies some key products in the value chain for which, given the existing climate crisis, there is an urgent need to propose a series of actions to form an integrated policy framework (European Commission, 2020).

Regarding sustainability (S), there are up to seven different approaches to address it: ecological, political, ethical, socioeconomic, democratic, lifestyle and theological (Vogt and Weber, 2019), in addition to the three dimensions on which it is often articulated: environment, society and economy (Rosen, 2018). All these discrepancies reach consumers who, despite their willingness to opt for sustainable products, find it difficult to make the correct choices (Naspetti et al., 2021). One of the new techniques implemented to achieve sustainable practices is the creation of "communities of practice". In them, co-creation is encouraged through the transfer of knowledge among the actors involved to promote more sustainable practices, where the experience of researchers is communicated to advisors willing to translate and transfer skills to professionals in the sector (Triste et al., 2018).

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Nomenclature

AGACA	Galician association of agri-food cooperatives
CE	Circular economy
C	Circularity
CDFi	Composite dairy farm index
CH_4	Methane
CISU	Integration of circularity and sustainable indicators
CISUDASE	Integration of circularity and sustainable indicators for the dairy sector
FEP	Freshwater eutrophication
FET	Freshwater ecotoxicity
FPCM	Fat- and protein-corrected milk
FPM	Fine particulate matter formation
FRS	Fossil resource scarcity
FU	Functional unit
GHG	Greenhouse gas
GW	Global warming
HTC	Human carcinogenic toxicity
HTN	Human non-carcinogenic toxicity
IR	Ionising radiation
LCA	Life cycle assessment
LCC	Life cycle cost
LU	Land use
MCDA	Multi-criteria decision analysis
MEP	Marine eutrophication
MET	Marine ecotoxicity
MRS	Mineral resource scarcity
N_2O	Nitrous oxide
NH_3	Ammonia
NO_3^-	Nitrate
NW	Northwest
OFE	Ozone formation
OFH	Ozone formation, human health
PO_4^{3-}	Phosphate
S	Sustainability
SLCA	Social life cycle assessment
SM	Supplementary material
SOD	Stratospheric ozone depletion
TA	Terrestrial acidification
TET	Terrestrial ecotoxicity
WC	Water consumption

Given the different initiatives to implement both C and S, there is a growing interest in creating frameworks to evaluate these two concepts concomitantly, such as the Sustainable Circular System Design (Abokersh et al., 2021) or the Sustainability and Circularity Evaluation of the Business Model (Antikainen and Valkokari, 2016). Even when combining the analysis, there are still gaps, such as considering only the environmental aspect in the case of S or not providing specific guidance for selecting and assessing C and S indicators.

The agricultural and dairy sectors constitute major sources of greenhouse gas (GHG) emissions (EPA, 2020), apart from being one of the main drivers of biodiversity loss and the transformation of natural habitats (Chaudhary et al., 2016). The main reason why these two sectors contribute to the same impacts is that they both share a mixed approach of agricultural crops for livestock and farm operation. Both systems are threatened by the same S-related problems: climate change (Zandalinas et al., 2021), resource scarcity (Tian et al., 2018), price volatility (Schulte et al., 2018) and generational replacement (Góngora et al., 2019). Given the above, many projects, policies and research are proliferating to reverse the current negative trend of agriculture and livestock farming activities based on the concepts of CE and S (Basso et al., 2021; Velasco-Muñoz et al., 2021). As examples in that sense, European agricultural production and rural livestock systems have committed to implement small-scale anaerobic digesters for biogas production as a form of bioenergy from animal manure and other wastes (O'Connor et al., 2021). For irrigation of crop fields, reclaimed water (i.e. treated wastewater) has potential for use as a substitute for fresh water from natural sources (López-Serrano et al., 2022). Likiwise, waste milk is commonly reused to feed dairy calves (Firth et al., 2021).

In relation to the search for a possible solution to the problem of waste or by-product management, industrial symbiosis emerges as an associative approach between waste-generating and waste-using companies, which generates environmental, economic and social benefits through the creation of collaborative business networks based on CE practices at the meso (i.e. industrial system) level (Neves et al., 2020). Additionally, there are currently several methodologies to assess the S of dairy products indirectly through Material Flow Analysis (Rebolledo-Leiva et al., 2022), Data Envelopment Analysis (Cortés et al., 2021), as well as Life Cycle Sustainability Assessment (Chen and Holden, 2018). However, there is still debate as to whether additional product specifics (e.g. carbon footprint) need to be included when performing C analysis, as some authors argue that C should be viewed as a means to sustainable development and not as a goal in itself (Corona et al., 2019). However, no study has so far addressed the challenge of measuring C and S from an integrative perspective in the dairy sector, making it the ideal sector to evaluate a framework combining CE and S indicators due to its relevance as staple food.

Therefore, despite the growing concern to improve the S of products by decreasing their impacts through C strategies, the main objective of this work is to fill this gap in the literature by proposing a novel framework for the holistic integration of CIrcularity and SUstainability indicators (CISU), according to the methodology described in **Section 2**. CISU has been adapted to be applied in the DAiry SEctor (CISUDASE) considering 50 farms in the region of Galicia (NW Spain). The results of CISUDASE are presented in discussed in **Section 3**. Finally, the conclusions are included in **Section 4**.

2. Methodology

The CISU framework is structured in four steps: (I) selection of indicators, (II) calculation of indicators, (III) integration of indicators through three consecutive sub-steps: normalisation, weighting and aggregation, and (IV) interpretation of results (see Fig. 1).

2.1. Step I: selection of indicators

2.1.1. Circularity indicators

Three types of indicators related to the fundamental principles of CE are proposed: (A) minimise external resource input, (B) optimise production-consumption system and (C) maximise waste prevention (Velenturf and Purnell, 2021).

2.1.2. Sustainability indicators

The three domains: (A) environment, (B) society and (C) economy, should be considered with the aim of representing a set of S indicators, as this is the most widespread practice worldwide among practitioners (James and Magee, 2016).

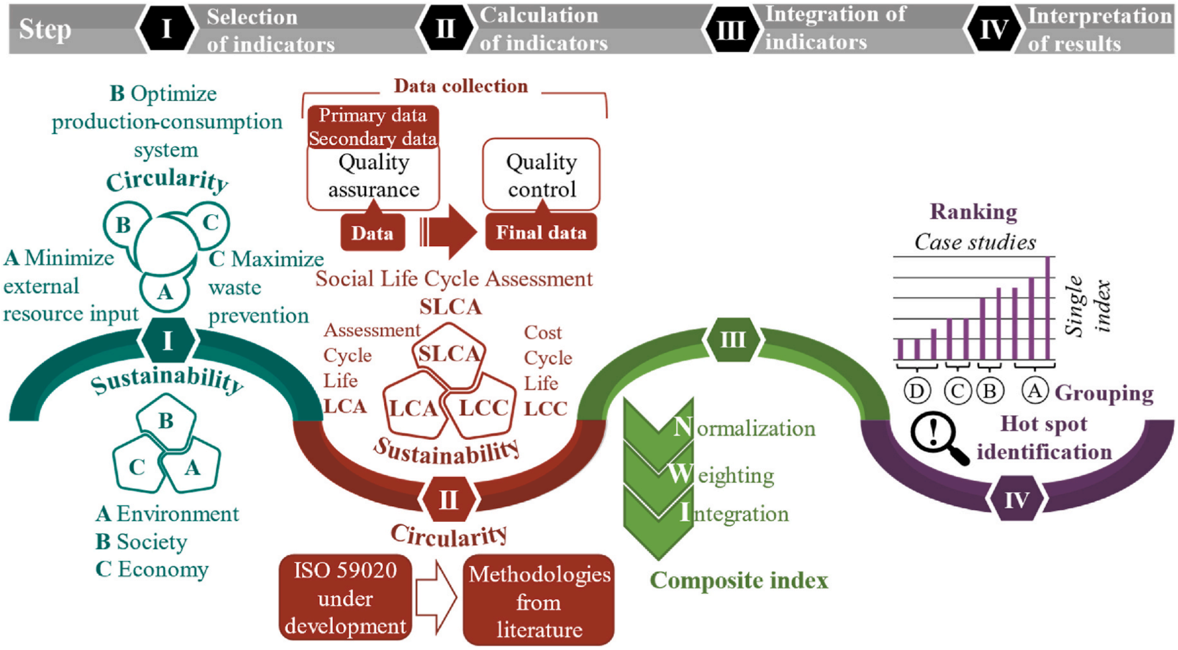

Fig. 1. Framework for the integration of CIrcularity and SUstainability indicators (CISU).

2.2. Step II: calculation of indicators

2.2.1. Data collection

The collection of information should consist of primary data to meet the needs of the study as accurately as possible by implementing a system to ensure confidence requirements (i.e. to implement quality assurance). However, this is not an easy task, as it requires all kinds of actions (e.g. surveys, interviews and/or direct observation) to be performed and interpreted by a quality assurance team. If this information is not available, it will be supplemented with secondary data from other sources, such as books, research papers or relevant statistics.

2.2.2. Circularity indicators

The International Standardization Organization (ISO) has created a Technical Committee (ISO/TC 323) with the aim of the challenging transition from the current linear economy to CE. The working group is developing a standard that provides a common understanding and principles of CE (ISO 59004). Out of this come two additional standards: ISO 59010, which captures CE strategies for transforming business models and value networks and ISO 59020, which provides a framework for measuring and evaluating circularity performance. However, as ISO 59020 is still under development, the proposal of C indicators can be approached and justified on the basis of bibliographic references that consider the principles of CE and the particularities of each productive sector being evaluated.

2.2.3. Sustainability indicators

Life Cycle Assessment (LCA), Social LCA (SLCA) and Life Cycle Costing (LCC) methodologies can be considered for the purpose of assessing the S of products (Kloepffer, 2008). LCA environmental indicators can be calculated according to ISO 14040 and 14,044 (ISO, 2006a, 2006b). LCA addresses the environmental impacts related to a product throughout its life cycle, and is divided into four phases: goal and scope, inventory analysis, impact assessment and interpretation.

The selection of indicators for the social aspects can be based on the SLCA methodological approach proposed by the United Nations Environment Programme (UNEP) (Life Cycle Initiative, 2021), and can be used depending on both the accessibility of information (which is often the most complex task in SLCA) and the goal and scope of the study.

LCC can be used to assess the economic aspect of a product system. This life cycle procedure aims to compile all costs related to a product over its lifetime and can be translated as the difference between cost (i.e. initial and subsequent investments, as well as recurring cost streams, such as material capital) and revenue (Sesana and Salvalai, 2013). Although there is currently no consensus on how to implement it, great efforts are being made to build a standard at the international level as in the case of LCA (Swarr et al., 2011). However, finding monetary valuation factors to compare production cost and environmental impacts to be used during the decision-making process represents a considerable challenge (Amadei et al., 2021).

2.3. Step III: integration of indicators

Multi-criteria decision analysis (MCDA) are mathematical procedures that allows to take a decision among different scenarios through the evaluation of multiple conflicting criteria (Ceballos et al., 2016). Different approaches can be taken into consideration, being one to consider equal importance to all the S aspects (environment, society and economy). Similarly, MCDA can be used to standardize a number of indicators so that they can be integrated and compared through a common unit (Ahi and Searcy, 2015). Moreover, C indicators have demonstrated to be a strong relation with the S ones (Terra et al., 2022) and, therefore, the same methodology could be considered to define the indicators used for the framework. Thus, considering the aspects just mentioned and the perspective that the framework should be simple enough to promote its implementation by policy-makers and to foster knowledge transfer among stakeholders, the integration of the S and C indicators can be carried out applying a three consecutive phases: normalisation of values, weighting of the indicators and aggregation into a single final score.

2.3.1. Normalisation of the values

Normalisation involves the first procedure for integrating the C and S indicators. This is necessary since these have different units, which makes difficult a direct comparison of the results obtained from **Section 2.2**. In this framework, **Equations 1 and 2** are applied according to the particularities of the sub-indicator to be normalised: (i) directly proportional to the single index (i.e. the minimum and maximum values of these sub-indicators should be assigned with 0 and 1, respectively); and (ii) inversely proportional to the single index (i.e. the maximum and minimum values of these sub-indicators should be assigned with 0 and 1, respectively).

$$N_{n,k} = \frac{K_n \text{ - } Kmin_k}{Kmax_k \text{ - } Kmin_k} \tag{Equation 1}$$

$$N_{n,k} = \frac{Kmax_k \text{ - } K_n}{Kmax_k \text{ - } Kmin_k} \tag{Equation 2}$$

Where:

n	option “n” being evaluated
k	circularity or sustainability sub-indicator
$N_{n,k}$	normalised value (0–1) for sub-indicator k and option n
K_n	value of sub-indicator k for option n
$Kmin_k$	minimum value for sub-indicator k
$Kmax_k$	maximum value for sub-indicator k

2.3.2. *Weighting of the indicators*

In this second sub-step, an egalitarian perspective regarding the number of sub-indicators is conducted to choose the values of the weighting factors. Thus, considering a total score of 100 (desirable for a single index that varies in percentage as it allows easy interpretation), an equal weighting was considered for each aspect (50 for circularity and 50 for sustainability). Subsequently, the same procedure was applied for the indicators (i.e. weights of 16.67 for environmental, social and economic indicators; as well as for minimising the input of external resources, optimising the production-consumption system and maximising waste prevention) and subsequent subcategories (i.e. sub-indicators composing the indicators). The same procedure was applied to the corresponding indicators and sub-indicators of the C and S indicators. This was decided following the same procedure a previous LCA study proposing a composite index (Ceballos-Santos et al., 2024), in which a combination of two weighting techniques were addressed. One was panel weighting, where a consensus was reached among the authors of this paper as LCA experts. The other was binary weighting, which consider null or equal weights (in this case, being the latter considered in this work). However, the weights can also be determined in an objective way thanks to the application of different MCDAs techniques, as can be consulted in the CRITIC method applied in another LCA study for the dairy sector (Entrena-Barbero et al., 2023). Therefore, different weights could be attributed to give different importance to C or S and their respective indicators, depending on the particularities of the case study or the approach followed to perform a sensitivity analysis (Mantalovas and Di Mino, 2020).

2.3.3. *Aggregation into a single index*

Finally, aggregation into a single index is performed according to **Equations (3)–(5)**.

$$C_n = \sum_{c=1}^{C} W_c \cdot N_{n,c} \tag{Equation 3}$$

$$S_n = \sum_{s=1}^{S} W_s \cdot N_{n,s} \tag{Equation 4}$$

$$CI_n = C_n + S_n \tag{Equation 5}$$

Where:

n	option “n” being evaluated
C_n	circularity aspect (0–50) score for option n
S_n	sustainability aspect (0–50) score for option n
c	circularity sub-indicator
s	sustainability sub-indicator
C	total number of circularity sub-indicators
S	total number of sustainability sub-indicators
W_c	weight of circularity sub-indicator
W_s	weight of sustainability sub-indicator
$N_{n,c}$	normalised value (0–1) for circularity sub-indicator and option n
$N_{n,s}$	normalised value (0–1) for sustainability sub-indicator and option n
CI_n	composite index (0–100) being evaluated for option n

2.4. *Step IV: interpretation of results*

After the calculation of the single index for the system or product in question, the last step is the interpretation of the results. For this purpose, it is recommended to group the results in order to carry out a comparative analysis and distinguish particularities or trends. The identification of critical points that contribute most to the single score should be carried out in order to implement improvement strategies aimed at minimising environmental, economic and social impacts, while representing an improvement in the C profile of the system or product under study.

3. Case study

The four steps of the CISU framework previously described in **Section 2** were herein adapted to evaluate the dairy sector in the form of a framework extension called CISUDASE. In addition, it was applied to a specific case study: raw milk produced on 50 dairy farms in the region of Galicia (NW Spain). The CISUDASE framework and the data collected for the 50 dairy farms are described in **Section 3.1** and the results and discussion are presented in **Section 3.2**.

3.1. *Integration of circularity and sustainability indicators in the dairy sector (CISUDASE)*

The CISUDASE framework is summarized in Fig. 2.

Likewise, given the large number of tables and equations used during the methodological process, the Supplementary Material (SM) includes a figure (Figure SM1) showing the initial data available, as well as further information used to estimate each of the indicators considered in the framework.

3.1.1. *Step I: selection of indicators*

The following C and S indicators were applied to calculate the single index (named Composite Dairy Farm index - CDFi) for each dairy farm evaluated.

3.1.1.1. Circularity indicators. Three indicators emerge to estimate the C of dairy farms: (A) minimise external resource input, (B) optimise production-consumption system and (C) maximise waste prevention.

3.1.1.1.1. Minimise external resource input. This indicator is used for estimating the level of minimisation of external resource input, applied to dairy farms is their self-sufficiency in milk production. Such autonomy can be considered as having the capacity to produce in the vicinity or attached crop fields the total amount of feed required by the cattle (Fernandez-Mena et al., 2020) or the availability of their own means to fertilise the crop fields (e.g. cow manure) and consequently, avoid dependence on external suppliers (Grillot et al., 2018). Hence, three sub-indicators have been proposed to estimate resource input:

- Feed autonomy: This indicator measures the extent to which the farms’ own crop fields provide feed to livestock mainly in the form of grass, maize and silage. If this feed is not sufficient to meet the dietary requirements of the animals, farms must purchase feed from other suppliers outside the region being evaluated. Therefore, the higher proportion of feed produced by the farms compared to those that have had to be purchased elsewhere translates into greater

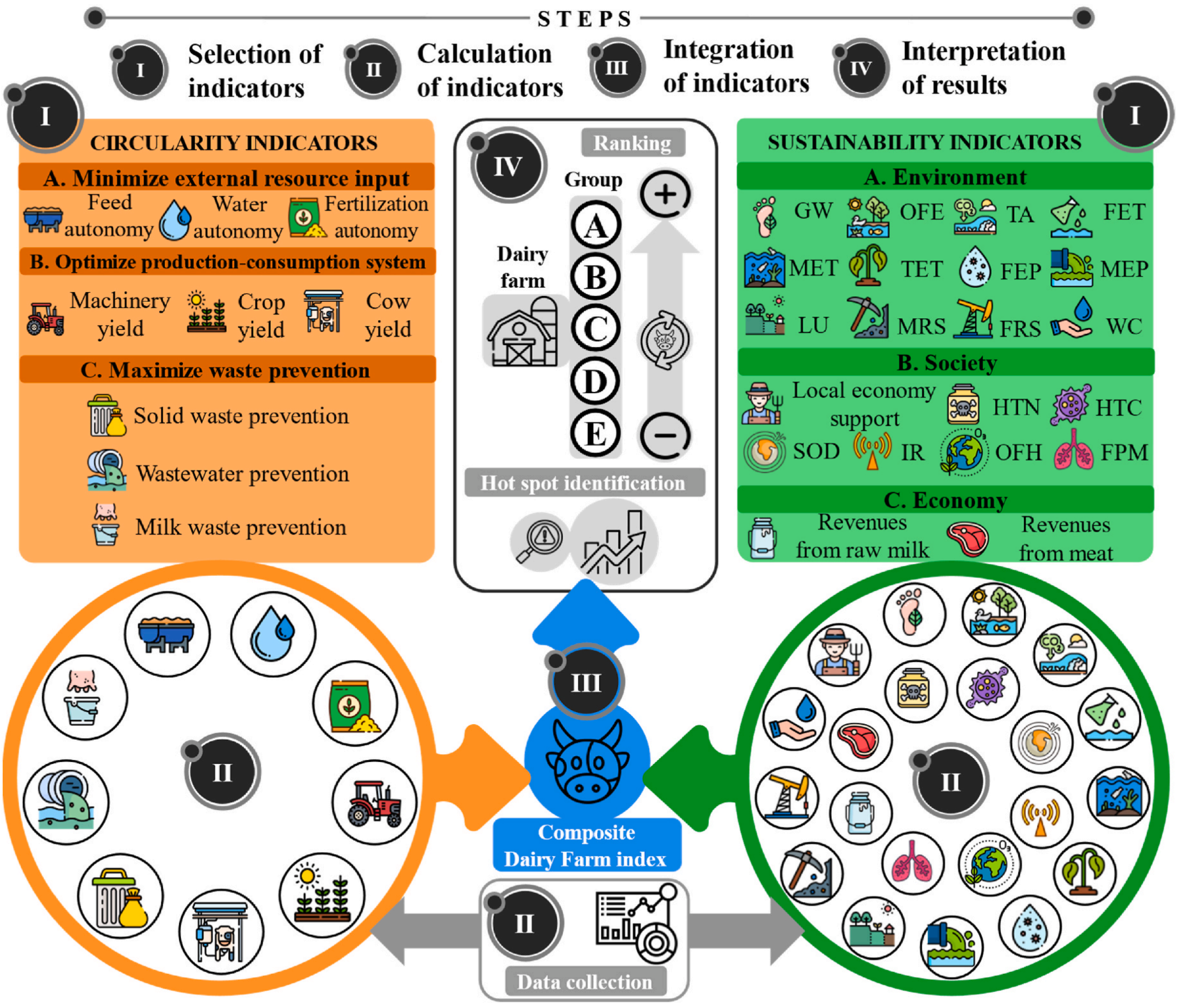

Fig. 2. Framework extension for the integration of CIrcularity and SUstainability indicators in the DAiry SEctor (CISUDASE). GW: global warming; OFE: ozone formation, terrestrial ecosystems; TA: terrestrial acidification; FET: freshwater ecotoxicity; MET: marine ecotoxicity; TET: terrestrial ecotoxicity; FEP: freshwater eutrophication; MEP: marine eutrophication; LU: land use; MRS: mineral resource scarcity; FRS: fossil resource scarcity; WC: water consumption; HTN: human non-carcinogenic toxicity; HTC: human carcinogenic toxicity; SOD: stratospheric ozone depletion; IR: ionising radiation; OFH: ozone formation, human health; FPM: fine particulate matter formation.

autonomy for the farmers. Therefore, this indicator gives an estimate of the level of independence of the dairy farm in terms of meeting the dietary needs of the cows.

- Water autonomy: Water used on farms for drinking, cleaning and hygiene can come from own or external sources, i.e. from wells or from the mains supply, respectively. Water can be used for drinking (cows only), cleaning (milking parlor) and hygiene (cows and farmers). Then, the availability of well water compatible with a greater number of different uses can translate into greater autonomy to cope with water shortages or possible leaks that may occur in the general water supply network.
- Fertilisation autonomy: The use of organic fertiliser is related to the minimisation of commercial synthetic fertilisers.

3.1.1.1.2. Optimise production-consumption system. Another aspect to consider when measuring the C of farms is the efficiency of their milk production system. More efficient production systems translate into lower resource demand per litre of raw milk produced (Vasa et al., 2017). Thus, three sub-indicators within the productive chain have been chosen to describe this indicator:

- Machinery yield: The amount of feed provided by the crop fields in relation to the fuel needed to run the fleet of agricultural machinery.
- Crop yield: The area of crop fields in relation to the amount of feed produced.
- Cow yield: The raw milk production of dairy cows relative to the total feed intake (from crops and elsewhere) provided by farmers.

3.1.1.1.3. Maximise waste prevention. The waste management system for dairy farms is usually very similar, with waste streams being transported to specialized managers (i.e. recycling or energy recovery plants and wastewater treatment plants, for solid and liquid waste, respectively). However, according to the waste hierarchy established by the European Union in the Waste Framework Directive 2018/851 (European Parliament, 2018), the option of preventing waste generation should be the preferred option. Therefore, it has been decided to differentiate farms on the premise of proportion between the amount of milk produced and the generation of waste streams, either in the form of solid waste (e.g. plastics from silos), liquid waste (e.g. wastewater from cleaning water) or milk waste. Three sub-indicators can be derived from the above:

- Solid waste prevention: The proportion of solid waste in relation to raw milk produced by dairy cows.
- Wastewater prevention: The proportion of wastewater in relation to the raw milk produced by dairy cows.

- Milk waste prevention: The ratio of milk loss due to mastitis in relation to the raw milk produced by dairy cows.

3.1.1.2. Sustainability indicators. Following the CISU framework, the S of the milk production process was evaluated considering the three pillars for which it is composed as indicators: (A) environment, (B) society and (C) economy, this practice being also common in previous studies on dairy production (Segerkvist et al., 2020).

3.1.1.2.1. Environment. For the assessment of the environmental performance of the dairy farms, 12 life cycle impact categories from the ReCiPe Midpoint 2016 method (Huijbregts et al., 2017) were considered as sub-indicators: global warming (GW); ozone formation, terrestrial ecosystems (OFE); terrestrial acidification (TA); freshwater ecotoxicity (FET); marine ecotoxicity (MET); terrestrial ecotoxicity (TET); freshwater eutrophication (FEP); marine eutrophication (MEP); land use (LU); mineral resource scarcity (MRS); fossil resource scarcity (FRS) and water consumption (WC). They were selected because they represent the most critical life cycle environmental issues related to milk production (EDA, 2018).

3.1.1.2.2. Society. All social aspects of the UNEP LCA methodological sheets should be considered whenever possible. For the specific case study of the 50 Galician dairy farms, certain social aspects have been neglected based on the accessibility of information in this work. In this sense, most of the subcategories covering "working" stakeholders have not been considered, such as fair salary, working hours or forced labour. This is because all farms are certified with the "Galega 100%" quality label, which in addition to guaranteeing the origin of milk from Galician dairy farms, also entails another series of requirements, such as animal health and welfare, in addition to restrictive food safety conditions (Xunta de Galicia, 2011). Moreover, these are located in the same geographical region and are part of the same agri-food cooperative. Consequently, it is expected that the farms studied are managed with the same worker policy and follow very similar processes. As this study only covers the production process stage, the stakeholder categories "society", "value chain actors", "consumer" and "children" are outside the scope of this assessment. Consequently, sub-indicators have been proposed to convey the particularities of the social aspects of the system under study considering the two most commonly used stakeholder categories in SLCA: "local community" and "worker" (Tragnone et al., 2022):

- Supporting the local economy (part of the "local community" stakeholder category): As explained above, to meet animal feed requirements, farmers must purchase feed from external suppliers (e.g. other regions). Therefore, this indicator represents the relationship between workers and the local community, more precisely in terms of evidence of a connection between primary buyers (farmers) and local employment. This indicator has been estimated taking into account the distances from supply centers to farms as well as the amount of feed purchased externally, as shorter distance and less feed purchased is an indication not only of less environmental impact and nutritional safety for the cows, but also of supporting the local economy as well as fostering the creation of closer working relationships between workers and the community.
- Health and safety (part of the "worker" stakeholder category): six indicators of the ReCiPe Midpoint 2016 method have been chosen, that is stratospheric ozone depletion (SOD); ionising radiation (IR); ozone formation, human health (OFH); fine particulate matter formation (FPM); human carcinogenic toxicity (HTC) and human non-carcinogenic toxicity (HTN).

3.1.1.2.3. Economy. To assess the economic aspect of dairy farms through a LCC, it is common to consider profitability as the difference between total costs and revenue from sales of milk and any other co-products obtained (meat) (Chen and Holden, 2018). Unfortunately, information in terms of cost was not available for the specific case of the 50 farms. Consequently, two indicators can be used:

- Revenues from raw milk: gross profit earned through milk production from dairy cows.
- Revenues from meat: gross profit obtained through meat production from slaughtered cows.

3.1.2. Step II: calculation of indicators

3.1.2.1. Data collection. Data collection procedures appear in Section I of SM.

3.1.2.2. Circularity indicators. The following are the procedures to be followed in calculating the C sub-indicators:

3.1.2.2.1. Minimise external resource input.

- Feed autonomy: The percentage (%) of the annual amount of feed obtained from crops (kg) compared to the total amount required to meet the nutritional needs of cows per year (kg of total feed, summed from feed produced by crops together with that from external suppliers) should be considered. For its estimation, Equation SM1 and the data in Table SM2 (both in SM) were used.
- Water autonomy: A distinction should be made between the sources of water present in the farm: own (well water) or external (mains water). In our specific case study, the crop fields in the 50 farms are only supplied with rainwater. Consequently, the water used in the sample of dairy farms evaluated is suitable for up to three different uses: cleaning, drinking or hygiene. In this way, a comparison (in %) can be made between the number of available water uses provided by own sources and the total number of water uses required by each farm. For its estimation, see Equation SM2 and the data in Table SM6 in SM.
- Fertilisation autonomy: For its estimation, the percentage (%) of the annual apport of organic fertilisers (cow manure) used on crops in relation to the total amount required to meet the nutritional needs of the fields (sum of organic and synthetic fertilisers) should be taken into account. To compare organic and synthetic fertilisers, a common unit was chosen for both: kg of N, since although each synthetic fertiliser has different compositions in terms of N, P and K, N was the most predominant element among the fertilisers used in the dairy farms analyzed. Equation SM3 and the data from Table SM2 in SM were used for its estimation.

3.1.2.2.2. Optimise production-consumption system.

- Machinery yield: The ratio ($kg{\cdot}L^{-1}$) of the annual amount of feed obtained from the crops (kg) in relation to the amount of fuel (L) used by the agricultural machinery fleet per year can be considered. For its estimation, Equation SM4 and the data from Table SM2 in SM were used.
- Crop yield: The ratio ($kg{\cdot}ha^{-1}$) of the annual amount of feed obtained from the crops (kg) compared to the field territory (ha) can be used. For its estimation, Equation SM5 and the data from Table SM2 in SM were used.
- Cow yield: It can be used the daily ratio of the amount of raw milk produced by the dairy cows (L raw milk$\cdot$(cow$\cdot$day^{-1})) to the amount of feed provided for the dairy cows (kg feed$\cdot$(cow$\cdot$day^{-1})). For its estimation, Equation SM6 and the data from Tables SM1 and SM4 in SM were used.

3.1.2.2.3. Maximise waste prevention.

- Solid waste prevention: Consideration should be given to preventing the amount of solid waste (kg of waste) in relation to the amount of raw milk produced (L raw milk). For its estimation, Equation SM7 and the data from Tables SM1 and SM7 in SM were used.
- Wastewater prevention: The amount of wastewater (L wastewater) should be considered in relation to the amount of raw milk produced (L raw milk). For its estimation, Equation SM8 and the data from Tables SM1 and SM7 in SM were used.

- Milk waste prevention: The amount of food waste (L milk waste due to mastitis) in relation to the amount of raw milk produced (L raw milk) should be considered. For its estimation, Equation SM9 and the data from Tables SM1 and SM7 in SM were used.

3.1.2.3. Sustainability indicators

3.1.2.3.1. Environment

3.1.2.3.1.1. Goal and scope definition

In this section an attributional LCA should be proposed to calculate the sub-indicators of the environmental performance of the raw milk production processes in 50 Galician dairy farms. For this purpose, the system boundaries of the dairy farms can be defined following a "cradle-to-farm gate" approach, as reflected in Fig. 3.

In line with the International Dairy Federation (IDF, 2015), the functional unit (FU) selected to estimate the impacts should be 1 kg of Fat- and Protein-Corrected Milk (FPCM), estimated using **Equation (6)**. This FU was selected for two main reasons: (1) it allows determining the energy content of milk, avoiding variations among breeds or feeding patterns, and (2) it constitutes the most predominant FU among the studies available in the literature, which facilitates the interpretation and comparison of the results obtained (Mancilla-Leytón et al., 2021).

$$FPCM = MP \cdot (0.1226 \cdot F + 0.0776 \cdot P + 0.2534) \qquad \text{Equation 6}$$

Where:

FPCM	fat- and protein-corrected milk produced by year (kg·year^{-1})
MP	annual milk production (kg·year^{-1})
F	milk fat content (4%)
P	milk protein content (3.3%)

3.1.2.3.1.2. Inventory analysis

For our specific case study, reliable primary data were collected from the 50 dairy farms in relation to an annual productive campaign (the year 2020, see **Tables SM1-SM7** in SM). However, since the farm outputs are both raw milk and meat, it was necessary to perform an allocation procedure for the corresponding environmental burdens. Therefore, a biophysical allocation between raw milk and meat was performed as shown in **Equations (7)–(9)**, this method being the most commonly used in LCA modelling of dairy farm systems (Kyttä et al., 2022).

$$MMR = \frac{LWAS}{FPCM} \qquad \text{Equation 7}$$

$$AF_{milk} = 1 - 6.04 \cdot MMR \qquad \text{Equation 8}$$

$$AF_{meat} = 1 - AF_{milk} \qquad \text{Equation 9}$$

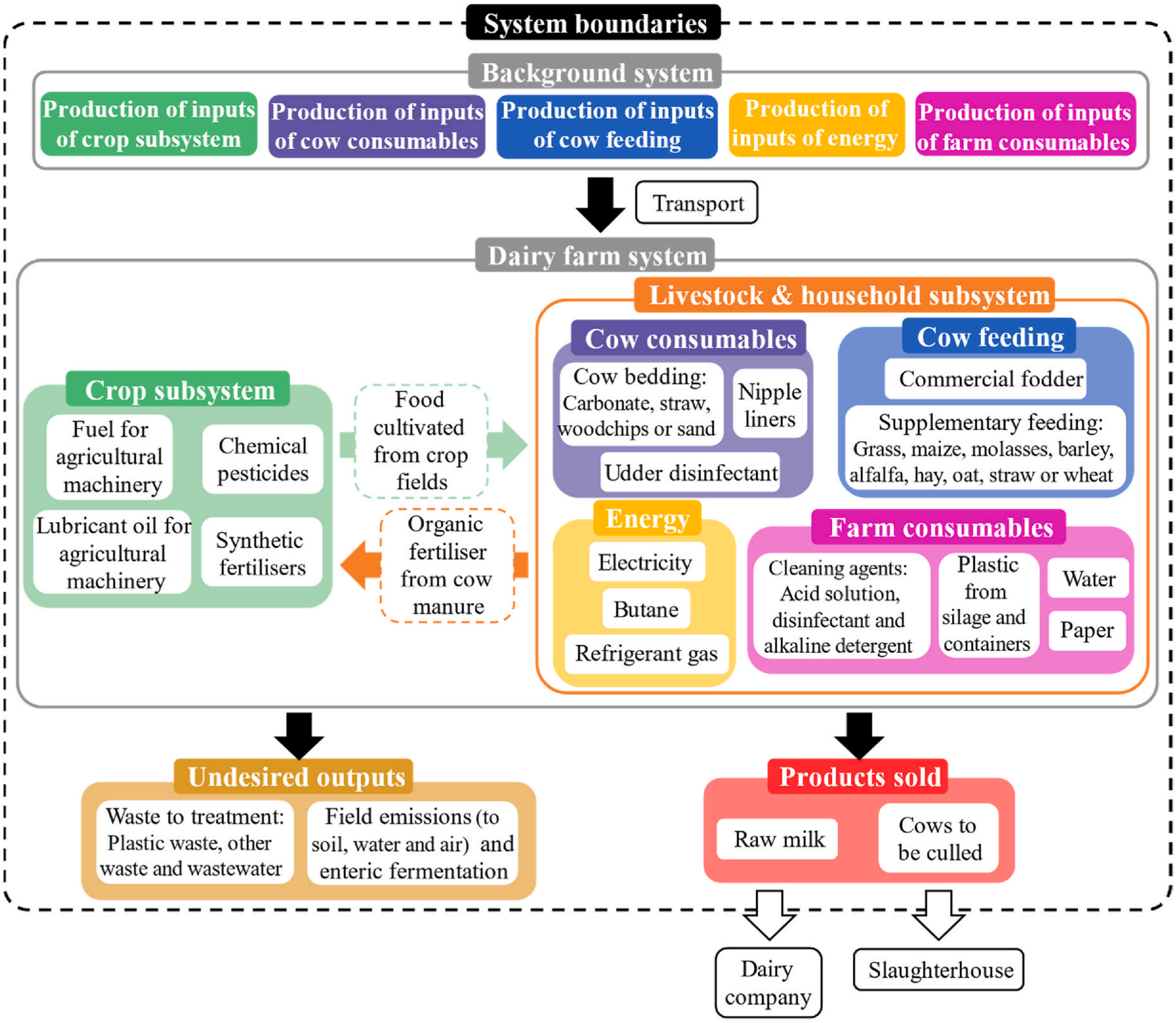

Fig. 3. Boundaries of the dairy farm system, from the production of the inputs in the background system up to the production of outputs along with other undesirable products.

Where:

MMR	meat to milk ratio
LWAS	live weight of animal sold by year ($kg \cdot year^{-1}$)
AF_{milk}	allocation factor of milk
AF_{meat}	allocation factor of meat

The results for the FPCM, LWAS and AFs from milk and meat for the 50 dairy farms are shown in Table SM8in SM. In addition, the following assumptions have been necessary during the impact assessment calculations in the modelling phase of the LCA:

- Direct emissions of GHGs to air from agricultural practices (soil and manure management) and from livestock (enteric fermentation) were estimated using the recommendations of the Intergovernmental Panel on Climate Change guidelines (IPCC et al. (2019): (i) methane (CH_4) from enteric fermentation and manure management, (ii) nitrous oxide (N_2O) from manure and soil management (manure application to soil).
- Direct emissions from the combustion of fuels (normally diesel or natural gas) were modelled using the updated EMEP/EEA air pollutant emissions inventory guidebook (EMEP/EEA, 2019).
- Indirect emissions of ammonia (NH_3) and nitrate (NO_3^-) from manure and soil management (N_2O) were calculated according to IPPC guidelines (IPCC et al., 2019), while distribution factors of 90 % and 10 % were applied to ammonia and nitrate, respectively (Denier Van Der Gon and Bleeker, 2005).
- Direct emissions from synthetic fertilisers application were assessed as: (i) phosphate (PO_4^{3-}) to groundwater by leaching and to surface water by run-off; (ii) phosphorus (P) from water erosion (i.e. removal of soil by water) to surface water; and (iii) heavy metals (Cd, Cu, Zn, Pb, Ni, Cr) to ground and surface water and through soil erosion (Nemecek et al., 2019).
- The distribution of the active ingredients from the chemical pesticides applied was calculated using the PestLCI Consensus model (Fantke et al., 2017), which allows to differentiate among the three compartments: soil, water and air.

To illustrate the life cycle inventory of the farms, the average result of the 50 farms studied can be consulted in Table SM9 in SM.

3.1.2.3.1.3. Impact assessment

For our specific case study, the ReCiPe 2016 hierarchist Midpoint (v1.06) World (2010) method was used for the impact assessment (Huijbregts et al., 2017). In this study, the background processes were modelled using the Ecoinvent database (v3.8) (Wernet et al., 2016), while the SimaPro (v9.1) software was considered to carry out the modelling and calculation procedures.

3.1.2.3.1.4. Interpretation of the sustainability results

In addition to providing indicators for the assessment of the environmental aspects in the CISUDASE framework (see **Section 3.1.1**), the results of the previous step (i.e. impact assessment) can be also used to estimate and identify hot spots of dairy farms related to health and safety indicators (see **Section 3.2.3**).

3.1.2.3.2. Society. The procedures to carry out the calculation of the social indicators are shown below.

- Support to the local economy can be calculated through the sum of the products of the distances (in km) from the destination (dairy farm) to the origins (supply centers) by the amount of feed purchased (in t), depending on the type of feed. Therefore, this indicator may vary according to the different types of feed required (maize, grass, alfalfa, straw, oat, molasses, commercial fodder or others). On the other hand, the distance from the centers which supply the commercial fodder has been assumed to be, on average, 40 km for all the farms according to the information provided by AGACA. For its estimatation, see. Equation SM10
- Health and safety indicators (HTN, HTC, SOD, IR, OFH and FPM) can be calculated following the same procedure previously described for the environmental indicators.

3.1.2.3.3. Economy. The economic indicators were calculated from data on the average annual selling price of raw milk (in € per litre of raw milk produced) and meat (in € per kg of meat sold) for each farm. The "revenues from raw milk" sub-indicator was calculated using total annual revenue from milk sales divided by the number of dairy cows, while the "revenues from meat" sub-indicator was estimated using total annual revenue from meat sales divided by the number of cows slaughtered. For their estimations, see Equations SM11 and SM12 in SM.

3.1.3. Step III: integration of indicators

The integration of the indicators into the CDFi for each dairy farm should be performed in three consecutive phases as described in **Section 2.3**: (i) normalisation, applying **Equation (1)** to the circular and economic sub-indicators; and **Equation (2)** to the environmental and social sub-indicators, since they are directly and inversely proportional to the CDFi, respectively, (ii) weighting, following a perspective of equality among all the indicators considered (see Table 1), and (iii) aggregation into the CDFi by applying **Equations (3)–(5)**.

3.1.4. Step IV: interpretation of results

Grouping farms according to the results could help with the analysis. In our specific case study, the 50 farms were classified into 5 different groups (A, B, C, D or E) composed of the same number of farms according to their CDFi. Therefore, the 10 farms at the top of the ranking were assigned with the letter A and so forth to the farms with the lowest score (group E). After that grouping, a detailed analysis of each group should be conducted, including the hot spots of the main sources of impacts and possible C improvements.

3.2. Results and discussion

3.2.1. Calculation of the Composite Dairy Farm index (CDFi)

Each CDFi of the 50 dairy farms is shown in Fig. 4. The non-normalised and unweighted primary results can be consulted in Tables SM10-SM15 in SM.

Given the CDFi results, it is possible to verify that the high homogeneity of the farms stands out. As can be observed, most of the results of the composite index vary between the range of 40–60 points, with the minimum for farm 10 (CDFi 36 points) and the maximum for farm 21 (CDFi 64 points). This homogeneity can be explained by two main reasons: i) the farms are located in the same geographical region; and ii) they are covered by the same agri-food cooperative. Therefore, the combined action of these factors leads to a similarity not only in the production processes of raw milk and fodders for cow feed, but also in terms of waste management systems and selling prices established for raw milk and meat. The above confirms that the analyzed indicators are indeed influenced by the same factors (e.g. geographical boundaries, legislation at regional level and internal regulation of the agri-food cooperative), leading to the average value of 51 (standard deviation ± 7.4) points.

As a consequence, none of the farms achieved a high overall score, since the maximum value of the CDFi is 100 points. The low scores could be attributed to a high number of indicators evaluated (30), making it unlikely that a farm will score well on all of them. However, a variety of indicators is needed when assessing complex concepts such as C or S, while constraints in terms of funding, time and data availability require a range of indicators that are meaningful enough to allow interpretation by stakeholders (Tanzer and Rechberger, 2020). A more detailed interpretation of the CDFi values in terms of C and S shows that the latter has a higher contribution to CDFi (average 29 points) compared to C (average 22 points).

Table 1
Weighting factors assigned to each type of indicators and (sub)indicators. Indicators: minimise external resource input (MI), optimise production-consumption system (PC), maximise waste prevention (WP), environmental (EN), social (SO) or economic (EC) according to the perspective followed.

Aspect						
	Circularity			Sustainability		
Weighting factor applied to each aspect	50			50		
Indicator	MI	PC	WP	EN	SO	EC
Weighting factor applied to each indicator	16.67	16.67	16.67	16.67	16.67	16.67
Number of sub-indicators (C/S)	3	3	3	12	7	2
Weighting factor applied to each sub-indicator (Wc/Ws)	5.557	5.557	5.557	1.389	2.381	8.335

3.2.2. *Ranking of the dairy farms*

The sample of 50 farms was subdivided into five groups composed of ten farms each (groups A, B, C, D and E) according to the CDFi results. This subdivision was made to carry out a more detailed evaluation in identifying trends or particularities among the groups of farms (Fig. 5). As mentioned earlier, the low variability in the CDFi of the assessed farms (Fig. 4) is also observed when divided into groups (Fig. 5). This low variability can be seen, for example, in the small difference of only 21 points between the best group (group A with 61 points on average) and the worst (group E with 40 points on average). Furthermore, the variability between groups follows the same trend, with an average of 6 additional points when moving from one group to another, with the only exception of groups C and D, with only 3 points difference.

A more in-depth analysis of the C indicators shows that the variability among groups regarding the "minimise external resource input" indicator is considerably higher (contribution to CDFi from 7 to 12 points) compared to "optimise production-consumption system" and "maximise waste prevention" (with minimum scores of 5 and 6 and maximum scores of 9 and 8, respectively). These results show "minimise external resource input" indicator has the largest differences, with the additional sum of at least 1 or 2 points each time a group is compared to its higher one. Likewise, in the "optimise production-consumption system" indicator there is a difference of 3 points between groups A and B, while the CDFi for the other groups remains constant with average values fluctuating between 5 and 6 points. Conversely, "maximise waste prevention" is the C indicator where the smallest variation is visualised, starting with a value of 8 points for group A, dropping one point in group B, until reaching group C, where the scores remain fixed at 6 points.

Concerning the S indicators, "environment" and "society" are those with the highest values for each of the 5 differentiated groups, with practically identical values, ranging from 9 to 12 points for the worst (group E) and the best group (group A), respectively. Likewise, although the variance by group is not remarkable for these indicators, ranging from 11 to 12 points for groups A, B and C, it is worth noting that this is where the greatest difference between the lowest scoring groups occurs (mean values of 11 and 9 points for groups D and E, respectively). In contrast, "economy" indicators have relatively low values for all groups, ranging from 5 to 8 points.

Given the results obtained for each indicator, it can be said that "minimise external resource input", "environment" and "society" are the most influential in terms of the total score obtained, although it is the indicator of C that gives rise to the greatest differences in the points recorded among the groups. On the other hand, "optimise production-consumption system" is a key indicator for a dairy farm to be classified in the best group (group A), as this is where the biggest inter-group difference occurs between groups A (9 points) and B (6 points). Environmental and social indicators turn out to be the most relevant to classify the worst groups, with differences of up to 3 points between groups D (11 points) and E (9 points). Therefore, for this case study, "maximise waste prevention" and "economy" indicators were detected as the least significant for the CDFi.

3.2.3. *Identification of hot spots*

"Minimise external resource input" has the highest score and variability within the C indicators of the groups shown in Fig. 5. Therefore, it was analyzed more closely which sub-indicator has the greatest influence on this indicator. All sub-indicators have a convergence between 0 and 6 points in the CDFi, with the averages for the farms being 4, 2 and 3 points for "feed, water and fertilisation autonomies", respectively. Thus, it can be concluded that having feed autonomy was the most influential C sub-indicator for the assessed dairy farms. On top of that, the application of the LCA methodology to calculate the environmental and some social S sub-indicators enables the identification of the exact sources of impact given the categories collected in the LCI (Table SM9 in SM). This can be consulted in terms of their average relative contributions of the 50 dairy farms in Fig. 6 considering the following categories: field emissions and enteric fermentation, cow consumables, energy, waste to treatment, farm consumables, cow feeding, and crop, divided by sub-indicator.

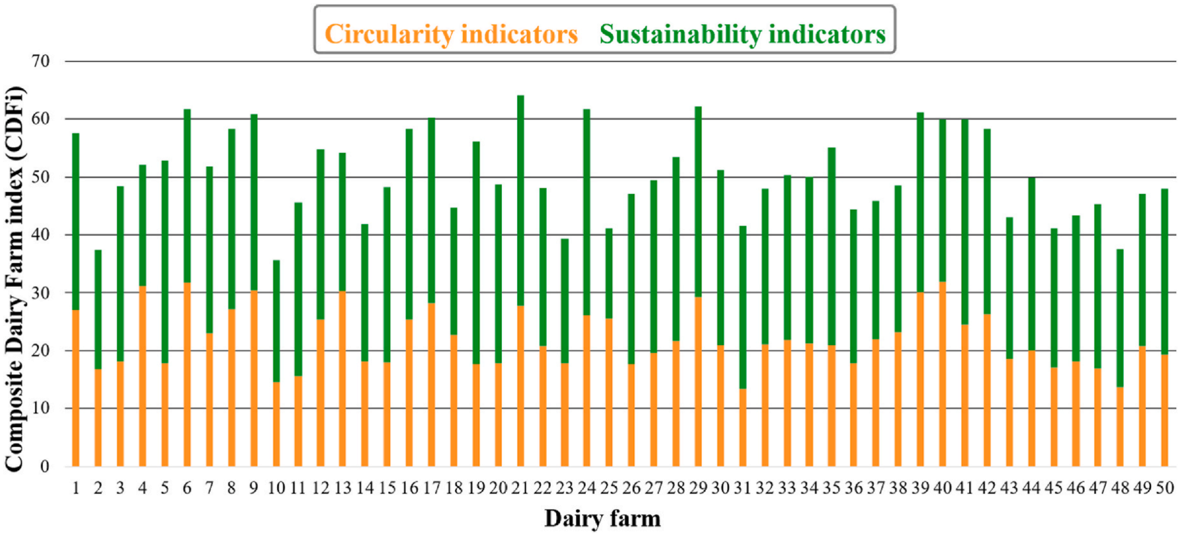

Fig. 4. Composite Dairy Farm index (CDFi) of the 50 dairy farms, being represented in accordance with the contribution of circularity indicators and sustainability indicators.

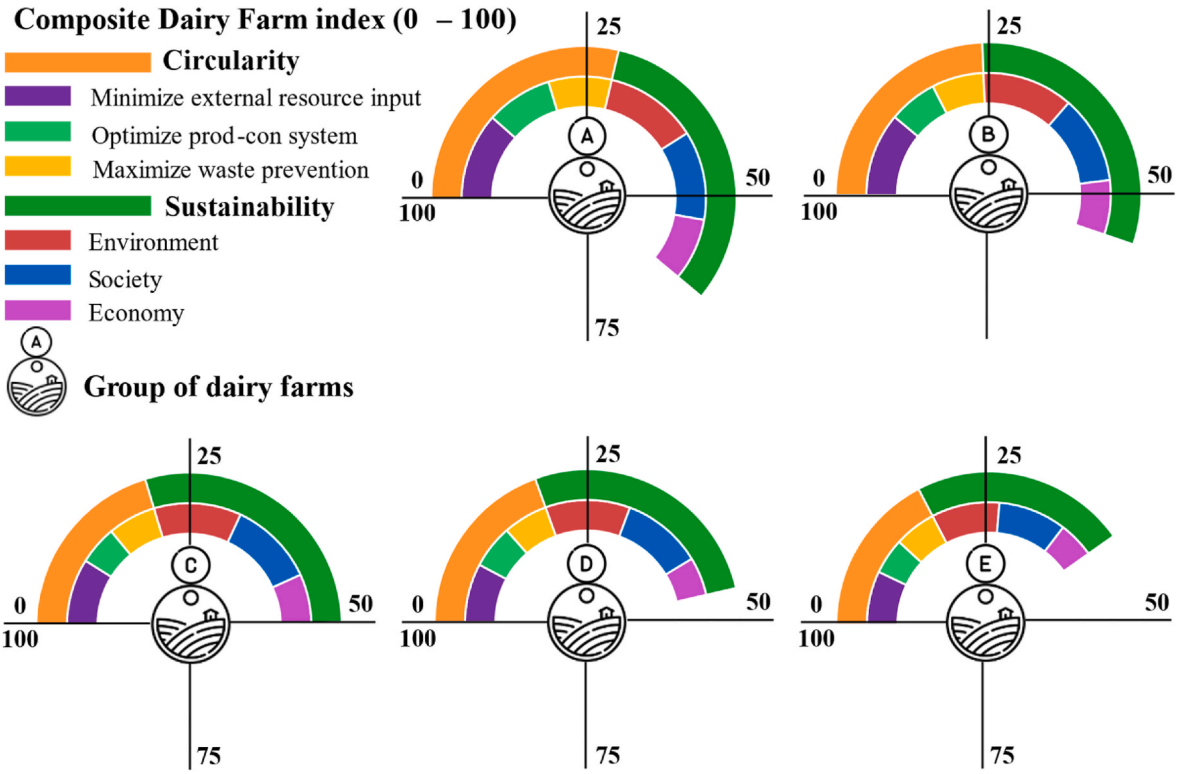

Fig. 5. Average Composite Dairy Farm index (CDFi) divided by aspect (circularity and sustainability) and subdivided indicator for the 5 groups (A, B, C, D and E) within the 50 dairy farms.

As observed in Fig. 6, the field emissions and enteric fermentation and the cow feeding account for almost the total contribution of four sub-indicators (GW, SOD, FPM and TA), with values above 90%. These results are related to the emissions (CH_4, N_2O and NH_3) from agricultural practices (manure management and its application in the soil) and the enteric fermentation by ruminants during the digestion of the food (Krzy zaniak et al., 2020). Likewise, cow feeding turns out to be a hot spot with contributions often exceeding 70% for 11 sub-indicators (OFH, OFE, FEP, MEP, FET, MET, HTN, LU, MRS, FRS and WC). These results are not surprising, as feed-related impacts have been shown to be an important factor in the environmental implications of livestock farming, with a strong correlation with the LU indicator due to the use of large areas of cropland to feed cows (Carvalho et al., 2022).

On the other hand, three indicators (IR, TET and HTC) show different trends. In the case of IR, more than half of the total impact is associated with the energy (i.e. electricity, butane and refrigerant gas), which could be relatated with the generation of electricity from nuclear power plants (35% of the Spanish energy supply during 2019–2021 was provided by nuclear plants (AIB, 2022)). Crop cultivation contributes more than 70% to the TET impact due to the fraction of pesticides remaining in the soil. Finally, in the case of HTC, the contributions of cow feeding (47%) and crop cultivation (38%) are relatively similar and are mainly associated with the use of pesticides and synthetic fertilisers (Mostafalou and Abdollahi, 2017).

Regarding the social sub-indicators, the local economy support sub-indicator proved to have the highest contribution for the CDFi in comparison with the others (SOD, IR, OFH, FPM, HTC and HTN). In addition, this sub-indicator shows to have great disparity among the farms (see Table SM14 in SM). In this sense, the five farms with the highest value (farms 4, 13, 14, 25 and 40) have an average of more than 171,000 t km per year, while the rest of the dairy farms barely exceed 27,000 t km per year, which is translated into general positive values for almost all the farms in terms of CDFi. To reverse this situation, it should be necessary to reduce dependence on food from external sources, apart from betting on local suppliers to meet the food shortage. Finally, since the main source of income of the farms is milk production, the economic indicator of revenues from raw milk prevails over revenues from meat (see Table SM15).

4. Conclusions

Climate change is one of the most prominent issues that modern society needs to face. The food sector (particularly, agriculture and livestock farming) is at the same time a major contributor and victim of this global threat. Notwithstanding, concerns about other environmental impacts, economic costs and social development should be taken into consideration when addressing climate change. Therefore, the concepts of sustainability (S) and circularity (C) have emerged as a way to guide and promote sustainable development. S and C approaches have been included in international initiatives and policies, and methodologies and frameworks for standardization have been developed. However, these two concepts, although interrelated, are today considered separately, resulting in a deterioration of how they can promote synergies. To fill this gap, a novel framework for the integration of CIrcularity and SUstainability indicators (CISU) is proposed to jointly assess both C and S levels in any sector. This same framework has been adapted to evaluate dairy farms (integration of CIrcularity and SUstainability indicators in DAiry Sector - CISUDASE) and has been implemented in 50 farms from Galicia (a region in NW Spain). CISUDASE framework evaluates the production process of dairy farms through a single value in which a multi-criteria perspective is brought together, allowing a clear and easy interpretation for stakeholders (farmers, dairy companies and consumers). Moreover, it can also enable green policies and measures, including stricter restrictions for high-impact tasks in the dairy sector.

The results after applying the CISUDASE framework to calculate the Composite Dairy Farm index (CDFi, ranging from 0 to 100), showed a relative homogeneity among the dairy farms evaluated. This level of

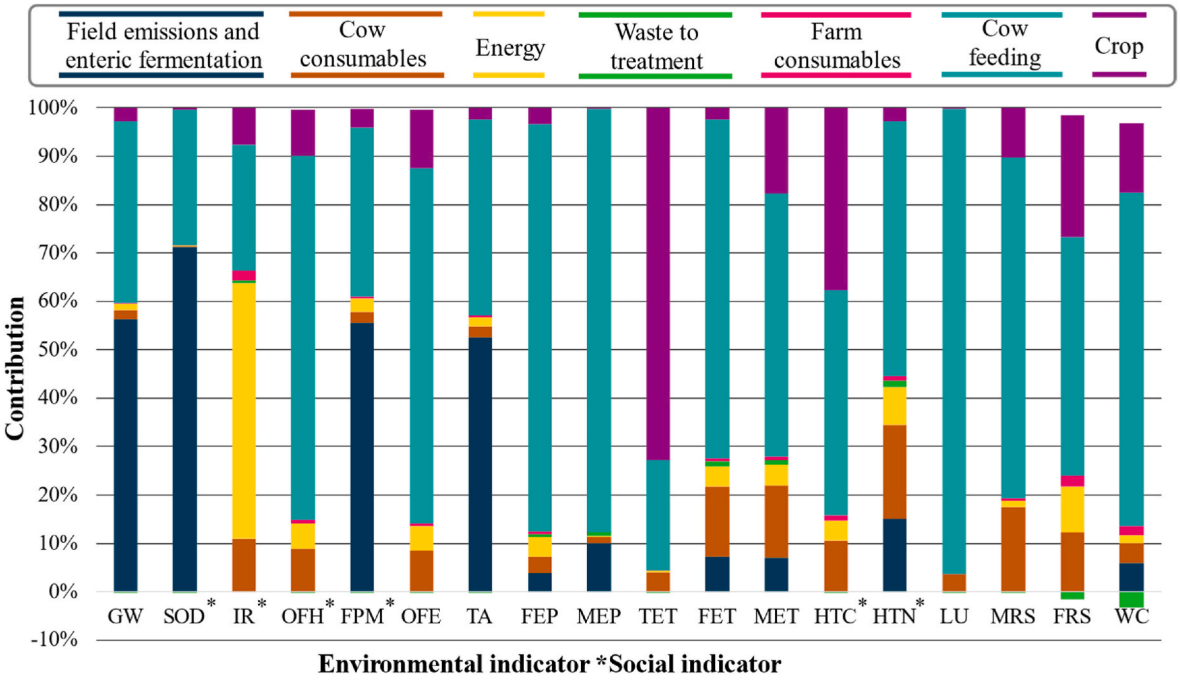

Fig. 6. Relative contributions of the life cycle assessment sub-indicators divided by category on average for the 50 dairy farms. GW: global warming; OFE: ozone formation, terrestrial ecosystems; TA: terrestrial acidification; FET: freshwater ecotoxicity; MET: marine ecotoxicity; TET: terrestrial ecotoxicity; FEP: freshwater eutrophication; MEP: marine eutrophication; LU: land use; MRS: mineral resource scarcity; FRS: fossil resource scarcity; WC: water consumption; HTN: human non-carcinogenic toxicity; HTC: human carcinogenic toxicity; SOD: stratospheric ozone depletion; IR: ionising radiation; OFH: ozone formation, human health; FPM: fine particulate matter formation.

homogeneity is attributed to similarities in their production models (all farms belong to the same agri-food cooperative) and to being located in the same geographical region. The farms obtained relatively low values (51 points on average), showing significant room for improvement, particularly from a C perspective. In this regard, "minimise external resource input" is the most influential indicator for the C result, with the "feed autonomy" sub-indicator being the most important contributor. As far as S is concerned, the environmental sub-indicators of "freshwater ecotoxicity", "marine eutrophication" and "land use" have a higher contribution to the CDFi, standing out mostly from "cow feeding" rate. On the other hand, regarding the social sub-indicators, "local economy support" and "ozone formation, human health" have the most significant contributions. Finally, between the two economic sub-indicators, "revenues from raw milk" is the most influential as raw milk is the main product produced by dairy farms.

The analysis carried out in this paper shows that cattle feeding management is vital to achieve a milk production system that is circular and sustainable. To this end, minimising dependence on external resource input in terms of cow feeding was found to be a key aspect for C. In addition, the use of own-produced fodder on the farm and proper management of crop fields have high implications for S. However, some aspects should be re-evaluated, such as whether S should prevail over C (or vice versa) or the normalisation and weighting factors used for the integration of indicators and sub-indicators (i.e. MCDA) into a single value. In addition, it is vital to include consensus on how to measure C in different sectors or products and to establish specific indicators. On the other hand, although great efforts have been made to quantify environmental impacts considering the life cycle assessment (LCA) methodology, there is usually a lack of information in the literature for more reliable economic (LCC) and social (SLCA) indicators used for S assessments.

Finally, the CISU framework allows the integration of C and S indicators for the case of a company or product (i.e. micro level), to obtain a single value that is easily interpretable to facilitate communication among stakeholders. However, in future iterations it should be modified to overcome three main shortcomings: (i) integration of other important aspects that are interrelated with C and S (e.g. industrial symbiosis), (ii) applicability at other levels (i.e. meso level: district or supply chain), as well as (iii) its scalability so that it can be adapted to the contextual situation of each case study.

CRediT authorship contribution statement

Eduardo Entrena-Barbero: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft. **Raphael Ricardo Zepon Tarpani:** Methodology, Validation, Writing – original draft, Writing – review & editing. **Mario Fernández:** Validation, Writing – review & editing. **María Teresa Moreira:** Project administration, Supervision, Writing – review & editing. **Alejandro Gallego-Schmid:** Methodology, Supervision, 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.

Data availability

Data appears in the supplementary material file

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.142508.

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