



## Water-Energy-Food nexus index proposal as a sustainability criterion on dairy farms



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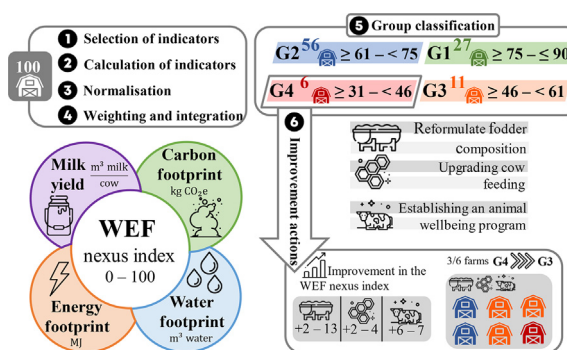
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### HIGHLIGHTS

- A WEF nexus approach is proposed and applied to a sample of dairy farms.
- Cow feeding and milk production levels are the main hotspots.
- Reformulate fodder composition reports significant improvements.
- The WEF nexus index can be a helpful supportive tool for stakeholders.
- Further iterations should focus on the weighting and aggregation procedures.

### GRAPHICAL ABSTRACT



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### ABSTRACT

Cow milk is a fundamental nutrients source for the human diet at all stages of life. However, the decline in cow milk consumption over the years has been driven by increased consumer awareness of animal welfare and the environmental burdens associated. In this regard, different initiatives have emerged to mitigate the impacts of livestock farming, but many of them without addressing the multi-perspective view of environmental sustainability. Thus, the Water-Energy-Food (WEF) nexus emerges as a framework to consider the complex synergies among carbon emissions, water demand, energy requirements and food production. In this study, a novel and harmonised WEF nexus approach has been proposed and applied to evaluate a set of 100 dairy farms. For that, the assessment, normalisation, and weighting of three lifecycle indicators such as carbon, water and energy footprints, as well as the milk yield were carried out to obtain a single value, the WEF nexus index (WEFni), which varies from 0 to 100. Results show that the WEF nexus scores obtained vary from 31 to 90, demonstrating large differences among the farms assessed. A cluster ranking was performed to identify those farms with the worst WEF nexus indexes. For this group, consisting of 8 farms with an average WEFni of 39, three improvement actions focused on the feeding, digestive process and wellbeing of the cows were applied to determine the potential reduction in the two main hotspots identified: cow feeding and milk production level. The proposed methodology can establish a roadmap for promoting a more environmentally sustainable food industry, although further studies are still required in the pathway of a standardised WEFni.

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### 1. Introduction

Milk is considered a mainstay of a healthy diet, not only during growth but at all stages of life, due to its composition based on proteins, fats, minerals and vitamins, among other micronutrients (Marangoni et al., 2019). Moreover, its content in Calcium and vitamin D are linked to the development and maintenance of several physiological processes, such as bones protection or blood coagulation (Pereira, 2014). In terms of production, Europe has consolidated its position as the second largest producer continent in the world, only behind Asia (FAO, 2021). Among the main producing countries in Europe, Spain ranks seventh with more than 5 % of the share (European Commission, 2020). The origin of Spanish milk comes mostly from the Autonomous Community of Galicia, covering around 38 % of total national production from 2015 to 2021 (Fig. 1) with around 6000 dairy farms (IGE, 2020; MAPA, 2022). Nevertheless, despite the recognised importance of dairy milk as a staple food, its consumption by Spaniards has been steadily declining over the years (MAPA, 2020a). The reason behind this trend could be explained by the increased purchase of plant-based alternatives (e.g., oat, rice or soy drinks) mainly due to vegan dietary patterns or food intolerances (Munekata et al., 2020). In addition, other social aspects such as animal welfare, ethical principles or environmental concerns could act as drivers for the transition towards a diet based on animal-free food (Kolbe, 2018).

Regarding the environmental impacts associated with dietary patterns, dairy products were some of the main contributors in certain European and American diets due to greenhouse gases (GHG) emissions and water demand (Cambeses-Franco et al., 2022). In the current climate change crisis, about 15 % of global GHG emissions are linked to agricultural activities, constituting sources of carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O) from enteric fermentation of ruminants, as well as from cropland-related activities (tillage and use of synthetic fertilisers) (Jantke et al., 2020). Likewise, the impact of dairy farms in terms of water demand is also significant, as they represent the third largest contributor in the agricultural sector with a share of 7 %, only behind other products such as meat (22 %) and cereals (27 %) (Mekonnen and Hoekstra, 2012). Regarding energy requirements of the on-farm facilities, animal housing and automatic milking stand out as the principal electricity-consumers (Todde et al., 2018). However, the introduction of this technology has meant a major breakthrough in the dairy sector, allowing production to be increased by up to 12 % (Jacobs and Siegford, 2012). Furthermore, no differences in animal stress were detected compared to cows subjected to hand milking (Jerram et al., 2020).

In the same way, productivity turns out to be a key factor under the premise of the narrow range of profits often associated with milk sales (Hanrahan et al., 2018). Consequently, in order to maintain the economic stability of dairy farms, it is also vital to minimise food losses

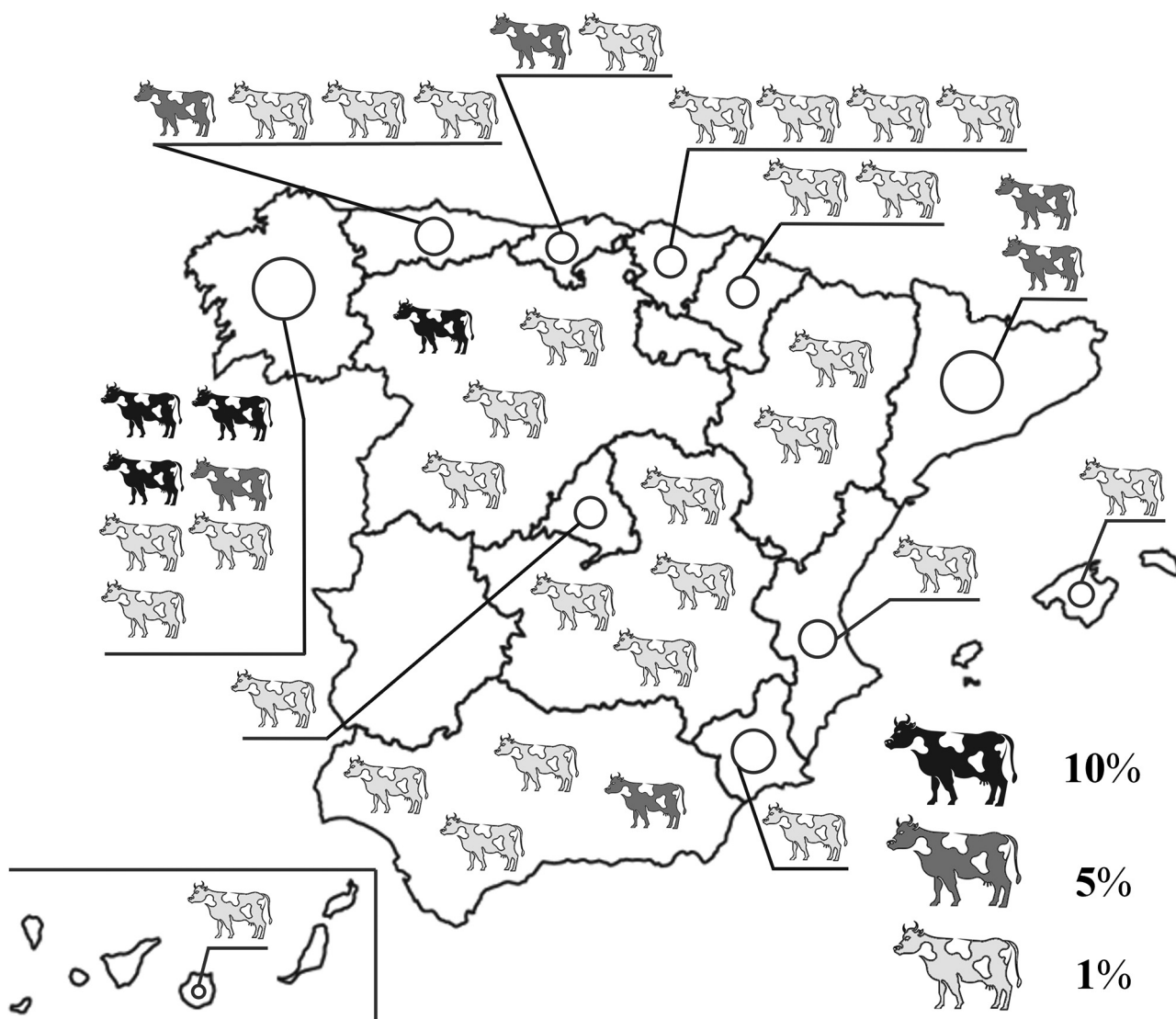


Fig. 1. Average percentage of milk production in the Autonomous Communities of Spain during 2015–2021 (MAPA, 2020b).

(Redlingshöfer et al., 2017). A clear example of this is mastitis, an infectious disease which leads to an inflammation of the mammary glands, resulting in alterations in milk production (Bhakat et al., 2020). Hence, with the purpose of tackling both the environmental and economic concerns related to milk production under the context of new consumption patterns and animal wellbeing awareness of the current society, several strategies have been emerged motivated by regulatory frameworks (Hennessy et al., 2020). Some of them are focused on the reduction of the CH<sub>4</sub> emissions derived from the digestion of ruminants through the application of feeding additives (Kholif et al., 2021). Of these, the addition of algae is proving to be the most convincing action to reduce global warming impacts associated with livestock activities (Honan et al., 2021). Although some studies have shown that this modification in animal feed does not adversely affect the quality of the final product, a longer-term analysis on different algae species, apart from the ideal dosage is essential to obtain plausible results (McCauley et al., 2020). Likewise, in the literature it is observed that mastitis is one of the main diseases in mammary animals (Gupta et al., 2020), constituting significant negative currency implications for the dairy sector (Puerto et al., 2021). Notwithstanding, this could be partly eradicated through the training and education of farmers through routine tasks based on barn cleaning, animal health and general herd welfare (Pettersson-Wolfe et al., 2018). In addition, many others management strategies have been applied to address specific issues such as water scarcity (Payen et al., 2018), energy requirements (Pagani et al., 2016), food waste (March et al., 2019) or climate contribution (Martinsson and Hansson, 2021). Thus, although there is a trend to integrate analytical methodologies such as eco-efficiency and circularity (Rebolledo-Leiva et al., 2022), most studies are focused on specific challenges, overlooking to consider a holistic approach that integrates several of the issues that are related to milk production systems.

It is then that the concept of Water-Energy-Food (WEF) nexus emerges as a framework to consider the complex relationships among water demand, energy requirements, and food supply (Zhang et al., 2018). This approach has been applied to evaluate different systems such as wastewater treatment (Panagopoulos, 2022; Panagopoulos and Giannika, 2022a, 2022b), urban and small landholder farming (Haitsma Mulier et al., 2022; Oviroh et al., 2023), irrigation systems (Cui et al., 2022), local and urban communities (Ding et al., 2023; Huang et al., 2023), among others. Regarding agri-food systems, the WEF nexus approach has been used in the evaluation of different fertilisation practices (Fabiani et al., 2020), combination of dairy farms with short rotation coppice willow systems (Livingstone et al., 2021), and integrative strategies of water savings, renewable energy generation and improvement of animal welfare (Sobrosa Neto et al., 2018). Despite this, no analogous proposal and application in livestock systems have been considered so far with the aim of studying, from a holistic approach, the synergies of the environmental burdens associated with the climate, water and energy perspectives, along with milk production. Thus, the aim of this work is to propose a novel methodology framework under a WEF nexus approach, which is applied for benchmarking a set of 100 dairy farms settled in Spain. For that, an integration procedure was carried out between the GHG emissions, the water demand and energy requirements under a life cycle perspective, as well as the food dimension (considering the milk yield) into one score: the WEF nexus index (WEFni).

## 2. Material and methods

The WEF nexus methodology proposed was applied to a set of 100 farms during an annual milk production campaign. These dairy farms were in the Autonomous Community of Galicia (NW Spain), in the provinces of Lugo (79 farms), La Coruña (18 farms), and Pontevedra (1 farm), whereas two farms (farms 61 and 68) were bordering the Principality of Asturias. All of them are integrated within the same livestock cooperative, which promotes competitiveness by developing actions focused on economic and social cooperation through skill and material support. The farms are equipped with automatic milking systems to carry out the milk extraction stage,

varying the annual production from 269 m<sup>3</sup> to 5289 m<sup>3</sup> of raw milk. Likewise, although most of the income of the farms comes from the sale of milk, they also sell the cows who have passed the lactating stage to slaughterhouses, which translates into the annual production of 600–37,400 kg of meat. The difference in these values come from the size of the herd, varying from 31 to 717 cows, which is made up of lactating and dry cows, as well as heifers. Besides, in most cases, these livestock farms are family-run with around 30 years in business, where smaller animals such as chickens or pigs are also bred to diversify earnings. Regarding the feed system, this is mainly constituted by maize and grass silage coming from the agricultural activity in their own crop fields, which are close to the farm facilities (from 10 to 880 ha). On the other hand, some farms have meadows from which the cows receive an extra nutritional supplement from grazing depending on the grass availability. Notwithstanding, this is not enough to meet the feed demand. Consequently, it is necessary to purchase fodders with different ingredients formulation from four factories that work for the cooperative, apart from any additional cereal required (alfalfa, straw, oat, etc.) from external supply centres. In terms of fertilisation, this is carried out by two different sources: one of them comes from the direct application of commercial synthetic fertilisers, while the other portion is provided by cow manure as organic fertiliser. The management of the latter consists of its storage in covered concrete pits with sufficient capacity to be emptied every three to four months. Thus, it is compatible with the rotational cultivation fields according to the sowing and harvesting periods of grass and maize.

In order to meet the objective of this manuscript, the methodology was divided into six steps (see Fig. 2): (1) selection of indicators that best represent the environmental and food dimensions of the system under assessment, (2) calculation of the chosen indicators, (3) normalisation, (4) weighting and integration into a single score, (5) group classification, and (6) evaluation of improvement actions applied to the group of dairy farms with the worst performance in the WEFni.

### 2.1. Step 1: selection of indicators

To estimate the environmental impacts associated with milk production, three life cycle indicators were selected: carbon footprint (CF), water footprint (WF), and energy footprint (EF). These footprints are traditionally considered when assessing a food system following a WEF nexus philosophy (Laso et al., 2022). On the other hand, the food pillar has been usually estimated through several nutritional indicators, for instance, the nutrient density (Drewnowski, 2009). Nevertheless, in this work the milk yield (MY) per cow was considered. The reason behind this is due to this indicator allows benchmarking a sample of dairy systems that produce the same product (i.e., raw milk). Moreover, the food security concept, one of the core elements of the WEF nexus concept, is addressed through this indicator (Fernández-Ríos et al., 2021).

### 2.2. Step 2: calculation of indicators

#### 2.2.1. Goal definition and functional unit

The CF, WF and EF indicators were calculated employing the life cycle assessment (LCA) methodology under an attributional approach according to ISO 14040 and 14044 guidelines (ISO, 2006a, 2006b). To do this, it was necessary to establish the objective of the study, which was the quantification of the impacts related to the production of 1 L of raw milk (functional unit: FU). This FU was chosen because milk production is the primary function of a dairy farm (Baldini et al., 2017).

#### 2.2.2. Data collection and system boundaries

Primary data from the 100 farms were collected through face-to-face surveys, corresponding to a production period of one year (2020) and identifying all relevant processes related to the farm activities. For that, the recommendations provided by the European Dairy Association (EDA, 2018) were followed, considering the productive system consisting of two stages: the cultivation of feed for the cows (feed crop cultivation) and the care and

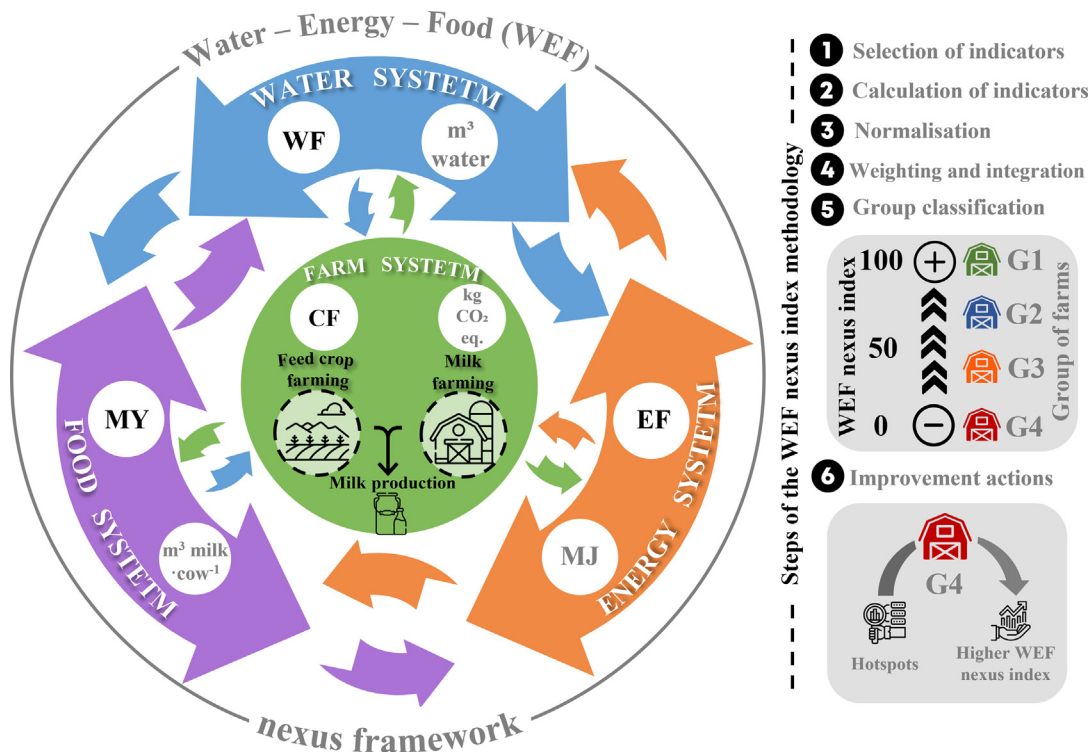


Fig. 2. WEF nexus framework (left side) and steps of the methodology followed (right side) for the implementation of a WEF nexus index (varying from 0 to 100) on dairy farms, calculating a series of indicators: carbon footprint (CF,  $kg\ CO_2\ eq.$ ), water footprint (WF,  $m^3$  of water), energy footprint (EF, MJ), and milk yield (MY,  $m^3$  of milk per cow), as well as the improvement actions for the group with the worst scores (fourth group: G4).

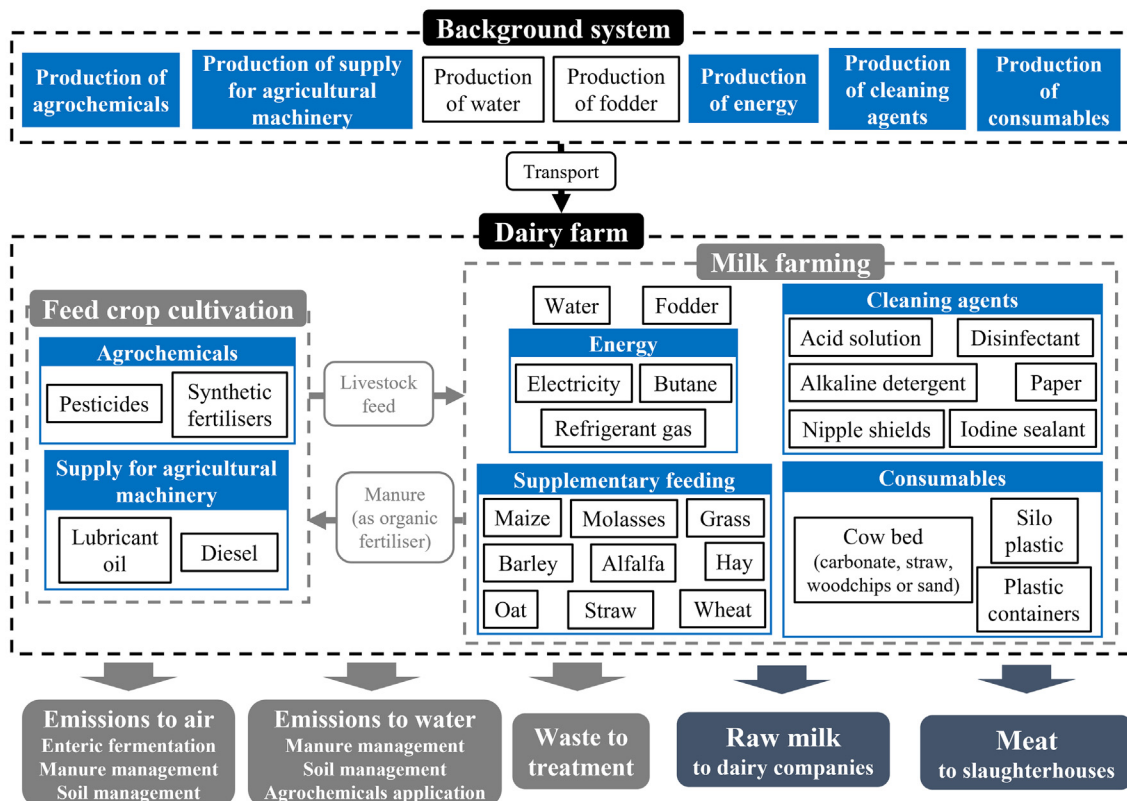


Fig. 3. Boundaries, inputs, products (milk and meat) and undesired flows (emissions to air and water and waste to treatment) of the systems considered (background system and dairy farm) during the milk production.

milking of the cows (milk farming). For the first stage, the agrochemicals (i.e., pesticides and synthetic fertilisers) used on the crops were considered, as well as the supplies needed to carry out the machinery activities (lubricating oil and diesel). On the other hand, the milk farming stage included fodder, water, as well as other flows for sanitation (cleaning products), nutrition (supplementary feeding), rest (cow bedding) and energy (for the milking parlour). In addition, the main waste streams generated by farms (e.g., plastics, cardboard, wastewater) were also recorded. Concerning background processes, the Ecoinvent® database v3.8 (Wernet et al., 2016) was used. With all this information, the system boundary was defined following a cradle-to-farm gate approach. Thus, all processes from raw materials extraction until raw milk production were considered (see Fig. 3).

### 2.2.3. Burden allocation methods

Given that dairy farms under study are multi-functional systems, an allocation method was employed to distribute the environmental burdens between meat and milk products. Mass, economic, and energy allocations are the most used methods for beef and dairy farming systems (Kyttä et al., 2022). However, taking into account that the revenue values used for the economic allocation may be affected by price fluctuations in the Spanish market during 2020 (MAPA, 2020c), and the energy content is similar for all dairy farms, the mass allocation method was selected as the reference approach to carry out the WEFni methodology. Nevertheless, the economic and energy allocation methods were evaluated as sensitivity analysis. To do this, it was collected the production levels and revenues of dairy farms, apart from the energy content of milk and meat for estimating the factors of the mass, economic and energy allocations, respectively. This is presented in the Table SM 101 in the supplementary material (SM).

### 2.2.4. Modelling and assumptions

Regarding fodder production, up to 52 different fodders were used in the sample evaluated, being modelled according to the Ecoinvent® database v3.8 (Wernet et al., 2016) (see Table SM 104). They were characterised based on the relative proportions of the 17 ingredients by which they were constituted (see Table SM 105).

Field emissions play a key role in the environmental performance of agri-food systems. Therefore, emissions from agrochemicals application, manure and soil management, and enteric fermentation were estimated following the Tier 1 of the Intergovernmental Panel on Climate Change guidelines (IPCC, 2019). These emissions were: i) CH<sub>4</sub> from enteric fermentation and manure management, ii) N<sub>2</sub>O, iii) ammonia (NH<sub>3</sub>) and iv) nitrate (NO<sub>3</sub><sup>-</sup>) from manure and soil management (i.e., fertilisers application). In the case of NH<sub>3</sub> and NO<sub>3</sub><sup>-</sup> emissions calculation, the distribution factors reported by Denier Van Der Gon and Bleeker (2005) were employed. This is, the N emitted in the gas phase as NH<sub>3</sub> and NO<sub>3</sub><sup>-</sup> in proportions of 90 % and 10 %, respectively. Regarding the emissions from mineral fertilisers such as: PO<sub>4</sub><sup>3-</sup> (leaching to ground water and run-off to surface water), P (erosion to surface water), and heavy metals (Cd, Cu, Zn, Pb, Ni, Cr) to ground and surface water (leaching), and to the soil (through erosion) were estimated following the guidelines of Nemecek et al. (2019). Pesticide emissions were calculated using the PestLCI Consensus model (Fantke et al., 2017). This model allows for estimating the fraction of the applied quantity of pesticides emitted to soil, water and air. The equations used for their estimation are provided in the section entitled: “Calculation of field and enteric fermentation emissions” in the SM.

Regarding the electricity production mix, data from the Association of Issuing Bodies (AIB, 2019) was taken into account. For the electricity modelling, it was considered the average values of the different generation sources in the electricity grid profile of Spain during a five-years period (2015–2019), avoiding annual energy fluctuations (see Table SM 103). Furthermore, the construction of the infrastructures as well as their maintenance phase are outside the system boundaries. This is often a recurring decision in LCA studies for dairy products, as the contribution of capital goods are not relevant for the environmental footprints (EDA, 2018). In addition, manure from livestock has not been considered as a system product,

as it is reused as organic fertiliser in the feed crops cultivation stage. Finally, the life cycle inventory (LCI) associated to each farm was built and compiled (see Tables SM 1–100).

### 2.2.5. Calculation procedures for the environmental footprints (CF, WF and EF)

To transform the inventory data into environmental impacts, the life cycle impact assessment (LCIA) method must be chosen. For the CF indicator, the characterisation factors relative to the global warming potentials (over a time horizon of 100 years) collected in the sixth assessment report of the IPCC (2021) were employed, following the recommendation suggested by the International Dairy Federation (IDF, 2015). This IPCC report considers, for example, a CO<sub>2</sub> equivalency of 29.8 kg for CH<sub>4</sub> of fossil origin and 273 kg for N<sub>2</sub>O. Regarding the WF indicator, the “available water remaining” (AWARE) method (Boulay et al., 2018) was used in line with the Product Environmental Footprint Category Rules (PEFCR) developed by the European Union (EU) Joint Research Centre (EDA, 2018). In terms of EF, the cumulative energy demand (Low Heating Values) (Frisknecht et al., 2007) was considered, as this is one of the most appropriate LCIA methodologies for environmental evaluations relative to energy requirements, apart from being aligned with the PEFCR. The SimaPro® software v9.4 was used to carry out the calculation procedures for the CF, WF and EF indicators.

### 2.2.6. Estimation of the milk yield (MY)

The productivity of the dairy cows can be measured through the product yield per animal (Gill et al., 2021). Thus, information about the annual milk production, as well as the composition of the herds for identifying the number of cows in lactation stage in each farm were employed. Lastly, the MY indicator was estimated thanks to Eq. (1).

$$MY \text{ (m}^3 \text{ milk} \cdot \text{cow}^{-1} \text{)} = \frac{\text{Annual milk production (m}^3 \text{ milk)}}{\text{Number of lactating cows}} \quad (1)$$

## 2.3. Step 3: normalisation

In this step, all indicators were normalised into a range from 0 to 1 to aggregate the four indicators, as they have different units. This normalisation was carried out using the equation Eq. (2) depending on whether the indicator contributes negatively (CF, WF and EF) or positively (MY: Eq. (3)) to the WEFni.

$$X_{ij} = \frac{Y_i^{\max} - Y_{ij}}{Y_i^{\max} - Y_i^{\min}}, \forall j \quad (2)$$

$$X_{ij} = \frac{Y_{ij} - Y_i^{\min}}{Y_i^{\max} - Y_i^{\min}}, \forall j \quad (3)$$

where:

*i*: indicator, *i* = {CF, WF, EF, MY}.

*j*: dairy farm evaluated, *j* = {1, ..., 100}.

*X<sub>ij</sub>*: normalised value of each indicator *i* of farm *j*.

*Y<sub>ij</sub>*: value of the indicator *i* of farm *j*.

*Y<sub>i</sub><sup>max</sup>*: maximum value of the indicator *i* of the sample assessed (100 farms).

*Y<sub>i</sub><sup>min</sup>*: minimum value of the indicator *i* of the sample assessed (100 farms).

## 2.4. Step 4: weighting and integration

For each analysed farm, the results obtained from the previous step were aggregated into a single score (i.e., the WEFni), through a weighting sum procedure. Thus, a range value of 0–100 was obtained following Eq. (4). The computation of each weight (namely *W<sub>CF</sub>*, *W<sub>WF</sub>*, *W<sub>EF</sub>* and *W<sub>MY</sub>* for each indicator) was conducted using a Multiple Criteria Decision Making (MCDM) method to determine objectively the weights used in the

aggregation procedure (Alemi-Ardakani et al., 2016). One of the most commonly used MCDM approaches is the criteria importance through intercriteria correlation (CRITIC) method (Lin et al., 2020) proposed by Diakoulaki et al. (1995). Briefly, this method uses the results obtained from the normalised indicators (i.e.,  $X_{ij}$  from Eqs. (2) and (3)) to determine the conflict among them through their correlation. In this sense, if there is a strong positive correlation among indicators, the conflict among the normalised indicators will be lower, as well as the assigned weight (Wen et al., 2022). The standard deviation of the sample for each indicator is then used to show the degree of information contained in each one. The higher the standard deviation, the greater the amount of information and, in turn, the higher the weight (Wen et al., 2022). For a more detailed information about the mathematical procedure conducted, see the “CRITIC method” section in the SM.

$$WEFni_j = (X_{CFj} \times W_{CF}) + (X_{WFj} \times W_{WF}) + (X_{EFj} \times W_{EF}) + (X_{MYj} \times W_{MY}) \quad (4)$$

where:

$WEFni_j$ : WEF nexus index of farm  $j$ .

$X_{CFj}$ ,  $X_{WFj}$ ,  $X_{EFj}$ ,  $X_{MYj}$ : normalised value of farm  $j$  for the CF, WF, EF and MY, respectively.

$W_{CF}$ ,  $W_{WF}$ ,  $W_{EF}$ ,  $W_{MY}$ : weight for the CF, WF, EF and MY, respectively.

## 2.5. Step 5: group classification

Once the WEFni was obtained for each dairy farm, a group classification was carried out based on the performance of this score. In this sense, all farms were classified into four groups (G1, G2, G3 and G4) based on quartiles (i.e., each group represent a quartile,  $G1 = Q1, \dots, G4 = Q4$ ). Where the first (Q1) and fourth (Q4) quartile represents the highest and the lowest WEFni values of the sample, respectively.

## 2.6. Step 6: improvement actions

After the group classification, three actions were considered, based on feeding (Froldi et al., 2022) and animal wellbeing (Villettaz Robichaud et al., 2019), to estimate the potential improvement of both environmental and productivity performance, and consequently, the WEFni. In terms of feeding, actions to reformulate the current composition of fodder and to improve cow feeding were evaluated, whereas a welfare programme was considered for animal wellbeing. Moreover, these actions were studied both individually and jointly (as there is no incompatibility between them) under hypothetical scenarios. These actions were applied to the group with the worst WEFni (i.e., G4). In addition, it is important to note that the reformulation of the fodder composition was calculated using data from the analysed farms, whereas the upgrading of cow feeding and the establishment of an animal wellbeing program were estimated using data from the literature. Consequently, the reformulation of fodder composition was focus on the reduction of CF, WF and EF, the upgrading of cow feeding was only related to CF, and the establishment of an animal wellbeing program modifies the 4 indicators that integrate the WEFni.

### 2.6.1. Reformulate fodder composition

Across the sample of dairy farms evaluated, 52 fodders were used with different ingredients formulations. These forages were then subjected to environmental analysis. They were also evaluated nutritionally by identifying their protein content (PC) on a percentage scale of the main ingredients (barley, maize, wheat, soy, rapeseed and oat), which represent nearly 90 % of the total composition. In this way, the one with the lowest environmental impacts will replace the fodders currently used in G4 farms, since the aim was to improve the WEFni as much as possible. According to the CF, WF, and EF values obtained (see Table SM 106), the fodder 52 (F52) from the farm 95 has been selected. This decision is based on the fact that dairy farms belong to the same cooperative and region, which could guarantee the availability of the fodder selected. Therefore, it could be a feasible

practice for farms of group G4 to improve their environmental performance. Later, in Section 3.3, it will be discussed whether the best environmental choice is also a good alternative from a protein-content point of view.

### 2.6.2. Upgrading cow feeding

Two types of feeding additives can be distinguished: inhibitors and modifiers rumen preventing CH<sub>4</sub> emissions (Ungerfeld, 2018). Among the ruminal modifiers, lipids, tannins and essential oils stand out, whereas ruminal inhibitors are made of 3-nitroxypropanol (3NOP), halogens (algae) and nitrates (Haque, 2018). Of these, the addition of algae to ruminant feed is proving to be the most convincing action to reduce global warming impacts associated with livestock activities (Honan et al., 2021). Among them, the seaweed *Asparagopsis armata* is the most promising (Félix et al., 2021). Its addition in a proportion of 0.5 % on the diet could result in a CH<sub>4</sub> reduction equal to 26.4 % without compromising MY or digestive issues (Roque et al., 2019). In this way, this additive has been hypothetically applied to the fodders of group G4. However, the environmental implications arising from its manufacturing stage have not been considered, since although this is a source of uncertainty, 3NOP has demonstrated to have net GHG emissions reductions in dairy cattle (Feng and Kebreab, 2020).

### 2.6.3. Establishing an animal wellbeing program

The FRISKKO health care system (Hogeveen, 2005) for dairy herds was assumed to be implemented in the Galician farms studied. This corresponds to a mastitis preventive program leading to an indirect increase in the MY indicator. The program is a decalogue of actions based on an optimisation and exhaustive control of the cleanliness, resting and general welfare of cows, through practices such as a continuous maintenance of the barn, dry beddings and a good, clean and friendly milking technique. To achieve this, farmers are supported with periodic visits of veterinaries to improve livestock management, avoiding the use of external chemical agents (antibiotics or hormones) (Ekman and Østerås, 2003). Moreover, it is necessary to monitor animals who have previously experienced a mastitis event, because they are more likely to suffer a re-infection. Therefore, milking them last may be beneficial to prevent the spread of the infection (Mbindyo et al., 2020).

Accordingly, the aforementioned health cow care protocol is assumed to be applied in farms from group G4. To do this, the results of a real case study previously implemented in a Galician dairy farm were considered. In that case, a net milk production improvement of 8 % per lactating cow was achieved (Hospido and Sonesson, 2005). In this regard, the higher the amount of milk produced per cow, the higher the MY indicator. In addition, an increase in the total amount of milk produced by the farm will mean that each environmental footprint will decrease when these are relative to each litre of milk produced (i.e., its FU).

## 3. Results and discussion

### 3.1. WEF nexus index

Firstly, after carrying out steps 1 and 2 of the proposed methodology, the results obtained can be consulted in the SM (Table SM 102). From this table, on the one hand, the values of the environmental footprints (CF, WF and EF) were shown based on the three allocation methods used (i.e., mass, economic and energy). Regarding the mass allocation method, which will be taken as the reference to estimate the WEFni of each farm, average values per FU (1 L of raw milk) of 1.15 kg CO<sub>2</sub> eq., 1.04 m<sup>3</sup> and 10.31 MJ were obtained for the CF, WF and EF footprints, respectively. Moreover, it is observed that very similar results were obtained for the other two allocation methods. The reason behind this is due to the very similar allocation factors assigned to the main product, i.e., milk (see Table SM 101). The average values of the allocation factors were 99.5 %, 96.3 % and 98.7 % for the mass, economic and energy methods, respectively. This can be explained since although meat has a higher market price (2.31€) and energy content (1670 kcal) per every kg compared to milk (0.34€ and

650 kcal), the latter is produced in much higher quantities (around 1105 tons of milk and 6 tons of meat produced in every farm per year). On the other hand, in relation to the MY indicator, a range value of 5.45–15.45 m<sup>3</sup> of milk per cow was observed. This shows a large difference among farms, as for the same number of cows, some of them achieve up to three times higher production levels.

Secondly, after the normalisation (step 3), and the weighting and integration procedures (step 4), the WEFni of the farms of each allocation method was obtained (see Table SM 107). Considering the three allocation methods, they obtained very similar results in terms of WEFni. This is mainly due to the same weighting factors assigned to each individual indicator for the mass and energy approaches (25 %, 20 %, 23 % and 32 % for the CF, WF, EF and MY, respectively), while values practically analogous were obtained for the economic allocation: 24 %, 20 %, 24 %, 32 % in terms of CF, WF, EF and MY. Now doing a deeper analysis on the WEFni obtained after selecting the mass allocation (see Fig. 4), an average of 70 was obtained, varying from 31 (farm 52) to 90 (farm 38). In respect of the mean values obtained by each indicator once these have been normalised were 17, 15, 17 and 21 for the CF, WF, EF and MY, respectively.

### 3.2. Group classification

Regarding the group classification step, which divided the sample of the farms into four groups in quartiles equally distributed, after having taken as reference the minimum (31) and maximum (90) values of the WEFni. For each group, Table 1 shows the WEFni range, the number of farms by which they are constituted, and the values obtained for the four individual indicators (with their corresponding standard deviations). From the above table, groups presented very different sizes. On the one hand, most of farms were classified into the G1 and G2 groups (i.e., those with the best scores). About 25 % of the sample were classified in the group G1, while more than half (i.e., 56 farms) were in the group G2 with WEFni values ranging between 61 and 75. On the other hand, a different situation arises for the other two groups. G3 is composed of eleven farms, while G4 is represented by six farms, representing only around 10 % and 5 % of the sample, respectively. This means that up to 83 % of the sample records relative similar results (G1 and G2), with average WEFni of 83 and 70, respectively. The remaining 17 farms stand out for having an average WEFni lower than 55 (G3 and G4).

According to the values obtained for the individual indicators, a more detailed analysis of the main differences among groups was carried out. From this, it was identified that between groups with the best performances, there were fewer differences, especially in CF and EF footprints, having only an increase of 0.13 kg CO<sub>2</sub> eq. and 1.11 MJ, respectively, when G2 was compared with G1. Conversely, the transition from G2 to G3 shows the greatest differences among all indicators, mostly regarding WF, experiencing an increase equal to 0.57 m<sup>3</sup> and 3.85 MJ in the EF indicator. Besides, the largest variation between G3 and G4 occurs in CF and MY indicators, with a rise of 0.30 kg CO<sub>2</sub> eq. and a decrease of 2.29 m<sup>3</sup> of milk per cow, respectively. Among all the groups, EF and MY indicators presented the greatest variations on average and standard deviation values between groups. On the contrary, small differences in terms of CF and WF occur between one group and another. Finally, based on the average values of the WEFni, differences between one group and the next one were similar and with an upward trend: 13 (G1 and G2), 15 (G2 and G3) and 16 (G3 and G4); whereas their standard deviations were decreasing. The above could be related to the smaller differences between the worst scored groups (G3 and G4), because they contain a smaller number of farms in comparison with the best group scored (G1 and G2).

After having analysed the main particularities among groups, a contribution analysis was carried out with the aim of identifying the main hotspots associated with the three environmental footprints addressed (see Fig. 5). Regarding CF, the main hotspot turns out to be field emissions and enteric fermentation, which ranges from 50 % to 55 % of the total. Doing a more detailed analysis of this key contributor, CH<sub>4</sub> emissions produced by the enteric fermentation during the digestion process of ruminants entail up to 55 % of the total emissions. Regarding the field emissions, the management of the cow manure represents a source of CH<sub>4</sub> and N<sub>2</sub>O with a relative contribution of 17 % and 1 %, respectively. Soil management is another N<sub>2</sub>O source, accounting for around a third part of the total emissions (27 %). On the other hand, fodders are in a second place in terms of CF with a contribution ranging from 32 % to 39 %. The differences among groups could be explained, apart from the sizes of the amounts of the rations that are provided to the cows, by the proportion of ingredients that constitute the fodder. On average, all of them are mainly composed of maize (35.5 %), soy (25.7 %), rapeseed (16 %), barley (10.2 %), wheat (2 %), and molasses (1.9 %). Notwithstanding, some farms of G4 employ fodders with relative more proportion of maize (farms 3, 46), soy (farm 66) or both (farm 52), which could be related to their lower scores in terms of WEFni. In relation to the rest of categories, these turn out to be of little importance, since the global contribution of all of them barely exceeds 10 % of the total GHG emissions related to milk production.

Concerning WF, fodders represent the biggest water demander, with an average contribution of 60 %, although for farms of G3 and G4 this value is increased up to 65 %. The second contributor turns out to be the direct

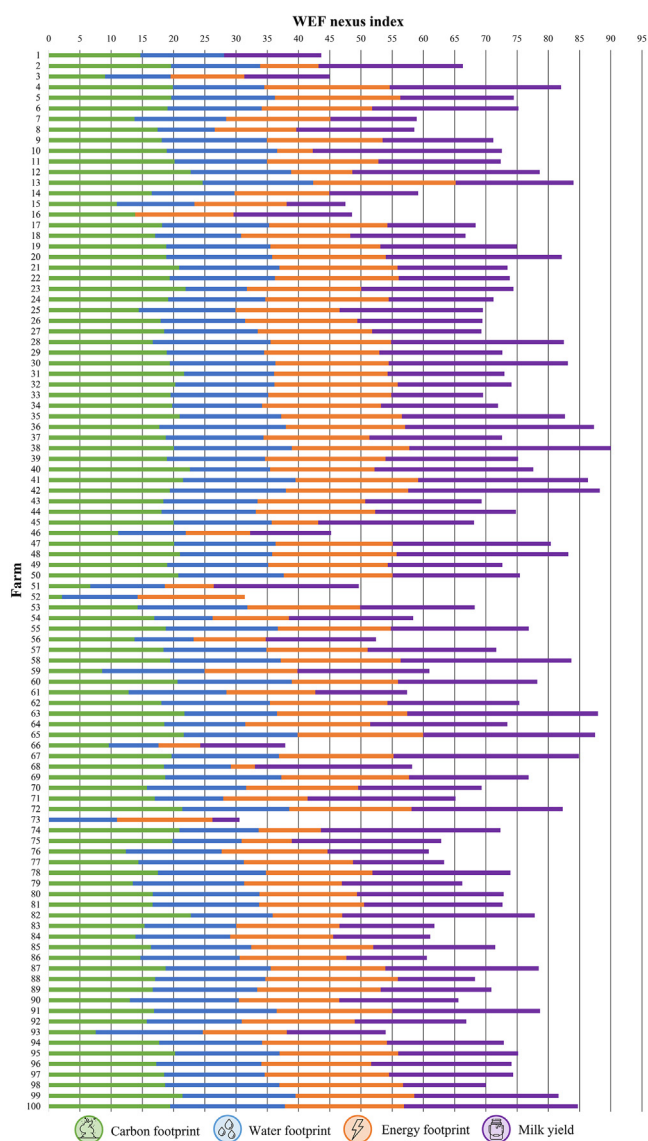


Fig. 4. WEF nexus indexes divided per indicator for the set of 100 dairy farms.

**Table 1**

Group, Water-Energy-Food nexus index (WEFni) range, number of farms, average values (in bold) and standard deviation of the four indicators: Carbon footprint (CF), water footprint (WF), energy footprint (EF) and milk yield (MY), and the WEFni.

Group	WEFni range	N° of farms	CF (kg CO <sub>2</sub> eq.)	WF (m <sup>3</sup> water)	EF (MJ)	MY (m <sup>3</sup> milk·cow <sup>-1</sup> )	WEFni
G1	[75–90]	27	<b>1.00</b> ± 0.29	<b>0.79</b> ± 0.24	<b>8.72</b> ± 5.22	<b>13.69</b> ± 1.95	<b>83</b> ± 6.72
G2	[61–75]	56	<b>1.13</b> ± 0.20	<b>0.99</b> ± 0.60	<b>9.83</b> ± 3.16	<b>11.55</b> ± 1.39	<b>70</b> ± 4.35
G3	[46–61]	11	<b>1.35</b> ± 0.13	<b>1.56</b> ± 0.22	<b>13.68</b> ± 2.73	<b>10.85</b> ± 1.10	<b>55</b> ± 4.25
G4	[31–46]	6	<b>1.65</b> ± 0.10	<b>1.60</b> ± 0.24	<b>15.69</b> ± 2.19	<b>8.56</b> ± 1.08	<b>39</b> ± 3.78

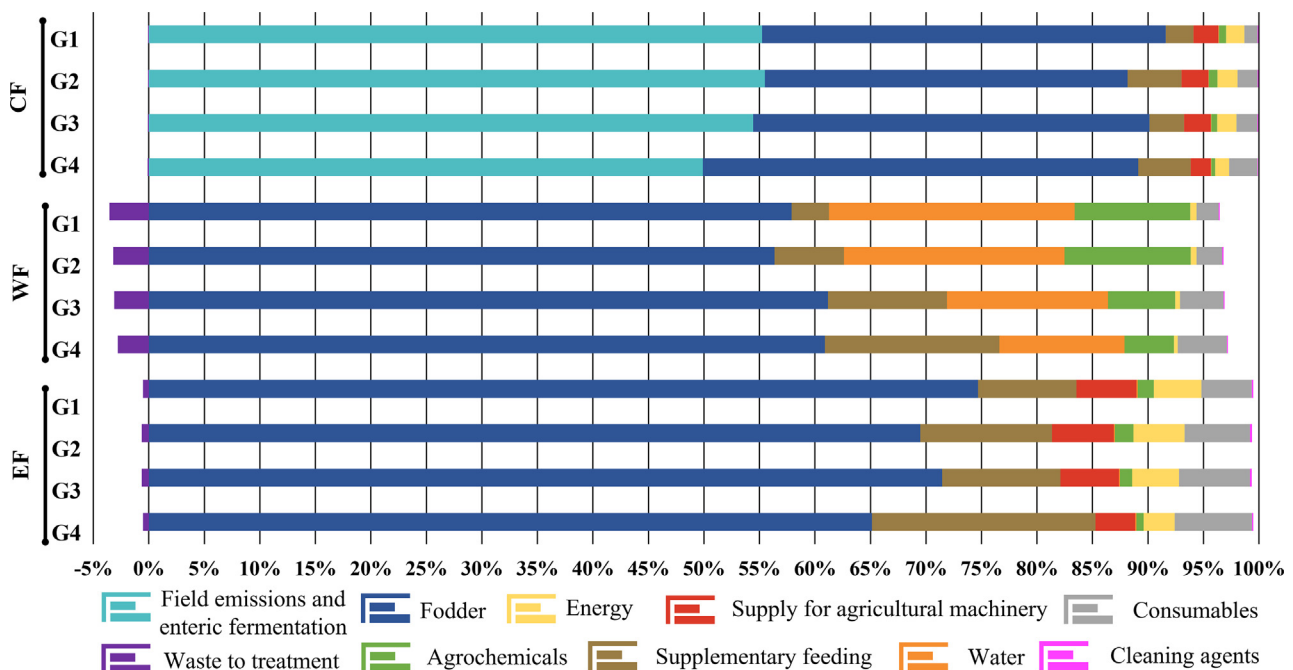
water consumed with different purposes: to hydrate the animals, clean the farmers or sanitize the facilities. These findings are in line with the study conducted by Krauß et al. (2016), in which it was reported that the water employed in the stable for drinking or cleaning purposes was considerably lower in comparison with the water required for feed production. On the other hand, two different trends can be observed in the groups with the highest WEFni (G1 and G2). Here, the supplementary feeding has a much less contribution to the WF in comparison with the production of agrochemicals (around 5 % and 12 %, respectively); while the opposite situation occurs in groups G3 and G4 with contributions of 14 % and 6 % for the supplementary feeding and the agrochemicals production, respectively. The above may be because farms from G1 and G2 require a smaller amount of supplementary feeding to meet the nutritional requirements of the animals, although the water demand goes to the agrochemicals used in the crop fields owned by farmers. With respect to the rest of the categories, the one that stands out the most are consumables, which are around 4 % of the WF.

According to the energy demand, the contribution of fodder once again stands out with values from 65 % to 75 %. Furthermore, the impact of the supplementary feeding is gradually increasing as the WEFni decreases (from values around 9 % to 20 % for groups G1 and G4, respectively), which is analogous to what was observed for the case of the WF. With respect to the remaining contributors, the consumption of consumables (around 6 %) such as cow bedding materials or plastics to carry out forage harvesting work, as well as the consumption of lubricating oil and the use (and combustion) of fuel in agricultural machinery (about 5 %), turn out to be greater contributors in comparison with the direct electricity consumption in the facilities, which only accounts for around 4 %.

**3.3. Improvement actions**

The three improvement actions proposed in this work: reformulating fodder composition, upgrading cow feeding, and establishing an animal wellbeing programme were evaluated, considering both their individual and joint implications, in the six dairy farms of G4 (1, 3, 46, 52, 66, and 73). The potential improvements in terms of WEFni are summarised in Fig. 6.

The reformulation of the fodder composition entails the most promising alternative among the three strategies proposed in four out of six farms of G4. The enhance of the WEFni could be more than 10 points in farms 3 and 66, due to the high environmental impacts of the animal fodder purchased (F2 and F38, respectively). As has been showed previously, fodder constitutes one of the main contributors in the three environmental footprints (see Fig. 5); so, their substitution by one with a lower environmental impact is crucial to obtain a higher WEFni. It is also important to note that these actions aim exclusively at improving the environmental performance of dairy farms of G4. Therefore, further analysis is required to consider, for instance, the economic aspects of this substitution, as cow feeding has demonstrated to be a key aspect for maximising the profitability level of dairy farms (Ruviano et al., 2020). From a nutritional point of view, the action promoted by the substitution of F52 focuses on the proportion of the main components already used by farmers. In this sense, rapeseed (39.81 %), maize (32.48 %) and barley (15.72 %) are the largest components of F52. Therefore, G4 farms should increase or reduce the proportion of these components, where appropriate. For instance, farm 1 should reduce soy and maize proportions, while farms 46 and 52 should reduce the content of maize and soy to increase the amount of barley and rapeseed.



**Fig. 5.** Contribution of each category in the four identified groups (G1, G2, G3 and G4) per environmental footprint: Carbon footprint (CF), water footprint (WF), energy footprint (EF).

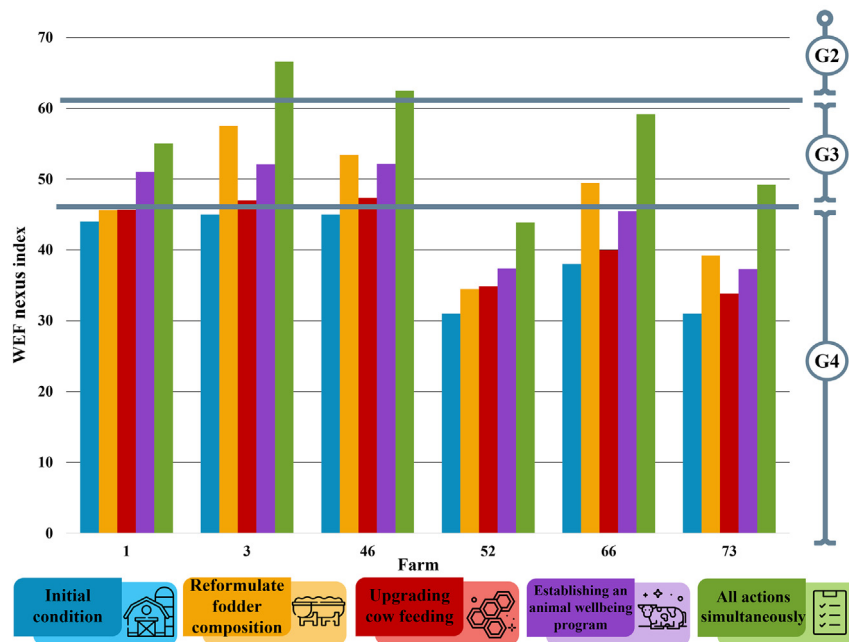


Fig. 6. WEF nexus index of each improvement action, as well as its jointly contribution, in comparison with the initial condition.

On the other hand, comparing the fodder F52 with F38 and F47 used on farms 66 and 73, respectively; the latter have similar maize proportions, while F2 (farm 3) has similar proportions in terms of barley content. In the same way, they all have to reduce the percentage of soy (up to 23 % on farm 66) and increase the rapeseed content (around 40 % for farm 73). This means that, in general terms, feed changes are based on the substitution of protein-rich ingredients. Likewise, the assessment of the protein content (PC) of fodders showed that the proposed substitution is suitable for some farms of G4. The fodder F52 (PC: 20.68 %) presents values close to the average of the rest of the fodders (PC: 20.64 %), constituting a better alternative in comparison with F1 (PC: 20.15 %), F33 (PC: 18.69 %) and F48 (PC: 16.18 %), employed in farms 1, 46 and 73, respectively. Despite the above, F52 is not always the most suitable alternative in terms of protein content, since it involves a lower protein intake compared to F26 (PC: 34.09 %). Based on this, although the PC was measured to evaluate whether the substitution could be optimal in nutritional terms, it has been remarked that the changes proposed in cow feeding have only been justified with the aim of achieving an environmental reduction. Thus, further analysis by animal welfare specialists would be required to avoid any negative consequences in animal nutrition.

In the opposite way, the improvements in the WEFni regarding the upgrading of the cow feeding are not so much effective, since it increases the values about 2–4 points. One of the reasons behind this could be related with the fact that this action only involves the improvement of one of the four indicators which encompass the WEFni. However, in farm 52 this action turns out to be better than reformulating fodder composition. This farm used a fodder (F36) which has a better environmental performance compared to the remaining farms. Furthermore, farm 52 uses a low amount of commercial fodder, as most of the cow feed comes from their own fields. Despite of this, the development of new feed additives to mitigate the CF associated with ruminant digestion is currently being studied (Feng and Kebreab, 2020). Therefore, they can lead to improvements in the fodder formulation to identify the one that best meets the nutritional requirements of cows with a lower environmental burden. To this aim, these new feeding additives must overcome first certain regulatory processes until they become available in the market (Escribano, 2018).

Establishing an animal wellbeing program obtains remarkable and almost identical results for the farms of G4 (varying between 6 and 7 additional points). The good values obtained by this action are justified by the fact that it represents an improvement in all the indicators that make up

the WEFni. This demonstrates the importance of focusing on increasing the performance of the production process, as it will also result in a reduction of environmental impacts when these are relativised by a FU related to the milk production yield.

In the light of the results obtained when the three actions are undertaken simultaneously, half of the farms of G4 achieve to be within G3, while two of them (farms 3 and 46) could be classified in G2. Therefore, for the implementation of a continuous improvement strategy, it is recommendable to start with the action that has registered the best improvement results (i.e., reformulate fodder composition), and then gradually implement the rest of the measures.

Finally, the improvement actions presented in this work were consistent with the hotspots identified, since the type and amount of feed provided to the animals have proven to be a critical factor in the environmental performance of dairy farms. Consequently, the modification (reformulate fodder composition) or enhancement (upgrading cow feeding) of the fodder used turns out to be a potential candidate to be studied in order to decrease the environmental impacts involved in milk production. Besides, this could be related not only to a greater or lesser number of resources to meet the nutritional demand, but also to the quantity of milk obtained during the production process (establishing an animal wellbeing program). The adoption of these changes should always be accompanied by technical support to farmers, since the refusal of them to implement any measure can be a major obstacle during the process (Fleming and Vanclay, 2009). Furthermore, a long evaluation period (at least two years of milk production campaign) should be considered to assess the performance of the proposed improvement actions.

### 3.4. WEF nexus index in the decision-making process

On the one hand, the indicators used in this study to encompass a WEF nexus approach were selected aiming to represent the main climate and social drivers that are causing increased pressure on water, energy and food resources, as originally defined by Hoff (2011). Regarding climate drivers, three footprints focus on climate change, water demand and energy requirements (CF, WF and EF, respectively) were chosen to provide a comprehensive perspective of the environmental issues related to the dairy industry. CF is a key indicator to accomplish the environmental targets in the mitigation of the climate crisis. Moreover, it also responds to the demand of society for a more transparency process in the environmental

declarations of dairy products, apart from promoting the development of green policies (Gollnow et al., 2014). As for water use (WF), this is mainly related to the use of green water (i.e., rainwater), although large amounts of blue water from rivers, lakes or aquifers is also needed, which often leads to local water shortages during periods of drought (Shine et al., 2020). Additionally, achieving optimal levels of energy efficiency is also a vital environmental issue, since a significant share of GHG emissions come from the energy consumption (EF) through two sources: direct consumption in the farm (lighting, cooling, automatic milking systems, among others), and indirect demand from the production of consumables such as cleaning agents or animal feed (Todde et al., 2017). In terms of social drivers, the MY indicator was considered as an alternative for addressing the food security purpose. Thus, its rationale is based on the need to increase the production efficiency to accomplish the food demand of an exponentially growing population (Fukase and Martin, 2020). However, it should also be noted that employing an output-oriented FU (i.e., 1 L of raw milk at the dairy gate) leads to the three environmental indicators are directly related to the amount of raw milk produced (i.e., the MY). Hence, bet on another indicator that also reflects some important issues on the assurance of a food security (e.g., food waste level) may be an issue to explore in future iterations of the WEFni methodology.

On the other hand, the individual analysis of the indicators allows the identification of specific hotspots (e.g., GHG emissions from enteric fermentation or water demand for feed production), while their aggregations into composite indicators leads to an easy interpretation that facilitates understanding the complexities of agri-food production systems, reducing trade-offs and increasing synergies among stakeholders (Endo et al., 2017). Furthermore, this is fundamental for benchmarking environmental performances of products or entities, enabling policy makers to propose continuous improvement strategies focused on those aspects that most affect the WEFni. Notwithstanding, the integration of perspectives may entail the loss of information, although the CRITIC method may provide adequate solutions, as it allows determining the weight of each indicator through a mathematical approach (Jahan et al., 2016). In this sense, it could be relevant to assess to what extent the selection of the aggregation method would affect the final overall score.

### 3.5. WEF nexus approaches in the literature

Lastly, for the purpose of methodological comparison with other studies available in the literature, only one paper was identified (Livingstone et al., 2021) related to the application of a WEF nexus perspective to a dairy farming system was identified. They evaluated a dairy farm combined with a short willow rotation system. In addition, a WEF nexus approach was followed, considering a set of indicators such as global warming potential, profit, milk production, gross energy production and eutrophication potential. Thus, to identify methodological aspects of the WEF nexus framework, additional studies related to agri-food systems were revised. In this regard, Fabiani et al. (2020) selected a series of indicators for measuring the performance of fertilisation techniques through five key aspects: water, energy, food, cost, and gross margin. The authors assigned an equal weight to each indicator, according to a normalisation process ranging from 1 to 5, which corresponded to a worsening or improvement, respectively, with respect to a certain baseline scenario, scored this with a normalised value of 3. In addition, El-Gafy (2017) integrated some indicators into a single score having considered water and energy consumptions, as well as mass and economic productivities. However, the author does not follow a life cycle perspective. Furthermore, the indicators were normalised by applying the same technique proposed in this paper, while no clear information was provided on the weights assumed in the aggregation step. Finally, Sobrosa Neto et al. (2018) proposed a model to address the WEF nexus concept within beef cattle production, integrating water savings through the rainwater harvesting, generating renewable energy, while improving animal welfare thanks to thermal comfort. However, this study was focused on these practical strategies rather than proposing a methodological approach. The papers abovementioned reflected that the WEF nexus approach has

been differently addressed, mainly motivated by the objective of the study. Thus, some issues require clarification and standardisation for the correct development of a WEFni methodology: the use of a life cycle perspective (i.e., environmental footprints), the sustainability dimension to be assessed, how to obtain unbiased weights for the proposed indicators, as well as the aggregation procedure to obtain a single score.

## 4. Conclusions

This paper introduced a novel methodology for calculating a WEFni under a holistic approach, combining the GHG emissions, water demand, energy requirements and productivity performance. The procedure was applied for benchmarking 100 dairy farms, identifying the main hotspots associated. Moreover, farms were grouped according to its WEFni to identify similarities in their livestock practices. Finally, three improvement actions were hypothetically applied to estimate the potential improvement in the WEFni performance.

The WEFni ranged from 31 to 90, demonstrating large differences among farms. This could be due to the MY indicator that showed differences of up to three times between farms, in addition to being the indicator with the highest weighting factor (32 %). Furthermore, when the grouping process was carried out, more than three quarters of the farms were classified into the two groups with the highest WEFni. In terms of the individual performance of the footprints, the main hotspot was field emissions and enteric fermentation in the CF (54 %), followed by fodder production (36 %). Conversely, fodders were the critical factor in the WF and the EF indicators, with contributions of 63 % and 71 %, respectively. In this regard, the reformulation of fodder composition turned out to be the most promising improvement action. On the opposite side would be the improvement of cow feed through algae-based additives. However, as feeding additives are still under development, they could become a potential alternative in the future.

The WEFni methodology proposed could become a useful support tool during decision-making process for all stakeholders thanks to its easy interpretation. In addition, this approach allows addressing the environmental sustainability and productivity perspectives to identify the best practices and potential trade-offs among them. Consequently, it is expected to establish a roadmap to promote a more sustainable food industry; in addition to opening the door for academics and practitioners to its replicability in other sectors. In this regard, further studies are vital to standardise the concept of the WEFni in the literature, as well as the need to consider the integration of a socio-economic standpoint. Finally, because WEFni is influenced by the type and number of indicators that compose it, in addition to the weighting procedure used, these are some of the topics that could be interesting to address in the development and improvement of the WEF nexus approach in the future.

### CRedit authorship contribution statement

**Eduardo Entrena-Barbero:** Conceptualization, Methodology, Investigation, Writing – original draft. **Ricardo Rebolledo-Leiva:** Conceptualization, Methodology, Investigation, Writing – original draft. **Leonardo Vásquez-Ibarra:** Conceptualization, Methodology, Investigation, Writing – original draft. **Mario Fernández:** Conceptualization, Methodology, Validation, Writing – review & editing. **Gumersindo Feijoo:** Project administration, Supervision. **Sara González-García:** Conceptualization, Methodology, Validation, Writing – review & editing. **María Teresa Moreira:** Conceptualization, Methodology, Validation, Writing – review & editing.

### Data availability

The authors are unable or have chosen not to specify which data has been used.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2023.162507>.

## References

- AIB, 2019. Association of issuing bodies - guaranteeing the origin of European energy. European Residual Mix for the period 2015-2019. Available online on: <https://www.aib-net.org/>.
- Alemi-Ardakani, M., Milani, A.S., Yannacopoulos, S., Shokouhi, G., 2016. On the effect of subjective, objective and combinative weighting in multiple criteria decision making: a case study on impact optimization of composites. *Expert Syst. Appl.* 46, 426–438. <https://doi.org/10.1016/j.eswa.2015.11.003>.
- Baldini, C., Gardoni, D., Guarino, M., 2017. A critical review of the recent evolution of life cycle assessment applied to milk production. *J. Clean. Prod.* 140, 421–435. <https://doi.org/10.1016/j.jclepro.2016.06.078>.
- Bhakat, C., Mohammad, A., Mandal, D.K., Mandal, A., Rai, S., Chatterjee, A., Ghosh, M.K., Dutta, T.K., 2020. Readily usable strategies to control mastitis for production augmentation in dairy cattle: a review. *Vet. World* 13, 2364–2370. <https://doi.org/10.14202/VETWORLD.2020.2364-2370>.
- Boulay, A.M., Bare, J., Benini, L., Berger, M., Lathuilière, M.J., Manzardo, A., Margni, M., Motoshita, M., Núñez, M., Pastor, A.V., Ridoutt, B., Oki, T., Worbe, S., Pfister, S., 2018. The WULCA consensus characterization model for water scarcity footprints: assessing impacts of water consumption based on available water remaining (AWARE). *Int. J. Life Cycle Assess.* 23, 368–378. <https://doi.org/10.1007/s11367-017-1333-8>.
- Cambeses-Franco, C., González-García, S., Feijoo, G., Moreira, M.T., 2022. Driving commitment to sustainable food policies within the framework of american and european dietary guidelines. *Sci. Total Environ.* 807, 150894. <https://doi.org/10.1016/j.scitotenv.2021.150894>.
- Cui, S., Wu, M., Huang, X., Wang, X., Cao, X., 2022. Sustainability and assessment of factors driving the water-energy-food nexus in pumped irrigation systems. *Agric. Water Manag.* 272, 107846. <https://doi.org/10.1016/j.agwat.2022.107846>.
- Denier Van Der Gon, H., Bleeker, A., 2005. Indirect N<sub>2</sub>O emission due to atmospheric N deposition for the Netherlands. *Atmos. Environ.* 39, 5827–5838. <https://doi.org/10.1016/j.atmosenv.2005.06.019>.
- Diakoulaki, D., Mavrotas, G., Papayannakis, L., 1995. *Determining Objective Weights in Multiple Criteria Problems: The CRITIC Method*. 22, pp. 763–770.
- Ding, T., Fang, L., Chen, J., Ji, J., Fang, Z., 2023. Exploring the relationship between water-energy-food nexus sustainability and multiple ecosystem services at the urban agglomeration scale. *Sustain. Prod. Consum.* 35, 184–200. <https://doi.org/10.1016/j.spc.2022.10.028>.
- Drewnowski, A., 2009. Defining nutrient density: development and validation of the nutrient rich foods index. *J. Am. Coll. Nutr.* 28, 421–426. <https://doi.org/10.1080/07315724.2009.10718106>.
- EDA, 2018. *Product Environmental Footprint Category Rules (PEFCR) for Dairy Products*.
- Ekman, T., Østerås, O., 2003. Mastitis Control and Dry Cow Therapy in the Nordic Countries. *Natl. Mastit. Counc. Annu. Meet. Proc.* pp. 18–30.
- El-Gafy, I., 2017. Water–food–energy nexus index: analysis of water–energy–food nexus of crop's production system applying the indicators approach. *Appl. Water Sci.* 7, 2857–2868. <https://doi.org/10.1007/s13201-017-0551-3>.
- Endo, A., Tsurita, I., Burnett, K., Orenco, P.M., 2017. A review of the current state of research on the water, energy, and food nexus. *J. Hydrol. Reg. Stud.* 11, 20–30. <https://doi.org/10.1016/j.ejrh.2015.11.010>.
- Escribano, A.J., 2018. Organic feed: a bottleneck for the development of the livestock sector and its transition to sustainability? *Sustainability* 10. <https://doi.org/10.3390/su10072393>.
- European Commission, 2020. *Milk and milk product statistics*. Eur. Stat. (Eurostat). Stat. Explain.
- Fabiani, S., Vanino, S., Napoli, R., Nino, P., 2020. Water energy food nexus approach for sustainability assessment at farm level: an experience from an intensive agricultural area in Central Italy. *Environ. Sci. Policy* 104, 1–12. <https://doi.org/10.1016/j.envsci.2019.10.008>.
- Fantke, P., Antón, A., Grant, T., Hayashi, K., 2017. Pesticide emission quantification for life cycle assessment: a global consensus building process. *J. Life Cycle Assess.* Jpn. 13, 245–251. <https://doi.org/10.3370/lca.13.245>.
- FAO, 2021. *World Food and Agriculture – Statistical Yearbook 2021*. Rome., World Food and Agriculture – Statistical Yearbook 2021. <https://doi.org/10.4060/cb4477en>.
- Félix, R., Dias, P., Félix, C., Cerqueira, T., Andrade, P.B., Valentão, P., Lemos, M.F.L., 2021. The biotechnological potential of *Asparagopsis armata*: what is known of its chemical composition, bioactivities and current market? *Algal Res.* <https://doi.org/10.1016/j.algal.2021.102534>.
- Feng, X., Kebreab, E., 2020. Net reductions in greenhouse gas emissions from feed additive use in California dairy cattle. *PLoS One* 15. <https://doi.org/10.1371/journal.pone.0234289>.
- Fernández-Ríos, A., Laso, J., Campos, C., Ruiz-Salmón, I., Hoehn, D., Cristóbal, J., Batlle-Bayer, L., Bala, A., Fullana-i-Palmer, P., Puig, R., Aldaco, R., Margallo, M., 2021. Towards a water-energy-food (WEF) nexus index: a review of nutrient profile models as a fundamental pillar of food and nutrition security. *Sci. Total Environ.* 789. <https://doi.org/10.1016/j.scitotenv.2021.147936>.
- Fleming, A., Vanclay, F., 2009. Farmer responses to climate change and sustainable agriculture. *Sustain. Agric.* 2, 283–293. [https://doi.org/10.1007/978-94-007-0394-0\\_15](https://doi.org/10.1007/978-94-007-0394-0_15).
- Frischknecht, R., Jungbluth, N., Althaus, H.J., Bauer, C., Doka, G., Dones, R., Hirschler, R., Hellweg, S., Humbert, S., Köllner, T., Loerincik, Y., Margni, M., Nemecek, T., 2007. *Implementation of Life Cycle Impact Assessment Methods*. ecoinvent Report No. 3, v2.0.
- Froldi, F., Lamastra, L., Trevisan, M., Mambretti, D., Moschini, M., 2022. Environmental impacts of cow's milk in northern Italy: effects of farming performance. *J. Clean. Prod.* 363, 132600. <https://doi.org/10.1016/j.jclepro.2022.132600>.
- Fukase, E., Martin, W., 2020. Economic growth, convergence, and world food demand and supply. *World Dev.* 132, 104954. <https://doi.org/10.1016/j.worlddev.2020.104954>.
- Gill, M., Gamsworthy, P.C., Wilkinson, J.M., 2021. Review: more effective linkages between science and policy are needed to minimize the negative environmental impacts of livestock production. *Animal* 15, 100291. <https://doi.org/10.1016/j.animal.2021.100291>.
- Gollnow, S., Lundie, S., Moore, A.D., McLaren, J., van Buuren, N., Stahle, P., Christie, K., Thylmann, D., Rehl, T., 2014. Carbon footprint of milk production from dairy cows in Australia. *Int. Dairy J.* 37, 31–38. <https://doi.org/10.1016/j.idairyj.2014.02.005>.
- Gupta, R., Kumar, S., Khurana, R., 2020. Essential oils and mastitis in dairy animals: a review. *Haryana Vet.* 59, 1–9.
- Haitsma Mulier, M.C.G., van de Ven, F.H.M., Kirshen, P., 2022. Circularity in the urban water-energy-nutrients-food nexus. *Energy Nexus* 7, 100081. <https://doi.org/10.1016/j.nexus.2022.100081>.
- Hanrahan, L., McHugh, N., Hennessy, T., Moran, B., Kearney, R., Wallace, M., Shalloo, L., 2018. Factors associated with profitability in pasture-based systems of milk production. *J. Dairy Sci.* 101, 5474–5485. <https://doi.org/10.3168/jds.2017-13223>.
- Haque, M.N., 2018. Dietary manipulation: a sustainable way to mitigate methane emissions from ruminants. *J. Anim. Sci. Technol.* <https://doi.org/10.1186/s40781-018-0175-7>.
- Hennessy, D., Delaby, L., van den Pol-van Dassel, A., Shalloo, L., 2020. Increasing grazing in dairy cow milk production systems in Europe. *Sustainability* 12, 1–15. <https://doi.org/10.3390/su12062443>.
- Hoff, H., 2011. *Understanding the nexus*. Background Paper for the Bonn 2011 Conference: The Water, Energy and Food Security Nexus, Bonn, Germany, 16–18 November 2011. Stockholm Environment Institute (SEI), Stockholm, Sweden.
- Hogeveen, H., 2005. *Mastitis in Dairy Production: Current Knowledge and Future Solutions*. Wageningen Academic Publishers, The Netherlands <https://doi.org/10.3920/978-90-8686-550-5>.
- Honan, M., Feng, X., Tricarico, J.M., Kebreab, E., 2021. Feed additives as a strategic approach to reduce enteric methane production in cattle: modes of action, effectiveness and safety. *Anim. Prod. Sci.* <https://doi.org/10.1071/AN20295>.
- Hospido, A., Sonesson, U., 2005. The environmental impact of mastitis: a case study of dairy herds. *Sci. Total Environ.* 343, 71–82. <https://doi.org/10.1016/j.scitotenv.2004.10.006>.
- Huang, D., Li, G., Chang, Y., Sun, C., 2023. Water, energy, and food nexus efficiency in China: a provincial assessment using a three-stage data envelopment analysis model. *Energy* 263, 126007. <https://doi.org/10.1016/j.energy.2022.126007>.
- IDF, 2015. *A common carbon footprint approach for the dairy sector. The IDF guide to standard life cycle assessment methodology*. Bulletin of the International Dairy Federation 479/2015. Bull. Int. Dairy Fed.
- IGE, 2020. Instituto Galego de Estatística. Agricultura e Pesca. Registro de Gando Bovino. Número de explotacións e número de bovinos. [WWW Document]. URL [https://www.ige.eu/igebdt/esqv.jsp?pagina=001&c=0301005&rta=verPpalesResultados.jsp?OP=1&B=1&M=&COD=2917&R=2\[all\]&C=9912\[all\]&F=T\[1:0\];1:0;3:11&S=&TI=1#](https://www.ige.eu/igebdt/esqv.jsp?pagina=001&c=0301005&rta=verPpalesResultados.jsp?OP=1&B=1&M=&COD=2917&R=2[all]&C=9912[all]&F=T[1:0];1:0;3:11&S=&TI=1#).
- IPCC, 2021. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y. (Eds.), *Climate Change 2021: The Physical Science Basis*. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change <https://doi.org/10.37274/sp.j1703161536>.
- IPCC, 2019. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories Task Force on National Greenhouse Gas Inventories.
- ISO, 2006a. *ISO 14040:2006 - Environmental Management - Life Cycle Assessment - Principles and Framework*.
- ISO, 2006b. *ISO 14044:2006 - Environmental Management - Life Cycle Assessment - Requirements and Guidelines*.
- Jacobs, J.A., Siegford, J.M., 2012. Invited review: the impact of automatic milking systems on dairy cow management, behavior, health, and welfare. *J. Dairy Sci.* 95, 2227–2247. <https://doi.org/10.3168/jds.2011-4943>.
- Jahan, A., Edwards, K.L., Bahraminasab, M., 2016. *Multi-criteria Decision Analysis for Supporting the Selection of Engineering Materials in Product Design*. Second ed. Butterworth-Heinemann.
- Jantke, K., Hartmann, M.J., Rasche, L., Blanz, B., Schneider, U.A., 2020. Agricultural greenhouse gas emissions: knowledge and positions of German farmers. *Land* 9. <https://doi.org/10.3390/LAND9050130>.

- Jerram, L.J., Van Winden, S., Fowkes, R.C., 2020. Minimally invasive markers of stress and production parameters in dairy cows before and after the installation of a voluntary milking system. *Animals* 10. <https://doi.org/10.3390/ani10040589>.
- Kholif, A.E., Hassan, A.A., El Ashry, G.M., Bakr, M.H., El-Zaiat, H.M., Olafadehan, O.A., Matloup, O.H., Sallam, S.M.A., 2021. Phyto-genic feed additives mixture enhances the lactational performance, feed utilization and ruminal fermentation of Friesian cows. *Anim. Biotechnol.* 32, 708–718. <https://doi.org/10.1080/10495398.2020.1746322>.
- Kolbe, K., 2018. Why Milk consumption is the bigger problem: ethical implications and deaths per calorie created of Milk compared to meat production. *J. Agric. Environ. Ethics* 31, 467–481. <https://doi.org/10.1007/s10806-018-9740-9>.
- Krauß, M., Drastig, K., Prochnow, A., Rose-Meierhöfer, S., Kraatz, S., 2016. Drinking and cleaning water use in a dairy cow barn. *Water (Switzerland)* 8, 1–16. <https://doi.org/10.3390/w8070302>.
- Kyttä, V., Roitto, M., Astaptev, A., Saarinen, M., Tuomisto, H.L., 2022. Review and expert survey of allocation methods used in life cycle assessment of milk and beef. *Int. J. Life Cycle Assess.* <https://doi.org/10.1007/s11367-021-02019-4>.
- Laso, J., Ruiz-salm, I., Villanueva-rey, P., Quinteiro, P., Cl, A., Almeida, C., Entrena-barbero, E., Feijoo, G., Loubet, P., Sonnemann, G., Cooney, R., Clifford, E., Regueiro, I., Alonso, D., Sousa, B.De, Jacob, C., Noirot, C., Martin, J., Raffray, M., Rowan, N., Mellett, S., 2022. Achieving sustainability of the seafood sector in the European Atlantic area by addressing eco-social challenges: the NEPTUNUS project. *Sustainability* 14. <https://doi.org/10.3390/su14053054>.
- Lin, L., Xia, Y., Wu, D., 2020. A hybrid fuzzy multiple criteria decision-making approach for comprehensive performance evaluation of tunnel boring machine disc cutter. *Comput. Ind. Eng.* 149, 106793. <https://doi.org/10.1016/j.cie.2020.106793>.
- Livingstone, D., Smyth, B.M., Foley, A.M., Murray, S.T., Lyons, G., Johnston, C., 2021. Willow coppice in intensive agricultural applications to reduce strain on the food-energy-water nexus. *Biomass Bioenergy* 144, 105903. <https://doi.org/10.1016/j.biombioe.2020.105903>.
- MAPA, 2022. El Sector Vacuno De Leche En Cifras 2021. Principales Indicadores Económicos. Ministerio de Agricultura, Pesca y Alimentación, Gobierno de España.
- MAPA, 2020a. Consumos y tendencias en alimentación. Panel de Consumo Alimentario en Hogares. Datos Anuales del periodo 2015-2020. Ministerio de Agricultura, Pesca y Alimentación. Gobierno de España, Gobierno de España.
- MAPA, 2020b. Estructura del Sector Vacuno Lechero en España 2016-2020. Subdirección General de Producciones Ganaderas y Cinegéticas. Dirección General de Producciones y Mercados Agrarios. Ministerio de Agricultura, Pesca y Alimentación, Gobierno de España.
- MAPA, 2020c. Declaraciones obligatorias del sector vacuno de leche. Diciembre 2020. Ministerio de Agricultura, Pesca y Alimentación. Secretaría General de Agricultura y Alimentación. Fondo Español de Garantía Agraria, Gobierno de España.
- Marangoni, F., Pellegrino, L., Verduci, E., Ghiselli, A., Bernabei, R., Calvani, R., Cetin, I., Giampietro, M., Peticone, F., Piretta, L., Giacco, R., La Vecchia, C., Brandi, M.L., Ballardini, D., Banderali, G., Bellentani, S., Canzone, G., Cricelli, C., Faggiano, P., Ferrara, N., Flachi, E., Gonnelli, S., Macca, C., Magni, P., Marelli, G., Marrocco, W., Miniello, V.L., Origo, C., Pietrantonio, F., Silvestri, P., Stella, R., Strazzullo, P., Troiano, E., Poli, A., 2019. Cow's Milk consumption and health: a health Professional's guide. *J. Am. Coll. Nutr.* 38, 197–208. <https://doi.org/10.1080/07315724.2018.1491016>.
- March, M.D., Toma, L., Thompson, B., Haskell, M.J., 2019. Food waste in primary production: milk loss with mitigation potentials. *Front. Nutr.* 6, 4–6. <https://doi.org/10.3389/fnut.2019.00173>.
- Martinsson, E., Hansson, H., 2021. Adjusting eco-efficiency to greenhouse gas emissions targets at farm level – the case of Swedish dairy farms. *J. Environ. Manag.* 287. <https://doi.org/10.1016/j.jenvman.2021.112313>.
- Mbindyo, C.M., Gitao, G.C., Mulei, C.M., 2020. Prevalence, etiology, and risk factors of mastitis in dairy cattle in Embu and Kajiado Counties, Kenya. *Vet. Med. Int.*, 2020 <https://doi.org/10.1155/2020/8831172>.
- McCauley, J.I., Labeeuw, L., Jaramillo-Madrid, A.C., Nguyen, L.N., Nghiem, L.D., Chaves, A.V., Ralph, P.J., 2020. Management of enteric methanogenesis in ruminants by algal-derived feed additives. *Curr. Pollut. Rep.* <https://doi.org/10.1007/s40726-020-00151-7>.
- Mekonnen, M.M., Hoekstra, A.Y., 2012. The green, blue and grey water footprint of farm animals and animal products. *Ecosystems* 15, 401–415. <https://doi.org/10.1007/s10021-011-9517-8>.
- Munekata, P.E.S., Domínguez, R., Budaraju, S., Roselló-Soto, E., Barba, F.J., Mallikarjunan, K., Roohinejad, S., Lorenzo, J.M., 2020. Effect of innovative food processing technologies on the physicochemical and nutritional properties and quality of non-dairy plant-based beverages. *Foods* 9, 1–16. <https://doi.org/10.3390/foods9030288>.
- Nemecek, T., Bengoa, X., Rossi, V., Humbert, S., Lansche, J., Mouron, P., 2019. *World Food LCA Database: Methodological Guidelines for the Life Cycle Inventory of Agricultural Products*. Version 3.5 88.
- Oviroh, P.O., Austin-Breneman, J., Chien, C.C., Chakravarthula, P.N., Harikumar, V., Shiva, P., Kimbowa, A.B., Luntz, J., Miyingo, E.W., Papalambros, P.Y., 2023. Micro water-energy-food (MicroWEF) nexus: a system design optimization framework for integrated natural resource conservation and development (INRC) projects at community scale. *Appl. Energy* 333, 120583. <https://doi.org/10.1016/j.apenergy.2022.120583>.
- Pagani, M., Vittuari, M., Johnson, T.G., De Menna, F., 2016. An assessment of the energy footprint of dairy farms in Missouri and Emilia-Romagna. *Agric. Syst.* 145, 116–126. <https://doi.org/10.1016/j.agry.2016.03.009>.
- Panagopoulos, A., 2022. Brine management (saline water & wastewater effluents): sustainable utilization and resource recovery strategy through minimal and zero liquid discharge (MLD & ZLD) desalination systems. *Chem. Eng. Process. Process Intensif.* 176, 108944. <https://doi.org/10.1016/j.ccep.2022.108944>.
- Panagopoulos, A., Giannika, V., 2022a. Comparative techno-economic and environmental analysis of minimal liquid discharge (MLD) and zero liquid discharge (ZLD) desalination systems for seawater brine treatment and valorization. *Sustainable Energy Technol. Assess.* 53, 102477. <https://doi.org/10.1016/j.seta.2022.102477>.
- Panagopoulos, A., Giannika, V., 2022b. Decarbonization and circular brine management/valorization for water & valuable resource recovery via minimal/zero liquid discharge (MLD/ZLD) strategies. *J. Environ. Manag.* 324, 116239. <https://doi.org/10.1016/j.jenvman.2022.116239>.
- Payen, S., Falconer, S., Ledgard, S.F., 2018. Water scarcity footprint of dairy milk production in New Zealand – a comparison of methods and spatio-temporal resolution. *Sci. Total Environ.* 639, 504–515. <https://doi.org/10.1016/j.scitotenv.2018.05.125>.
- Pereira, P.C., 2014. Milk nutritional composition and its role in human health. *Nutrition* 30, 619–627. <https://doi.org/10.1016/j.nut.2013.10.011>.
- Petersson-Wolfe, C.S., Leslie, K.E., Swartz, T.H., 2018. An update on the effect of clinical mastitis on the welfare of dairy cows and potential therapies. *Vet. Clin. North Am. Food Anim. Pract.* 34, 525–535. <https://doi.org/10.1016/j.cvfa.2018.07.006>.
- Puerto, M.A., Shepley, E., Cue, R.I., Warner, D., Dubuc, J., Vasseur, E., 2021. The hidden cost of disease: I. Impact of the first incidence of mastitis on production and economic indicators of primiparous dairy cows. *J. Dairy Sci.* 104, 7932–7943. <https://doi.org/10.3168/jds.2020-19584>.
- Rebolledo-Leiva, R., Vázquez-Ibarra, L., Entrena-Barbero, E., Fernández, M., Feijoo, G., Moreira, M.T., González-García, S., 2022. Coupling material flow analysis and network DEA for the evaluation of eco-efficiency and circularity on dairy farms. *Sustain. Prod. Consum.* 31, 805–817. <https://doi.org/10.1016/j.spc.2022.03.023>.
- Redlingshöfer, B., Coudurier, B., Georget, M., 2017. Quantifying food loss during primary production and processing in France. *J. Clean. Prod.* 164, 703–714. <https://doi.org/10.1016/j.jclepro.2017.06.173>.
- Roque, B.M., Salwen, J.K., Kinley, R., Kebreab, E., 2019. Inclusion of *Asparagopsis armata* in lactating dairy cows' diet reduces enteric methane emission by over 50 percent. *J. Clean. Prod.* 234, 132–138. <https://doi.org/10.1016/j.jclepro.2019.06.193>.
- Ruviaro, C.F., de Leis, C.M., Florindo, T.J., de Medeiros Florindo, G.I.B., da Costa, J.S., Tang, W.Z., Pinto, A.T., Soares, S.R., 2020. Life cycle cost analysis of dairy production systems in southern Brazil. *Sci. Total Environ.* 741. <https://doi.org/10.1016/j.scitotenv.2020.140273>.
- Shine, P., Murphy, M.D., Upton, J., 2020. A global review of monitoring, modeling, and analyses of water demand in dairy farming. *Sustainability* 12, 1–20. <https://doi.org/10.3390/su12177201>.
- Sobrosa Neto, R.de C., Berchin, I.I., Magtoto, M., Berchin, S., Xavier, W.G., Guerra, J.B.S.O.de A., 2018. An integrative approach for the water-energy-food nexus in beef cattle production: a simulation of the proposed model to Brazil. *J. Clean. Prod.* 204, 1108–1123. <https://doi.org/10.1016/j.jclepro.2018.08.200>.
- Todde, G., Murgia, L., Caria, M., Pazzona, A., 2018. A comprehensive energy analysis and related carbon footprint of dairy farms, part 2: investigation and modeling of indirect energy requirements. *Energies* 11, 1–13. <https://doi.org/10.3390/en11020463>.
- Todde, G., Murgia, L., Caria, M., Pazzona, A., 2017. Dairy energy prediction (DEP) model: a tool for predicting energy use and related emissions and costs in dairy farms. *Comput. Electron. Agric.* 135, 216–221. <https://doi.org/10.1016/j.compag.2017.02.014>.
- Ungerfeld, E.M., 2018. Inhibition of rumen methanogenesis and ruminant productivity: a meta-analysis. *Front. Vet. Sci.* 5. <https://doi.org/10.3389/fvets.2018.00113>.
- Villettaz Robichaud, M., Rushen, J., de Passillé, A.M., Vasseur, E., Haley, D., Pellerin, D., 2019. Associations between on-farm cow welfare indicators and productivity and profitability on Canadian dairies: II. On tiestall farms. *J. Dairy Sci.* 102, 4352–4363. <https://doi.org/10.3168/jds.2018-14818>.
- Wen, X., Nie, Y., Du, Z., Huang, L., 2022. Operational safety assessment of straddle-type monorail vehicle system based on cloud model and improved CRITIC method. *Eng. Fail. Anal.* 139, 106463. <https://doi.org/10.1016/j.engfailanal.2022.106463>.
- Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. *Int. J. Life Cycle Assess.* 21, 1218–1230. <https://doi.org/10.1007/s11367-016-1087-8>.
- Zhang, C., Chen, X., Li, Y., Ding, W., Fu, G., 2018. Water-energy-food nexus: concepts, questions and methodologies. *J. Clean. Prod.* 195, 625–639. <https://doi.org/10.1016/j.jclepro.2018.05.194>.