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A material flow or life cycle analysis perspective for the Water-Energy-Food nexus assessment of organisations? A comparative study

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ABSTRACT

Nowadays, food production systems play a relevant role as the steady increase of global population and food demand. The water-energy-food (WEF) nexus is a suitable approach to tackle resources management associated with these three pillars recognizing synergies and trade-offs. Different approaches have been used in the literature to measure the WEF nexus, being material flow analysis (MFA) and life cycle assessment (LCA), two of the most proven methodologies. The MFA approach is based on the amount of resources consumed, while using the LCA perspective considers all flows of the system (LCA footprints approach) or considering only the flows associated with water, energy, and food pillars as the inventory data (WEF-LCA approach). This manuscript compares the three mentioned approaches to identify their strengths and weaknesses. To do this, a sample of 100 Spanish dairy farms is analysed, where a single WEF nexus index (WEFni) is obtained using Data Envelopment Analysis. Results show that only four farms achieved a WEFni equal to 100 in all approaches, while the main difference between them is the number and type of resources considered for calculating the WEF nexus, which could imply a partial identification of hotspots of food systems.

1. Introduction

The global population is projected to reach 9.5 billion by 2050 (United Nations, 2019), which will require about 954 million hectares of agricultural land, increasing potential environmental impacts (Tello et al., 2021). Currently, the food industry is responsible for approximately one quarter of greenhouse gas (GHG) emissions, with livestock accounting for 14.5 % (Lazarus et al., 2021). In this regard, it is widely recognised that dairy products have a great impact on GHG emissions, generating about 21 gigatons of carbon dioxide equivalent (CO_2-eq) per year, as well as contributing to water pollution and shortages (Gerber et al., 2013; Mazumder et al., 2023). In food systems, water is needed to irrigate crops, which requires energy to be pumped, delivered, treated, and so on. Furthermore, water could also be needed to generate electricity (e.g., in a thermal power plant cooling system), and both water and energy are required throughout the life cycle of food products (i.e., cultivation, processing, packaging, among others) (Afshar et al., 2022). Therefore, the interconnection analysis between water, energy and food, commonly known as the Water-Energy-Food (WEF) nexus, has emerged as a potential solution to address this multicriteria problem exacerbated by several factors such as population growth, urbanization, technological changes, among others (Fernández-Ríos et al., 2021; Rhouma et al., 2024).

Based on this multicriteria issue, the WEF nexus can also be understood as a holistic and transdisciplinary approach to assess the trade-offs associated with resources allocation (Lee et al., 2023). In this regard, it is essential that the WEF nexus can not only analyse a variety of scenarios, but also demonstrate efficiency, robustness and adaptability, thus facilitating the development of different strategies to guide the policy-making process (Lee et al., 2023). One of the major weaknesses of the WEF nexus is that practitioners for instance, scholars, researchers and technicians, do not have appropriate tools to evaluate resource allocation strategies (Wu et al., 2021), due to the different methodologies used for its quantification. In this context, although progress has been made in understanding the dynamics of the WEF nexus from a technical point of view, there is a research gap in terms of policy or regarding the

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implications of the methodology used (Van Gevelt, 2020). Consequently, understanding the implications of how different methodological approaches address the relationship of the three pillars of the WEF nexus can guide managers and decision-makers in accurate decisions about which methodology may be more appropriate for their interest (Afshar et al., 2022; Wu et al., 2021).

The WEF nexus has been the subject of numerous approaches that aim to quantify the interaction between its pillars (Afshar et al., 2022). Among them, three approaches have been the most common: (i) Material Flow Analysis (MFA), (ii) Environmental Footprint through the Life Cycle Assessment methodology (LCA footprints), and (iii) a mixture of them, which can be called as WEF-LCA (Al-Thani and Al-Ansari, 2021). Concerning the first one, MFA studies focus on the resource flows on which a system relies and how they interact with it (Covarrubias, 2019). As such, the emphasis of this approach is on the material cycles and waste flows to optimise resource utilisation (Ramírez-Márquez and Ponce-Ortega, 2023). Some studies using MFA for the assessment of the WEF nexus include Covarrubias (2019), Ngammuangtueng et al. (2023), Villamayor-Tomas et al. (2015) and Villarroel Walker et al. (2012). However, none of these compare the results using additional WEF approach. The second approach uses the LCA methodology for assessing, firstly, the environmental footprints related to the WEF nexus (e.g., water and energy), and then, identifying their interconnections. One of the main reasons for using LCA in the WEF nexus may be that it allows considering entire supply chains, which are increasingly globalised, where production and consumption often occur in different parts of the world and affecting the nexus in different ways (Laso et al., 2018). In addition, De Laurentiis et al. (2016) highlighted that LCA enables users to dismantle common sense assumptions, such as food miles, creating information for guiding consumers choices. Examples of studies using LCA for WEF nexus assessment include Armengot et al. (2021), Karabulut et al. (2018) and Lee et al. (2023). However, these studies either integrated new dimensions or evaluate efficiency of the system. Finally, the third approach takes the life cycle perspective of only the material flows related to the WEF nexus (water, energy, and food), and then uses LCA to determine their footprints. Examples of studies using WEF-LCA for WEF nexus assessment include Chen et al. (2020), Villalba-Pastrana and Güereca (2024), and Villarroel Walker et al. (2014). These studies aim to identify activities for reducing impact rather than focusing on methodological differences.

The above approaches are convenient for data integration (Wang et al., 2021). However, although there has been a rise in studies analysing the WEF nexus, Rhouma et al. (2024) have recently identified that there is a need to explore tools and approaches to identify their pros and cons for measuring the WEF nexus. For instance, while the LCA footprints have the advantage of showing where the resources are used (Yu et al., 2021), its precision may be limited by the accessibility or quality of data (Corona-López et al., 2021). On the other hand, MFA involves a mass conservation analysis of WEF resources, but there are factors and interactions along the whole supply chain that should be considered (Chen et al., 2020). Therefore, research is required to identify the advantages and disadvantages of WEF nexus approaches from both theoretical and practical perspectives, to guide decision-makers towards less resource-intensive systems.

Regardless of the method used, addressing WEF challenges requires an understanding of the complex behaviour of the WEF nexus (Wu et al., 2021), and an easy way to communicate the sustainability of food products under this nexus. Therefore, Entrena-Barbero et al. (2023a) proposed a technical guidance to calculate a single WEF nexus index (WEFni), which was applied to a series of seafood production systems throughout the European Atlantic area (Ceballos-Santos et al., 2024). This nexus is particularly relevant for food industry to secure its sustainable production and consumption (Dai et al., 2024), in line with Sustainable Development Goals (SDG) (e.g. SDG 12) . As a result, policy and research communities worldwide have called for action to develop strategies which provide a comprehensive nexus approach (Lee et al., 2023).

Another aspect to be highlighted in the WEF nexus development is the inclusion of further dimensions in the assessment beyond the originally proposed, e.g., water, energy and food. For instance, Entrena-Barbero et al. (2023b) integrated a climate change perspective owing to its relevance to policy makers, Caputo et al. (2021) introduced a social dimension to assess the urban agriculture or Nika et al. (2022) included ecosystems and their services as another pillar. From these, the inclusion of GHG emissions (through the carbon footprint) has arisen to consider the interaction of water, energy and food with external pressures such as climate change (Sušnik et al., 2022).

In addition to the modification of the traditional pillars for measuring the WEF nexus, different techniques have emerged to quantify the interaction among these three dimensions (Teutschbein et al., 2023; Zhang and Xu, 2022). Some of these methodologies include Data Envelopment Analysis (DEA) (Li et al., 2016), System Dynamics (Halbe et al., 2015), among others. From these, DEA appears as a suitable technique to integrate the dimensions of the WEF nexus in a set of productive firms that consume and produce multiple resources, as well as to identify their best practices. In this regard, Li et al. (2016) stated that DEA is a reasonable tool to select the best WEFni to overcome hurdles in data processing and obtain its best performance. WEF nexus-related studies using DEA have emerged since the work of Li et al. (2016), but they consider a geographical perspective, e.g., at province and region levels. Although this analysis has benefits, such as the implementation of policies and regulations, it could fall to determine specific targets and best practices (i.e., benchmarking) for firms. Therefore, there is a need to understand resource-intensive sectors (e.g. agriculture) to explore in depth their interactions with water, energy, and food (Zhang et al., 2022a), which could use DEA methods to identify best management practices for the development of sustainable production.

This research contributes a discussion about the different ways of approaching the WEF nexus concept towards a single-score assessment under an organisational perspective, evaluating their performance through a multi-criteria decision tool like DEA. In this context, the aim of this manuscript is to compare the three WEF nexus approaches mentioned above (LCA footprints, MFA and WEF-LCA) to identify the advantages and disadvantages of each one, and the theoretical and practical implications of their use for a decision-making process towards less resource-intensive food systems. In this regard, the three WEF nexus approaches are applied to a sample of 100 Spanish dairy farms. The selection of this case study is based on its contribution to environmental degradation and its relevance in the food sector. For example, Spanish dairy sector is a major industry with about 850,000 milking cows producing around 7.1 million tonnes of raw milk per year and accounting for 7 % of all carbon emissions in Spain (MITECO, 2023).

2. Literature review

This section reviews the current literature on the different approaches to the WEF nexus assessment (Section 2.1), and the use of DEA as a multicriteria tool in this framework (Section 2.2).

2.1. Approaches for the assessment of the Water-Energy-Food nexus

In addition to the three pillars: food, water, and energy, that make up the WEF nexus, the links have also been examined in pairs, i.e. by considering only two pillars. An example of this is the Water-Energy (WE) nexus, which is understood as the relationship between the need to use water directly or indirectly to generate electricity, as well as the energy required to extract and distribute water, apart from other tasks such as desalination, wastewater treatment or freshwater purification (Hamiche et al., 2016). In addition, the WE nexus has also been used to assess the integration of renewable energy sources into thermal- and membrane-based water technologies for desalination (Panagopoulos, 2021). Another two-pillar approach is the one that considers the Water-Food (WF) nexus, which has been applied mainly in agricultural systems to better understand the synergies between water consumption and food production, through different models such as the Global Food and Water System (GFWS) or the Soil and Water Assessment Tool (SWAT) (Corona-López et al., 2021).

Carbon emissions has gained special attention in the WEF nexus due to its relevance for the climate change, emerging the Water-Energy-Food-Climate/Carbon (Sambo et al., 2023). For this purpose, LCA supports their measurement through the carbon footprint (CF). For instance, an LCA was used by Ren et al. (2022) to measure the carbon sinks and emissions in agricultural systems in a WEFC (including the Carbon pillar) nexus optimisation model to propose strategies focused on increasing irrigation water productivity and reducing carbon emissions. Moreover, Yoon et al. (2022) analysed the effect of climate change in the heating system of farms to protect crops from the external environment, considering both climate change and carbon dioxide concentration, following a so-called heating temperature-based WEFC nexus model.

Likewise, other works have broadened the WEF nexus perspective to include additional dimensions, such as the Water-Energy-Food-Environment nexus or Water-Energy-Food-Ecosystem perspectives (Sambo et al., 2023). For instance, Correa-Cano et al. (2022) addressed a Water-Energy-Food-Environment nexus based on the integration of environmental indicators calculated through LCA, together with irrigation simulation and economic modelling, which allowed the evaluation of agricultural expansion in terms of both environmental impacts and socio-economic outcomes. Besides, Nika et al. (2022) proposed a framework for determining the level of circularity in the water sector, using a list of sustainability and circular economy indicators from a Water-Energy-Food-Ecosystem nexus perspective. In addition, the above nexus approach has been also applied to evaluate the resilience of different ecosystems to obtain future drought projections based on climate model simulations (Teutschbein et al., 2023). For their part, Cristiano et al. (2021) considered the same approach through a conceptual map which correlated with the SDGs of the 2030 Agenda, to review the benefits and limitations of installing green roofs on buildings to promote more resilient cities to the adversities of climate change.

Lastly, there are other perceptions covering five dimensions, such as the Water-Energy-Food-Land-Climate (WEFLC) nexus, which has been applied at the country level to study the effects of the anthropogenic impacts into the ecosystem services in Sweden (Van Den Heuvel et al., 2020), as well as the policy implications in Latvia (Sušnik et al., 2021).

2.2. Data envelopment analysis in the Water-Energy-Food nexus context

Studies that make joint use of WEF and DEA have emerged mainly because DEA can deal with multiple inputs and outputs, and there is no need to build a production function (Sun et al., 2023). For instance, Li et al. (2016) built what they call an "input output index system" at the city level to understand their statues and trends in a holistic way. Their assessment was based on the interaction of the WEF nexus with population, economic, and environmental systems applied to a case study of 30 Chinese provinces. Zheng et al. (2019) assessed the agricultural production efficiency and quantified the optimal use of agricultural resources using a three-stage DEA method. Sun et al. (2021) applied a super-efficient network DEA model to combine the WEF nexus with the efficiency measure and spatial autocorrelation test in Chinese provinces during 2005-2015. Maia and Junior (2021) examined the ecoefficiency of the Brazilian food and beverage industries using critical indicators of environmental degradation and resource scarcity, such as water stress and fossil energy consumption, from WEF nexus perspective. They also proposed a methodology that integrates a multiregional input-output table, and the DEA Malmquist index to help decision-makers assess and compare different sectors across countries in the context of the WEF nexus. Zhang and Xu (2022) proposed a three-dimensional network structure to describe the Water-Energy-Food-Economy using data from 19 Chinese regions, which more accurately describes the structure of a WEF nexus system. Zhang et al., 2022a used a DEA model to allocate water resources in 30 provinces and regions of China to improve distribution efficiency and watershed. Zhang et al., 2022b calculated the efficiency of the WEF nexus with an intensity and quantity index system using a DEA model applied to 30 Chinese provinces. Ni and Chen (2022) calculated the input–output efficiency of the WEF nexus focusing on the spatial distribution analysis of the 11 Chinese regions in the Yangtze River Economic Belt. To achieve this, the authors used DEA and standard deviation ellipse model to propose two new indicators (area expansion degree and subsystem influence degree). Huang et al. (2023) calculated the real efficiency of the WEF nexus in China and explored the impact of the external environment through stochastic frontier analysis.

As can be seen from the literature review above, most of the studies using DEA to assess the WEF nexus have focussed on the regional analysis. However, no studies have been identified that use DEA in the WEF context to analyse a specific case study.

3. Methodology

This section is divided into three sections. The case study is described in Section 3.1. Later, the methodology of each WEF nexus approach, i.e., LCA footprints, MFA and WEF-LCA, is presented in Section 3.2. Lastly, the indicators obtained using each approach are implemented into a DEA model to obtain a WEFni for each farm in Section 3.3.

3.1. Case study

This research uses a sample of 100 Spanish dairy farms analysed by Entrena-Barbero et al. (2023b), from which 98 are in the Autonomous Community of Galicia and two are border the Principality of Asturias. Galicia is the main region of Spain in terms of milk production, accounting for 38 % of total national milk produced in the period 2015-2021 (MAPA, 2022). The data were collected through face-to-face interviews in the 2020 season. In addition, dairy farms activities include two main stages: agricultural and milk production.

The agricultural stage refers to the activities associated with growing crops to feed cattle. This stage includes the use of agrochemicals (pesticides and synthetic fertilisers), their corresponding field emissions (N_2O, NH_3, NO_3^-, P, and heavy metals), as well as machinery activities during the crop production (with the consumption of lubricating oil and diesel). Milk production stage refers to those activities involved in caring for and milking the cows. Therefore, it considers purchased fodder (such as maize, molasses, alfalfa, and hay), water consumption, cow bedding (carbonate, straw woodchips, or sand), cleaning products (alkaline detergent, acid solution, disinfectant, paper, and nipple shields), silo plastic, plastic containers, and electricity. It also includes the collection and management of manure, which is used as an organic fertiliser, and its associated emissions. The detailed type and amount of inputs and emissions can be found in the work carried out by Entrena-Barbero et al. (2023b).

3.2. Water-Energy-Food nexus index assessment

Fig. 1 presents an illustrative summary of the methodology used in this research. Firstly, the indicators are calculated according to the WEF approach (Sections 3.2.1 to 3.2.3). Afterwards, a DEA model and a normalisation step are applied to obtain a single score (WEFni), based on the indicators that represent the WEF nexus according to the perspective. Thus, this procedure is applied for each WEF perspective analysed. Table 1 presents a statistical summary of the indicators considered in each approach.

3.2.1. The material flow analysis (MFA) approach

This approach measures the flow consumption related to water,

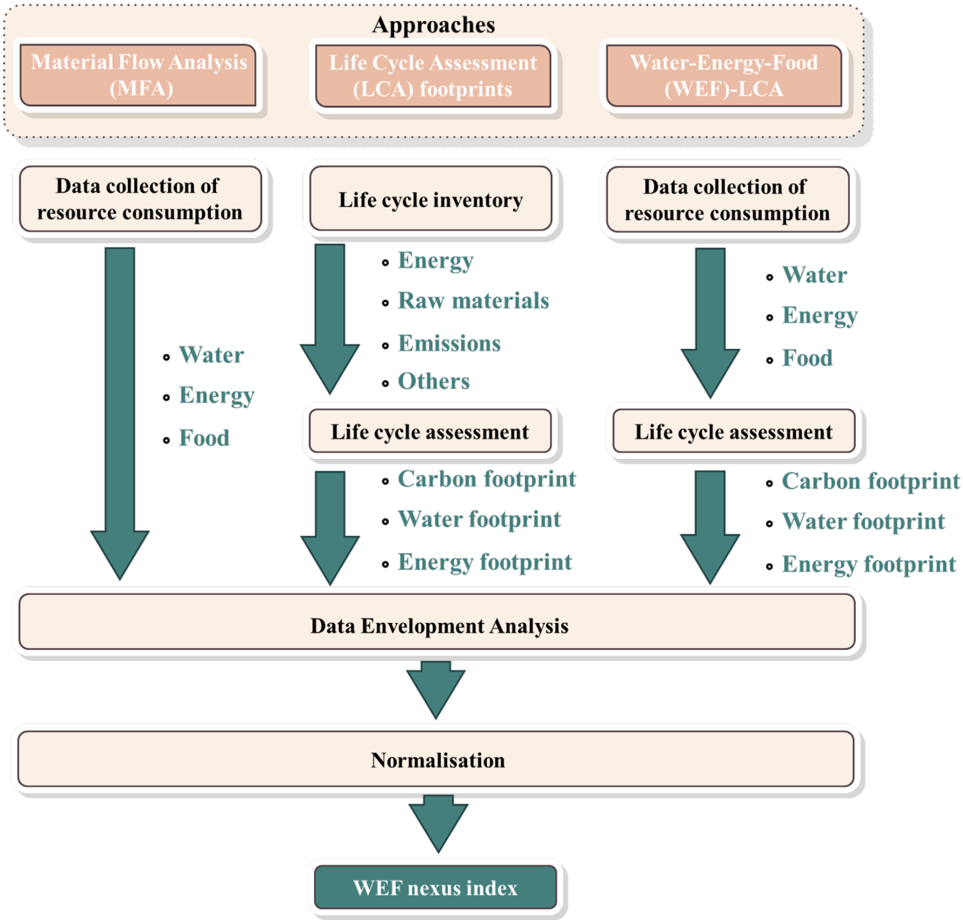

Fig. 1. Schematic summary of the Material Flow Analysis (MFA), Life Cycle Assessment (LCA) footprints, and Water- Energy- Food (WEF)-LCA approaches.

Table 1
Statistical summary of the indicators used in each approach.

Approach	Indicator	Average	Max	Min	Standard Deviation
Material Flow Analysis (MFA)	Water (m^3)	789	3,696	306	490
	Electricity (kWh)	38,330	243,577	10,543	31,581
	Diesel (kg)	7,554	76,358	928	9,155
	Milk (l)	1,071,586	5,289,310	268,956	883,646
Life Cycle Assessment (LCA) footprints	Carbon footprint (kg CO_2-eq)	426,344	762,626	286,826	80,620
	Water footprint (m^3)	384,099	1,123,686	144,670	143,605
	Energy footprint (MJ)	3,824,227	9,002,512	1,901,215	1,268,353
	Milk (l)	1,071,586	5,289,310	268,956	883,646
Water-Energy-Food (WEF)-LCA	Carbon footprint (kg CO_2-eq)	15,633	42,718	6,869	5,539
	Water footprint (m^3)	25,612	74,469	770	20,556
	Energy footprint (MJ)	156,080	268,726	72,350	48,100
	Milk (l)	1,071,586	5,289,310	268,956	883,646

energy, and food without any further calculation. Thus, traditional indicators used in this approach are consumption of tap water, electricity, diesel, and irrigation water, as well as food production, and water stress, among others (Zheng et al., 2019; Maia and Junior, 2021; Lee et al., 2023).

In this manuscript, data collection comprises foreground activities, i.e., those processes which are under the control of the farmer, and it considers direct flows related to WEF pillars: i) water: consumption of water, ii) energy: electricity and diesel consumption, and iii) milk production. Water consumption account for the amount water used for cleaning and disinfection purposes. Electricity refers to energy usage in milk extraction and facilities, and diesel consumption is related to machinery activities (fertilisation, pesticide, and manure application). The amount of cow milk produced during the season is an output of the system and represent the food pillar.

Fig. 2 presents the system boundaries and highlight in blue colour the resources considered under the philosophy of this approach for the assessment of the WEF nexus. Based on this figure, data were directly collected from the involved farms. Detailed data of each dairy farm were provided in Table SM1 in the Supplementary Material (SM).

3.2.2. *LCA footprints approach*

This approach uses LCA methodology to obtain the environmental footprints related to the WEF nexus: water footprint (WF) and energy footprint (EF). In addition, the CF indicator is used because it is representative of climate change concerns for decision-makers (Entrena-Barbero et al., 2023a). Therefore, in this study, the WF, EF, and CF are used as indicators for quantifying the WEF nexus of dairy

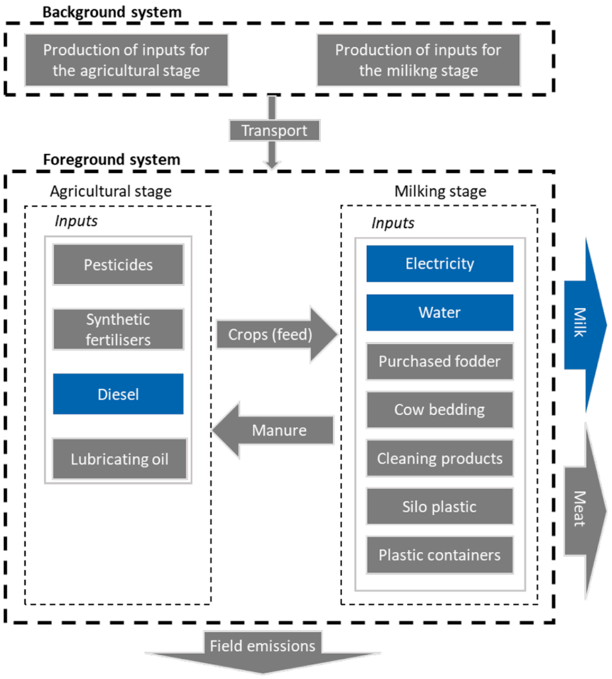

Fig. 2. Flows considered for the WEF nexus assessment (highlighted in blue) under the Material Flow Analysis (MFA) approach.

farms considering a cradle-to-farm-gate system boundary. Foreground processes were extracted from the previous work conducted by Entrena-Barbero et al. (2023b), while background processes were obtained from the Ecoinvent v3.8 database (Wernet et al., 2016). In addition, since dairy farms not only produce milk but also meat, a mass allocation procedure was conducted to distribute the environmental burdens between both products. Fig. 3 presents direct (foreground), and indirect (background) inputs and outputs considered for the WEF nexus assessment (in blue) following the philosophy of this approach. The detailed data of each dairy farms were provided in Table SM2 in the SM.

3.2.3. *WEF-LCA approach*

Three indicators are used to determine the WEF nexus index under this approach using LCA methodology: WF, EF, and CF. However, unlike the approach presented in Section 3.2.2, in the WEF-LCA approach only the foreground processes associated with water and energy flows, as well as their corresponding background processes for performing LCA are considered. The life cycle inventory considered the same system boundaries and allocation procedure as the LCA approach. Fig. 4 presents the resources considered for this WEF nexus assessment (in blue). The detailed data of each dairy farms were provided in Table SM3 in the SM.

3.3. *Data envelopment analysis and WEFni calculation*

Once the indicators of the WEF nexus were obtained, DEA model, as a multicriteria tool, helps to aggregate them into a single value: the WEFni. To this aim, the slack-based inefficiency (SBI) DEA model proposed by Fukuyama and Weber (2009) is used. Its selection lies on accounting for expanding outputs and reducing inputs considering the slacks of both (Fukuyama and Weber, 2009), as the goal is to reduce environmental burdens and increase food dimension. The mathematical formulation of the SBI model proposed by Fukuyama and Weber (2009) for evaluating a decision-making unit (DMU0), assuming variable return

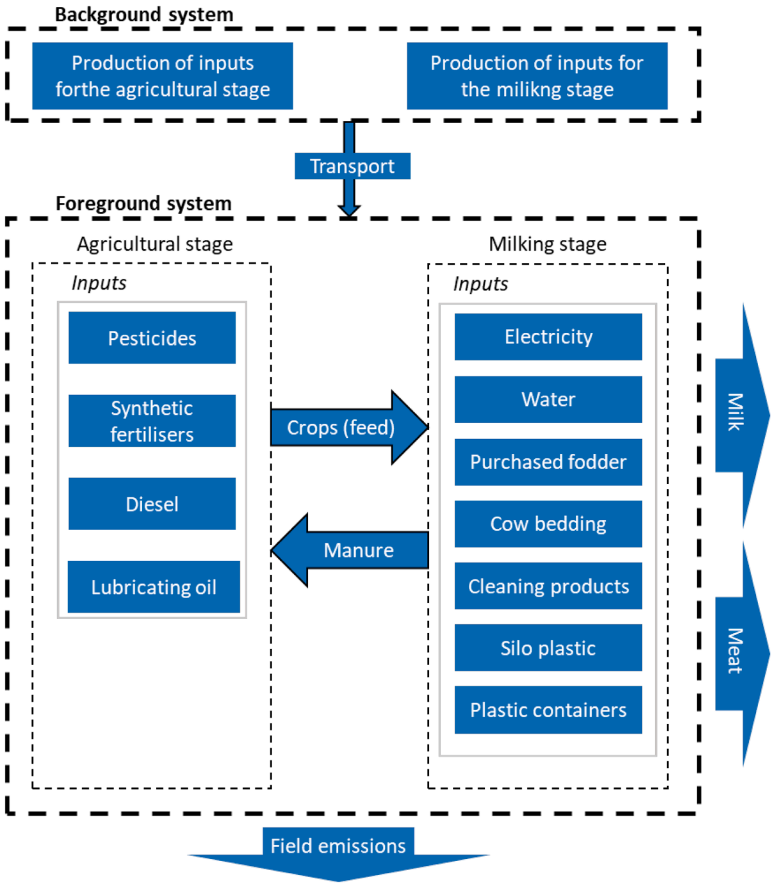

Fig. 3. Flows considered for the WEF nexus assessment (highlighted in blue) under the LCA approach.

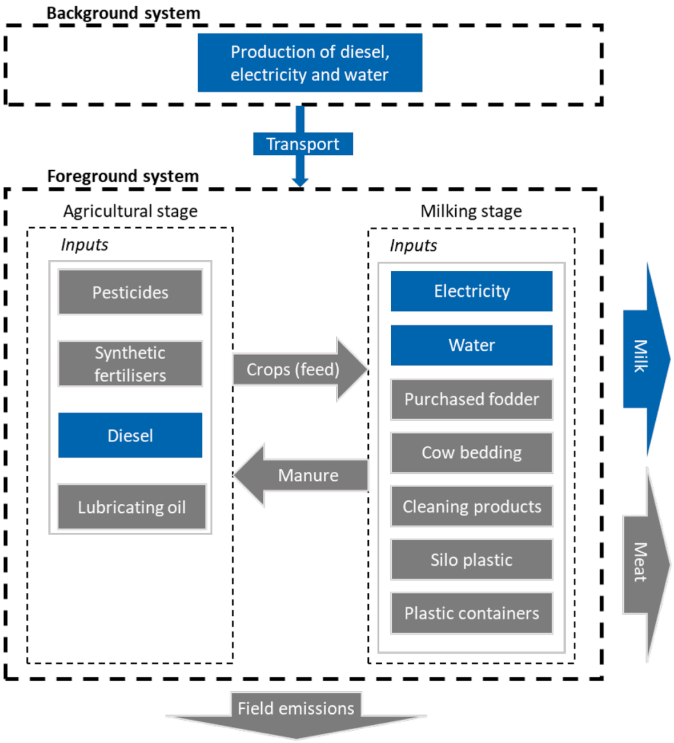

Fig. 4. Flows considered for the WEF nexus assessment (highlighted in blue) under the WEF-LCA approach.

to scale (VRS), is presented in Eqs. (1) to (5). The sets, parameters, and decision variables for this formulation are defined in Table 2.

$$\vec{s}(x_0, y_0; g^x, g^y) = max \left(\frac{1}{M}\sum_{i=1}^{M}\frac{s_i^x}{g_i^x} + \frac{1}{S}\sum_{r=1}^{S}\frac{s_r^y}{g_r^y} \right) * \left(\frac{1}{2}\right) \tag{1}$$

$$x_{io} = \sum_{j=1}^{n} x_{ij}\lambda_j + s_i^x \ \forall i \in I \tag{2}$$

$$y_{ro} = \sum_{j=1}^{n} y_{rj}\lambda_j - s_r^y \ \forall r \in R \tag{3}$$

$$\sum_{j=1}^{n} \lambda_j = 0 \tag{4}$$

$$s_i^x,\ s_r^y,\ \lambda_j \geq 0 \tag{5}$$

Table 2
Nomenclature used in the formulation of the SBI model.

Model nomenclature	
Sets	
N	The set of DMUs (dairy farms)
M	The set of inputs
S	The set of outputs
Parameters	
x_{ij}	Amount of input *i* consumed by DMU *j, j* ∈ *N, i* ∈ M
y_{rj}	Amount of output *r* consumed by DMU *j, j* ∈ *N, r* ∈ S
x_{io}	Amount of input *i* consumed by DMU 0, *i* ∈ M
y_{ro}	Amount of output *r* consumed by DMU 0, *r* ∈ S
g_i^x	Directional vector of input *i, i* ∈ M
g_r^y	Directional vector of output *r, r* ∈ S
Decision variables	
s_i^x	Slack of input *i, i* ∈M
s_r^y	Slack of output *r, r* ∈ S
λ_j	Intensity variable of DMU *j, j* ∈ *N*

In the model presented in Eqs. (1) to (5), Eq. (1) determines the inefficiency score. Eqs. (2) and (3) estimate the input and output slacks, respectively. On the other hand, Eq. (4) considers the VRS assumption. Finally, Eq. (5) represents the nature of the decision variables. In addition, if the efficiency score of the DMU0 is equal to 0, then the unit is efficient; otherwise, it is inefficient. The higher the score, the more inefficient the DMU is.

This model was applied for each of the WEF nexus approaches presented previously. For each one, the directional vector ($g_i^x,\ g_r^y$) is set as ($x_i,\ y_r$) seeking to reduce the inputs and increase the outputs simultaneously. Table 3 presents the inputs and outputs (i.e. pillars of the WEF nexus) used in each approach.

Finally, once the efficiency scores were obtained for all DMUs, they were normalised using the cost criteria approach presented in Eq. (6) to obtain values for the WEFni in the range between 0 to 100 (Tzeng and Huang, 2011). In this equation, EF_j^{max} and EF_j^{min} corresponds to the maximum and minimum efficiency of the sample, respectively, while EF_j refers to the efficiency of the DMU*j*. In this regard, the DMU with the highest inefficiency level obtains the lowest WEFni, i.e., a WEFni equal to zero, while the DMU with the lowest inefficiency level obtain the highest WEFni, i.e., a WEFni equal to 100.

$$WEFni_j = \frac{EF_j^{max} - EF_j}{EF_j^{max} - EF_j^{min}} \tag{6}$$

4. Results

Figs. 5–7 show the WEFni for the 100 dairy farms analysed with the MFA, LCA footprints and WEF-LCA approaches, respectively. The detailed values of each DMU are available in Table SM4 in the SM.

Based on Fig. 5, results of MFA approach indicated that 18 farms reached a WEFni of 100 and one farm encompassed a value of zero. For those farms with a score different to 100, the average WEFni is 63.2, ranging from 0 to 98.9. Thus, these farms should improve the WEFni score by decreasing, on average, the amount of water, electricity and diesel used per litter of milk by 44 %, 33 % and 55 %, respectively. The targets obtained with the SBI DEA model per litter of milk are presented in Table SM5 in the SM.

According to Fig. 6, related to the LCA approach, seven farms had a WEFni of 100 and one farm obtained a value of zero. For those farms that did not reach the maximum value, the average WEFni is 59.7, ranging from 0 to 97.3. These farms should decrease, on average, the amount of water, electricity and diesel used per litter of milk by 79 %, 80 % and 83 %, respectively. The targets obtained with the SBI DEA model per litter of milk are presented in Table SM6 in the SM.

Based on Fig. 7, 14 farms obtained a WEFni of 100 and one received a value of zero. For those farms without a score of 100, the average WEFni is 64.4, ranging from 0 to 98.2. In this regard, these farms could improve the WEFni score by reducing the amount of water, electricity and diesel used per litter of milk by, on average, 78 %, 85 % and 76 %, respectively. The targets obtained with the SBI DEA model per litter of milk are presented in Table SM7 in the SM.

Table 3
Inputs and outputs included in the DEA model to determine WEFni under the three approaches evaluated.

Approach	Inputs	Output
MFA	Water (m^3) Electricity (kWh) Diesel (kg)	Milk production (l)
LCA footprints	Carbon footprint (kg CO_2-eq) Water footprint (m^3) Energy footprint (MJ)	Milk production (l)
WEF-LCA	Carbon footprint (kg CO_2-eq) Water footprint (m^3) Energy footprint (MJ)	Milk production (l)

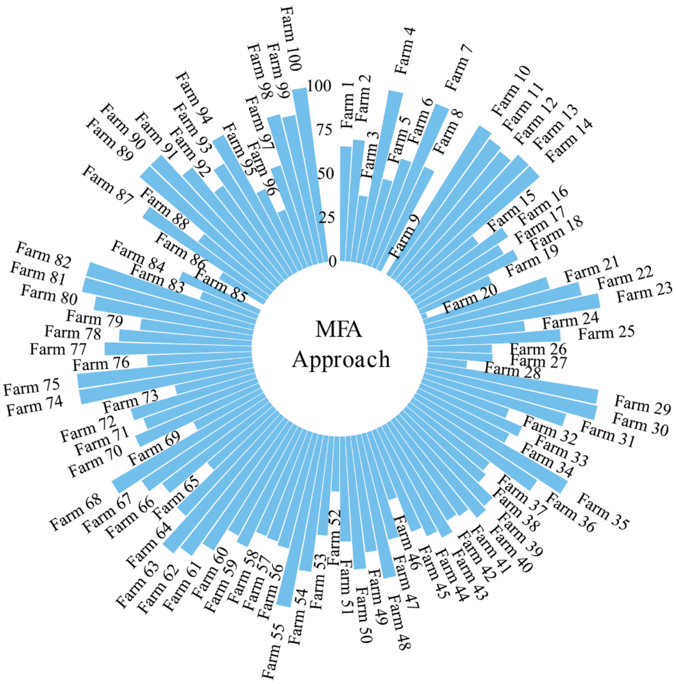

Fig. 5. Water-Energy-Food nexus index of the 100 dairy farms using the Material Flow Analysis approach.

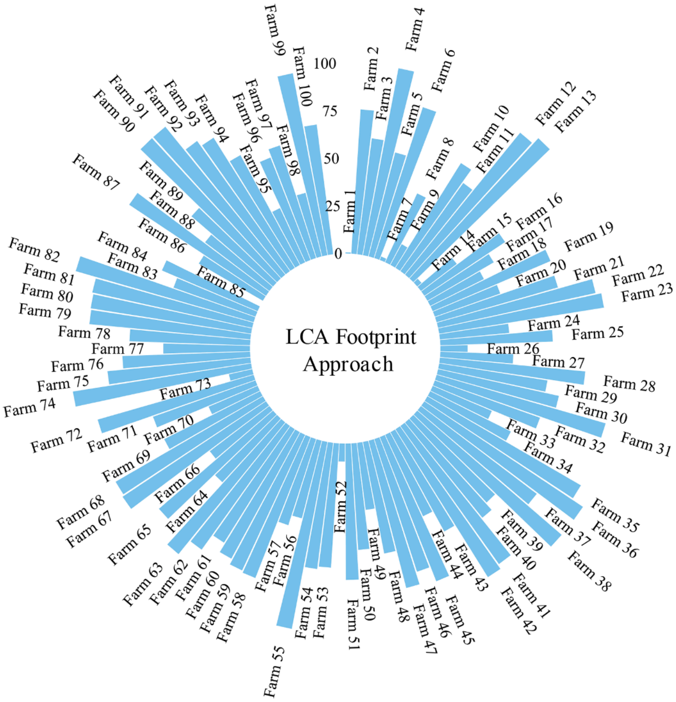

Fig. 6. Water-Energy-Food nexus index of the 100 dairy farms using the Life Cycle Assessment footprints approach.

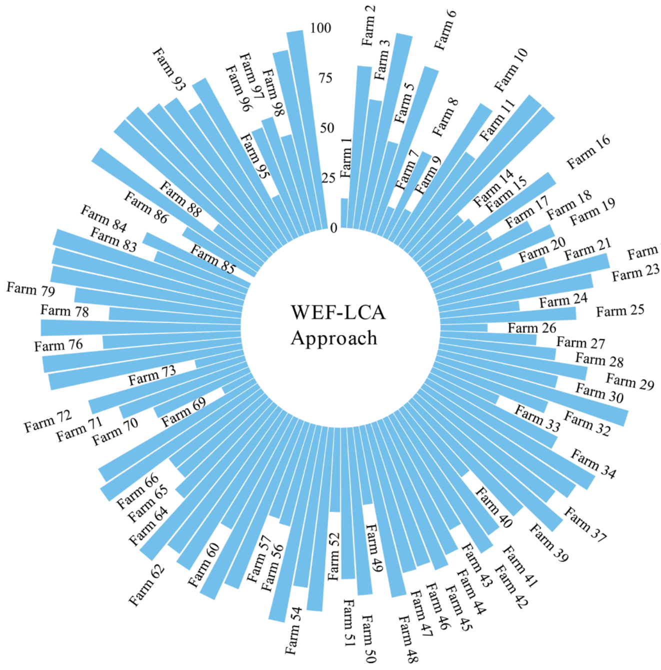

Fig. 7. Water-Energy-Food nexus index of the 100 dairy farms using the Water-Energy-Food-Life Cycle Assessment approach.

The worst performance in the SBI DEA model can be due to a higher use of resources compared to the average consumption of the sample. This is the case of farm 85, which obtained the highest score in the SBI DEA model, which then is equivalent to the EF_j^{max} value in the normalisation step that explain the WEFni of 0 in all approaches (see Table SM4 in the SM). On average, this farm uses twice of resources per litter of milk and produces one-third of milk compared compared to the average sample. For instance, while average sample consumed 30 Wh in terms of electricity, farm 85 used 60 Wh, and farm 85 produces 322 m^3 whereas the average milk production of the sample reaches 1071 m^3.

5. Discussion

A typical issue that may arise in the discussion related to the use of MFA and LCA approaches to estimate the dimensions of the WEF nexus is the extent to which these represent its philosophy. In the work of Hoff (2011), it was mentioned that a nexus approach can improve water, energy and food security by integrating management across different economic sectors, however this depend on the extent of information and depth of information considered. While, MFA considers the direct flows of WEF context (Chen et al., 2020), LCA delivers a detailed analysis of each pillar based on an unified methodological structure (Lee et al., 2023).

5.1. Comparing methodological aspects of the MFA, LCA footprints and WEF-LCA approaches

It is beyond the scope of this study to identify the best approach for calculating the pillars of the WEF nexus, but rather to compare them and identify the advantages and disadvantages of each. These approaches vary in modelling requirements (e.g., methodological procedure, number and type of inputs considered in the assessment), system boundaries, and hotspots identification. These variations may lead to different outcomes and conclusions due to the information required for the environmental performance of the system. Thus, bearing in mind these differences between each approach could help decision-makers to a more suitable selection of them.

The extent of detail and further processing of the data gathered are also different for the three approaches. In the MFA approach, a systematic examination is conducted based on the mass conservation to ensure the integrity of the directions, quantities, and processes of WEF material flows (Chen et al., 2020). Thus, the MFA approach does not require extensive calculation of the data collected to evaluate the pillars of the WEF nexus, although mass and energy balances could also be required in other contexts, e.g., for the evaluation of biorefinery designs. Furthermore, the results are easy to understand and interpret for managers (Islam et al., 2021). On the contrary, the LCA footprints is challenging in terms of not only the extensive data collection required for the foreground system, but also for the background processes related to the upstream activities of the product system (Hauschild et al., 2018). The main differences between LCA footprints and the WEF-LCA approaches lies on the type and number of flows, as well as the system boundary considered. While LCA footprints account for all flows and stages during the life cycle of the product, the WEF-LCA approach considers the environmental impacts during the life cycle of only the flows associated with the WEF nexus (as can be seen in Fig. 4). Therefore, the WEF-LCA approach is a mixture between the MFA and LCA footprints approaches, as it offers a simplified but biased LCA assessment. In this regard, in the LCA footprints and the WEF-LCA approaches, practitioners need to be aware of LCA methodological aspects prior to its application. For example, it requires the appropriate choice of the impact assessment method for the footprint indicator representing each pillar of the WEF nexus, e.g., the WF indicator could be obtained using different methods such as Available Water Remaining - AWARE (Boulay et al., 2018), Water Footprint Assessment (Egan, 2011) or Water Stress Index (Pfister et al., 2009), which could be a barrier for non-practitioners in the LCA context.

By identifying hotspots, practitioners can act to reduce high-impact consumption while minimising the risk of burden shifting (Lavers Westin et al., 2019). Supported by the mass balance, the MFA approach allows identify the process with higher consumption of water, energy or food entering or leaving the foreground system. On the other hand, LCA is an environmental methodology widely recognised for being able to identify environmental hotspot considering the whole life cycle (including upstream processes). For instance, under the MFA approach electricity and diesel are the flows associated with energy pillar, while under the LCA footprints approach, energy for fodder production is identified as the main hotspot. This made the system boundaries definition a critical step in defining which stages are included in the assessment. Therefore, the stand-alone use of MFA could be more suitable for macro-analysis of the material flows but it does not allow the identification of hotspots in as much detail as LCA (Lopes Silva et al., 2015). In this regard, some implication for the decision-maker could be a biased perspective in their intention for improving their practices or a limited scope of action. Possibly if we consider an MFA approach (either MFA or WEF-LCA), potential improvements could be required more urgently in a critical factor of the system that is not directly observed with water-energy-food flows. In the case study of the milk production in Galicia, Spain, the main environmental hotspot is the fodder demand, as indicated the results of water and energy footprints (Entrena-Barbero et al., 2023b). However, this information is not obtained with any MFA approach. Furthermore, in the hypothetical scenario that electricity demand was the critical factor to be addressed by the decision maker, possible solutions could be related to the foreground scope through the implementation of an efficiency program with new equipment or the intention to change the generation source, e.g., with renewable energies, thus changing some background processes. In this way, the selected approach has relevant implications in the type of decision to be implemented through improvement plans both in the economic perspective (e.g., capital investment) and in the time horizon (short- or medium-term decisions).

In addition, another difference that arise between the evaluated approaches is the inclusion of carbon footprint as a further indicator for calculating the WEFni. This is a typical issue in WEF studies that use LCA methodology, such as the LCA footprints or WEF-LCA (Zhang et al., 2021). The CF has been identified as one of the environmental impacts with highest concern for managers, which could be a reason to include it into WEF nexus (Bois et al., 2024). This is more relevant for food industry case studies which are denoted as the responsible of one quarter of greenhouse gas (GHG) emissions (Lazarus et al., 2021). Finally, even though the LCA footprints and WEF-LCA establish a more directly relation between the water and energy resource consumption with their consequent environmental impact by including CF as a further pillar, this inclusion may be further from the original definition of the WEF nexus. Therefore, studies including this pillar need to clearly mention it.

The approaches evaluated in this manuscript could be suitable for different case studies based on their methodological framework. When the focus is to analyse the WEF nexus from a geographical perspective, the MFA approach seems to be suitable because: i) it accounts for direct consumption of the resources allowing to identify flows among regions, and ii) it does not require extensive data collection and processing for practitioners. On the other hand, when the objective is to analyse of WEF nexus of products, services or organisations, then the LCA footprints or the WEF-LCA approaches could be appropriate because attempt to account for all the resources consumed during their life cycle (Sušnik et al., 2022). Table 4 shows a summarise of the main advantages and limitations found in this study.

5.2. Differences in the results of the dairy farm case study and comparison with previous studies

After the application of the three WEF approaches to the dairy farm case study, it was possible to observe differences between them. In a global point of view, only four farms (4, 13, 55 and 90) achieved a WEFni equal to 100 in all approaches. For the MFA and WEF-LCA approaches, this could be explained by the lower amount of water, electricity, and diesel per litter of milk (16 %) compared to the average of the sample. In addition, farms 4, 55 and 90 have the highest amount of milk produced during the season, about five million litters on average.

Table 4
Summary of the main advantages and limitations of each approach used for the Water-Energy-Food nexus assessment.

Topic	Material Flow Analysis approach	LCA footprints approach	Water-Energy-Food-LCA approach
Advantages	• Simple interpretation • Quick computational procedure. • Data requirement is comparatively easy. • Direct resources related to WEF nexus are considered.	• All resources and emissions are considered. • It avoids shifting environmental burdens. • Higher level of details of the process. • Unified methodological framework. • Environmental hotspots identification. • May consider other environmental indicators related to the WEF nexus.	• Direct resources related to WEF nexus are considered. • Environmental hotspots identification associated specifically with water and energy usage.
Limitations	• Stages of the supply chain are partial covered. Mainly focused on foreground processes. • Lack of identification of hotspots.	• Requires practitioners on LCA. • Select an impact assessment method in a wide variety of alternatives. • Specialized software expertise is required. • Availability of LCA databases.	• Requires practitioners on LCA. • Partial LCA. • Partially avoids the transfer of environmental loads. • Select an impact assessment method in a wide variety of alternatives. • Specialized software expertise is required. • Availability of LCA databases.

The case of farm 13 is interesting because it produces 609,803 litter of milk per season, while the average of the sample is more than one million. In this case, the highest efficiency performance could be explained by the lower amount of water and electricity (305 m^3 and 14 MWh, respectively) compared to the average of the sample, which are 789 m^3 and 38 MWh, respectively. For the LCA footprints approach, the highest performance of these four farms in the WEFni can be explained by the lower use of agricultural resources, mainly cow bedding, water, agrochemicals, and purchased feed for cows per litter of milk produced. For example, farms 13, 55 and 90 use 20 % less amount of fodder compared to the average sample (0.5 ton), while farm 4 uses 43 % less agrochemicals for crop cultivation and water for cleaning tasks.

The MFA and WEF-LCA approaches consider the same elementary flows for water and energy dimensions, which could explain the close number of farms (18 and 14, respectively) that obtained a WEFni of 100. In contrast, the LCA footprints considers a wide range of resources and emissions, and only seven farms reach the total WEF score. Considering two farms that exhibit clear differences between their direct water consumption and their WFs, farm 7 reported a direct water consumption of 373 m^3, while its WF is 414,602 m^3. These values contrast with those of farm 36, whose direct water consumption reaches 665 m^3 (twice as much as reported by farm 7), while its WF was calculated in 144,760 m^3 (about 2/5 of that of farm 7).This shows that farms with a WEFni of 100 in the MFA approach but not in the LCA footprints is explained by two main reasons: i) the LCA footprints considers a higher number of flows (upstream processes) to determine the WEF indicators, and ii) they use resources that require a higher amount of water to be produced but much of this water is reused. This shows the importance of considering not only the direct consumption, but also the resources involved throughout the product's life cycle.

Focusing on the main contributor of each pillar of the MFA approach, water used for cleaning facilities represent 97 % of the total consumption, while the rest is for washing staff. In the case of the energy pillar, electricity is only required in milking facilities and therefore no further breakdown is calculated. Diesel is used for agricultural machinery, where 38 % goes to moving cow feeding and manure management, and the remaining 62 % is used for farm activities such as sowing, agrochemical applications, mowing, among others. In the case of the LCA approach, as it considers all upstream resources and emissions, including the agricultural stage, contributors are not only identified at this stage. For the CF, field emissions and enteric fermentation are the main contributor with almost 50 % of the total CF, while for both the WF and the EF, fodder production is identified as the hotspot with about 60 % and 70 %, respectively. Finally, in the WEF-LCA approach, for the CF, diesel is identified as the main contributor with an average of 53 %, while for the WF it is water for cleaning and disinfection purposes with 94 %, and for the EF it is electricity with 98 %.

Regarding works in the literature, as mentioned in the introduction section, Entrena-Barbero et al. (2023a) was the first study that proposed a technical guidance to calculate a WEFni score for the WEF nexus. The authors used several seafood systems to show how this index can be implemented. As such, the aim was to present a novel approach following an integrative perspective for seafood ecolabelling. Furthermore, Entrena-Barbero et al. (2023b) used this WEFni score for evaluating the WEF nexus of Spanish dairy farms for benchmarking under a like cycle perspective. For this purpose, the authors used the LCA footprints approach, quantifying three environmental indicators: CF, WF and EF. The milk yield was set as indicator for food pillar. Finally, the WEFni approach is also applied in the work of Ceballos-Santos et al. (2024) to estimate the environmental, energy and nutritional profiles of seafood products from fisheries or aquaculture production systems under a life cycle perspective. Contrary to these studies, here we evaluated and compared three WEF approaches to identify advantages and disadvantages from a methodological perspective. Consequently, it is clear that the idea of a single score for the WEF nexus has been proposed and applied in agri-food systems, but none of them has discussed the different ways of measured this concept.

5.3. The interrelations and interconnections of WEF pillars among the analysed approaches

The WEF nexus aims to identify the different interrelations and interconnections between the resources which are intricately intertwined in terms of production and consumption, with the production and supply of any resource dependent on the others (An et al., 2024). While interrelations refer to relations that exist within the system boundary of each WEF subsystem, interactions are those mutual impacts of one subsystem on another (Afshar et al., 2022). Therefore, studies such as Vahabzadeh et al. (2023) have devoted to analyse the interrelations and interconnections between the WEF pillars. However, as mentioned by Gao et al. (2024), the model did not explicitly reflect the interrelations among these three subsystems.

The analysed approaches evaluated in this manuscript consider interrelations and interconnections to different extent (seen Figs. 2–4). The MFA approach considers the interactions between water consumption (water subsystem), diesel and electricity consumption (energy subsystem), and milk production (food subsystem) (see Fig. 2). In this sense, the interconnections under this approach are limited to the geographical scope of the farm and to the flows evaluated. For example, in the dairy farms studied, increasing efficiency of the agricultural machinery could decrease the consumption of diesel or electricity consumed in the farm (energy subsystem) and increase the amount of milk produced (food subsystem). Therefore, the implications of decisions under the MFA approach in terms of the interconnections are limited to the geographical area of the farms and to the resources evaluated.

The LCA footprints approach considers the interrelationships of not only the direct resources of the WEF nexus, but also other flows associated with milk production, such as agrochemicals, cow bedding and fodder purchases, among others. In this sense, water-energy-food interactions under this approach are beyond the foreground stage of farms. For instance, reducing the level of fodder purchased could imply a decrease in the demand of energy and water for its production. Thus, the implications of decision-making processes under the LCA footprints approach have a greater impact on achieving better sustainable performance of organisations.

Finally, the WEF-LCA approach considers the interrelations and interconnections of the direct resources of the WEF nexus, but it fails in deeper interrelations with other relevant resources of milk production. As shown Fig. 4, this approach accounts for the direct use of diesel, electricity, water, and milk (foreground system), and also the upstream stages involved in their production (background system). For instance, changing the source of electricity used in the dairy farm from the current electric grid, where water is employed in thermal power plants for cooling, to a non-renewable, such as the wind power, could result in a reduction in water used far away from the farm. Therefore, the implications of decisions under the WEF-LCA approach in terms of interactions are limited to foreground processes and the life cycle of water-energy-food resources at the nexus.

5.4. Policy implications and the assessment of the food pillar of WEF nexus

The WEF nexus presents a multi-criteria challenge where the interactions between these resources generate relevant impact for sustainable agri-food systems. To improve food production in a WEF nexus perspective, policymakers and decision-makers address complex trade-offs and choices. Food production is dynamic and highly demanding for water and energy, which has environmental consequences such as climate change and droughts. Addressing the convergence between political and environmental concerns requires informed decisions, conscious trade-offs, and innovative solutions based on clear scientific knowledge (Javan et al., 2024).

Even though the relevance of including the WEF nexus in policy decisions, current literature has shown that the link between the WEF nexus and policy-making still remains weak (Daher and Mohtar, 2015; Herrera-Franco et al., 2023; Jordan and Adelle, 2013). This could be because it is often difficult for environmental concerns to impact on policy development due to political cycles are short-term or they may not be clear, making their relevance to specific policy outcomes limited (Hooper et al., 2018). Therefore, boosting knowledge and technical guidance could strengthen communication mechanisms and capabilities to facilitate and improve decision-making processes.

WEF nexus indicators have been assessing under different approaches. Particularly, LCA and MFA have proven to be valuable methodologies in the areas of water and energy, as well as carbon footprint. However, they have not been used to evaluate food perspectives of the WEF nexus. The food perspective could be challenging for practitioners as it has different aims to be evaluated, such as production, accessibility, and nutritional quality. For example, nutritional indicators such as the Nutrient Rich Food index (Drewnowski, 2013), which considers the weighted sum of the impact of a set of nutrients to be promoted minus other nutrients to be limited (Entrena-Barbero et al., 2023a), or through the food production performance of each farm evaluated (Entrena-Barbero et al., 2023b). As such, there is no one-size-fits-all approach for assessing the food dimension. Nevertheless, the specificities of the food pillar within the WEF nexus could be addressed through its functional unit which typically refers to the product mass. Currently, it is recommended to use additional functional units to reflect in a more appropriate way the true function of food systems, which would be to nourish and satiate (Weidema and Stylianou, 2020). In this context, functional unit based on nutrient or calorie content might also be an appropriate option. However, their evaluation has a higher uncertainty and is therefore less commonly used at present (Weidema and Stylianou, 2020).

5.5. *Multicriteria approaches for obtaining a single WEF nexus index*

There are different DEA models that can be used for WEF nexus assessment. However, in order to obtain a WEFni ranging from 0 to 100, the normalization step is mandatory only when the efficiency index is higher to 100. This could occur either when the orientation of the model is to outputs, or when an advanced models are used such as Slack Based Measure (SBM), Directional Distance Function (DDF), etc. (Cooper et al., 2007).

The computation of a single score could be beyond the use of DEA. In this sense, there are multiple other tools and approaches that can also be used to obtain a WEFni, such as TOPSIS (Bilbao-Terol et al., 2014), criteria importance through intercriteria correlation (CRITIC) method (Lin et al., 2020), Analytic Hierarchy Process (AHP) (Saaty, 1990), among others. The selection of a particular approaches depends on several factors such as the objective (ranking, classification, etc.), definition of criteria, application of weights, etc (Nowak et al., 2020).

6. Conclusions

This work discusses different approaches for the evaluation of the WEF nexus, identifying their pros and cons of using material flow analysis or a life cycle assessment approach. These approaches are compared using a sample of 100 dairy farms case study and considering a multi-criteria decision tool like DEA for obtaining a single score, and cost criteria approach for calculating a single WEFni for each farm.

The approaches use different information for calculating WEF indicators. The MFA approach uses the direct flows consumption related to water, energy, and food without any further calculation. Thus, the interrelationships are limited to the foreground WEF subsystems and to the flows evaluated. The LCA footprints approach account for all flows and stages during the life cycle of the product and indicators are in terms of water footprint, energy footprint, carbon footprint and amount of food. As such, the interrelationships of not only the direct resources of the WEF nexus but also other flows associated with food production are considered, extending the implications beyond the foreground stage of the evaluated system. Finally, the WEF-LCA approach takes into account the environmental footprints during the life cycle of the direct flows associated with the WEF nexus. Thus, the interrelationships of the direct resources of the WEF nexus are considered, but it fails in deeper interrelations with other relevant resources of food production.

Based on these differences and how the interactions between the resources are considered, the pros and cons of each approach can be summarized as follows. While the MFA approach is faster to calculate than the LCA footprints and WEF-LCA approach, and its results are easy for managers to understand and interpret, it fails to identify the impact of a specific stage throughout the life cycle of a product/service, as it considers only foreground stage. On the other hand, although the LCA footprints approach considers foreground and background processes of the system analysed, allowing the identification of hotspots. Although its application is challenging due to the extensive data collection required and the proper selection of a method for calculating the footprint indicators, which could be a barrier for non-LCA practitioners. Finally, the WEF-LCA approach performs an LCA where footprints are calculated from inventory data based only on water and energy flows, representing a biased view of the resource demand for organisations.

The advantages and disadvantages above presented allow proposing different practical applications of each method, depending on the objective of the study and the target audience. The MFA approach could be suitable for analysing the WEF nexus considering resources from a geographical point of view to establish regulations, laws, etc. Conversely, the LCA footprints approach could be appropriate for an in-depth study aimed at practitioners seeking to the interlinkages of the WEF nexus along the entire food supply chain. Finally, the WEF-LCA approach could be seen as a preliminary approach as it requires a partial LCA study. Therefore, these outcomes are expected to provide guidance to LCA practitioners, scholars, researchers and policymakers for selecting an appropriate approach to evaluate WEF nexus concept.

Future research could have to be focused on how to include other dimensions related to this philosophy, which could imply the use of methodologies that cannot follow a life cycle thinking. Another issue that also needs further research is the integration of variability and uncertainty. This is of particular interest in the agricultural sector, where different management practices can be taken into account, for example in small farms.

Ethical statement

The authors confirm that the study did not involve experimentation on human or animal subjects; however, the respondents were selected among those who voluntarily indicated the readiness to participate in the study.

CRediT authorship contribution statement

Leonardo Vásquez-Ibarra: Writing – original draft, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Ricardo Rebolledo-Leiva:** Writing – original draft, Methodology, Investigation, Conceptualization. **Eduardo Entrena-Barbero:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis. **Mario Fernández:** Writing – review & editing, Data curation. **Gumersindo Feijoo:** Writing – review & editing, Validation, Supervision, Funding acquisition. **Sara González-García:** Writing – review & editing, Validation, Supervision, Funding acquisition. **María Teresa Moreira:** Writing – review & editing, Validation, Supervision.

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 will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.fufo.2024.100444.

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