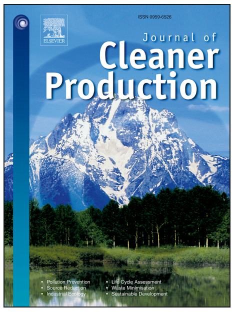

Pursuing the route to eco-efficiency in dairy production: the case of Galician area

Antonio Cortés, Gumersindo Feijoo, Mario Fernández, Maria Teresa Moreira

PII: S0959-6526(20)34905-2

DOI: https://doi.org/10.1016/j.jclepro.2020.124861

Reference: JCLP 124861

To appear in: *Journal of Cleaner Production*

Received Date: 9 March 2020

Revised Date: 24 September 2020

Accepted Date: 26 October 2020

Author Statement

Manuscript title: Pursuing the route to eco-efficiency in dairy production: the case of Galician area

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Category 1
Conception and design of study: M. T. Moreira; G. Feijoo; M. Fernández
Acquisition of data: M Fernández; A. Cortés
Analysis and/or interpretation of data: A. Cortés; M. T. Moreira, G. Feijoo, M. Fernández

Category 2
Drafting the manuscript: A. Cortés; M. T. Moreira, G. Feijoo
Revising the manuscript critically for important intellectual content: M. T. Moreira; G. Feijoo, M. Fernández

Category 3
Approval of the version of the manuscript to be published (the names of all the authors must be listed): A. Cortés; G. Feijoo; M. Fernández; M. T. Moreira

Acknowledgements

All persons who have made substantial contributions to the work reported in the manuscript (e.g., technical help, writing and editing assistance, general support), but who do not meet the criteria for authorship, are named in the Acknowledgements and have given us their written permission to be named. If we have not included an Acknowledgements, then that indicates that we have not received substantial contributions from non-authors.

Pursuing the route to eco-efficiency in dairy production: the case of Galician area

Antonio Cortés[a*], Gumersindo Feijoo[a], Mario Fernández[b] and Maria Teresa Moreira[a]

[a] CRETUS Institute. Department of Chemical Engineering, Universidade de Santiago de Compostela, 15705 Santiago de Compostela (Spain)

[b] Galician Association of Agri-food Cooperatives, 15703 Santiago de Compostela (Spain)

* Corresponding author

E-mail. antoniojose.cortes.montoya@usc.es

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Antonio Cortés[a*], Gumersindo Feijoo[a], Mario Fernández[b] and Maria Teresa Moreira[a]

[a] CRETUS Institute. Department of Chemical Engineering, Universidade de Santiago de Compostela, 15705 Santiago de Compostela (Spain)

[b] Galician Association of Agri-food Cooperatives, 15703 Santiago de Compostela (Spain)

* Corresponding author; E-mail. antoniojose.cortes.montoya@usc.es

Abstract

The search for more efficient and sustainable processes has become the cornerstone of any production system. It is within this framework that it is highly relevant to propose improvement actions based on a detailed eco-efficiency analysis of different facilities so that roadmaps for more sustainable processes are considered. The joint use of Life Cycle Assessment (LCA) and Data Envelopment Analysis (DEA) appears to be an appropriate methodology to assess the eco-efficiency of multiple units, providing targets and benchmarks for inefficient ones. This work advances in this direction by integrating both analysis methodologies in the calculation of environmental indicators associated with milk production for a large group of farms, nearly 100 decision-making units. Twenty-one dairy farms were identified as efficient, and the average efficiency score of the inefficient farms was 0.58. Based on the comparison of current operation levels with target levels, it was possible to quantify average reductions of up to 53% for input consumption levels, resulting in average impact reductions of 49% in carbon footprint and 55% in water footprint. Comparing the outcomes of this study with those reported in 2011 for Galician farms (Northwest Spain), a slight decrease in eco-efficiency was noted in the dairy sector. This study shows how the Galician dairy sector must address sustainable development objectives, especially those established in Agenda 2030 to achieve constant improvement and sustainable and efficient production.

Keywords

Life Cycle Assessment; Data Envelopment Analysis; Dairy farms; Eco-efficiency; Carbon footprint; Water footprint

1. Introduction

The concept of sustainable development is only possible if all people are food secure and well-nourished (Caron et al., 2018). The world population is expected to increase to 9.7 billion people by 2050 (United Nations, 2017), which implies that the demand for food will increase by 70% (FAO, 2012). This growth framework must be materialised in active and concrete policies developed to reduce environmental impacts in food production, in order to ensure a constant and sustainable production chain (Coscieme et al., 2020).

The environmental impacts of the food industry are largely driven by livestock production, which accounts for 3-8% of total energy consumption and emits 14.5% of total anthropogenic GHG emissions worldwide (Eurostat, 2020), associated with emissions of nitrous oxide (N_2O) and methane (CH_4) from enteric fermentation, fertilisation activities and manure storage (Aguirre-Villegas et al., 2015). Despite their relevance, the impacts of this sector on other environmental aspects, such as eutrophication, acidification and water scarcity, should not be ignored (González-García et al., 2013).

Today, milk is one of the most widely produced foods in the world (Üçtuğ, 2019), with dairy products being a fundamental pillar of the human diet (Wang et al., 2018). In the context of the European Union, Spain is the seventh largest producer of cow milk, with 5% of the total (Eurostat, 2019). In Spain, the dairy sector is the second most important of all the livestock sectors. The latest data published by the Spanish Agrarian Guarantee Fund (FEGA, 2019) show that the Spanish dairy industry processes more than 7 million m^3 of milk. Galicia, a region in northwest Spain, produces 38% of the national milk production (MAPA, 2019), making it the ninth largest dairy region in Europe, with a remarkable turnover of 800 million euros and more than 25,000 people employed. Given this context, it is desirable to propose strategies for environmental improvement in livestock and milk production.

Among the different methods to evaluate the environmental performance of milk production, Life Cycle Assessment (LCA) has been applied in recent years for a wide range of production systems in different countries (Baldini et al., 2020; Berton et al., 2020; Djekic et al., 2019; Egas et al., 2020; Escribano et al., 2020; Famiglietti et al., 2019; Knudsen et al., 2019; Woldegebriel et al., 2017). Noya et al. (2018) evaluated the environmental burdens of milk production in facilities of Northeast Spain. Although a wide range of environmental indicators were calculated, the study focused mainly on the water footprint according to the Water Footprint Network (WFN). The capital importance of feed production in the water footprint was demonstrated due to characterisation factors of agricultural products. Baldini et al. (2018) compared the environmental profile of three Italian dairy farms within two different scenarios. On one side, the direct gaseous emissions were estimated according with the Intergovernmental Panel on Climate Change (IPCC) and European Environmental Agency (EAA) guidelines. On the other hand, emissions measured in other papers were taken as input data to quantify the emissions associated to manure management. The results showed the importance of the emission factors since IPCC equations underestimated manure management emissions while overestimated ammonia related emissions. Pirlo and Lolli (2019) carried out a different comparison, eight conventional and six organic dairy arms from Italy. This study concluded that conventional production is slightly higher that organic (9,004 vs. 7,736 kg/cow per year, respectively). However, the differences in environmental impacts in terms of GWP, ACP and EUP categories were not significant. Other authors focus their research on establishing the environmental performance of milk production based on a single indicator. Thus, numerous papers on carbo footprint (Finnegan et al., 2017; Horrillo et al., 2020; Laca et al., 2020; Morais et al., 2018; Vida and Tedesco, 2017) or water footprint (Lu et al., 2018; Mekonnen et al., 2019; Payen et al., 2018; Usva et al., 2019) were published in recent years.

All these studies present differences in the selection in the FU, system boundaries, allocation factors… These are precisely the characteristics that make LCA a versatile tool, but whose methodology still lacks a comprehensive approach to milk production systems.

Since the use of high-quality data is essential for a study to be transparent and reliable, it is often necessary to collect inventory data from different similar facilities to ensure the representativeness of the data. A common solution for managing a large volume of data is to establish an average. However, the high degree of variability that results from such a system can lead to uncertainty in the results obtained. An alternative approach to dealing with these cases is to conduct individual analyses for each inventory. However, this approach makes the results difficult to interpret. It is therefore necessary to use methodologies that allow performance indicators to be determined for the operating system as a whole, considering all facilities. Data Envelopment Analysis (DEA) is a linear programming based technique to assess the relative efficiency of a set of similar units known as Decision Making Units (DMU), which considers multiple inputs and multiple outputs simultaneously (Cooper et al., 2007). This is how the combined use of the LCA and DEA methodologies came about, which allows for the assessment of the eco-efficiency of similar production systems that enables the environmental and operational assessment of similar production systems. According to the World Business Council for Sustainable Development (WBCSD), eco-efficiency is defined as "the delivery of competitively priced goods and services that satisfy human needs and provide quality of life, while progressively reducing ecological impacts and resource intensity throughout the life-cycle, to a level at least in line with the earth's estimated carrying capacity” (Schmidheiny et al., 2000), or more generally “doing more with less”.

The first joint use of these two methodologies dates from a scientific publication in which a 3-step procedure was established to determine a relationship between operational efficiency and the environmental impacts of a sample of 62 mussel cultivation racks (Lozano et al., 2009). Over time, other researchers have expanded and improved this methodology to a 5-step method that allows for the environmental assessment of current and virtual DMUs. This 5-steps method has been widely applied in different production systems: WWTPs (Lorenzo-Toja et al., 2015), organic blueberry orchards (Rebolledo-Leiva et al., 2017), grape production (Mohseni et al., 2018), grocery stores (Álvarez-Rodríguez et al., 2019) or farm-scaled biogas plants (Lijó et al., 2017). This methodology was applied to Galician dairy industry in 2011 to evaluate the eco-efficiency of a set of 72 farms (Iribarren et al., 2011). This study demonstrated that farm size had no influence on the efficiency score. However, there was a tendency for small inefficient farms to perform worse than medium and large farms.

The main objective of this study focuses on the application of LCA + DEA methodology to a group of 96 dairy farms throughout Galicia to evaluate the eco-efficiency of the Galician dairy sector. This last decade has been strongly influenced by a society concerned for sustainable production, which causes consumers to be increasingly demanding with environmental aspects in production methods. A secondary objective is to establish the "hot-spots" in milk production process by determining two widely used environmental indicators: Carbon Footprint (CF) and Water Footprint (WF).

2. Materials and methods

2.1. Definition of the case study

Galicia is the leading Spanish autonomous regions in milk production at national level since 2001, with 38% of the total Spanish production. In fact 39% of the Spanish dairy farms are located in the Galician region (MAPA, 2019). The dairy industry is the most important food industry sector in Galicia, followed in terms of turnover by the canning industry (Torres López et al., 2017). Galician dairy farms are characterised, like all agricultural and livestock farms, by a great variability in the consumption of materials and production models (Aguirre-Villegas et al., 2017). Thus, it is necessary to include as many farms as possible in the analysis so that the sample is characteristic of the Galician dairy sector. Taking this premise as a key element in the analysis, 96 farms distributed throughout Galicia were considered. All the farms studied have an agricultural area around the farm within a 5 km radius to grow mainly corn and grass, which is subsequently stored in silos and used as cattle feed. This agricultural land is managed by the farmers themselves and was included within the system boundaries. In this way, the processes of grass and maize cultivation were modelled considering the use of machinery, the time of use per hectare, the consumption of diesel and other materials, such as fertilizers or agrochemicals.

In some cases, dry grass is also cut for hay production. All farms also use concentrate as cattle feed, to a greater or lesser extent. The composition of this feed is variable for dairy cows, dry cows and heifers, but in general it is composed of 30%, 26%, 17% and 12% maize, soybean, rapeseed and barley respectively, in addition to other minor components.

The size of the different farms is variable; the smallest farm is composed of 13 animals with annual production around 20,000 kg of milk, while the largest farm has 520 animals and produces 3,000,000 kg of milk per year. Although milk is the main objective of the farms, meat production should not be neglected. Thus, the production obtained from old cows slaughtered for meat has been considered a co-product of the farms.

In relation to manure management, due to its high amount of nutrients, it is used as an organic fertiliser in the agricultural land. The direct emissions produced during the storage of the manure and its subsequent application to the land have been estimated. Infrastructure related to the farm has not been included, as it has an impact that can be considered insignificant throughout its useful life (Castanheira et al., 2010; de Léis et al., 2015). However, the manufacture of tractors and implements used in crops has been computed within the production of on-farm feed (grass and maize). The main characteristics of each of the farms evaluated (number of animals and production of milk and meat) can be found in Table S1 of the Supplementary material.

2.2. LCA methodology

Life Cycle Assessment is a fundamental element as a tool to determine the impacts and give a global vision of the environmental performance of Galician dairy farms. The environmental performance of dairy farms was analysed, and the main "hotspots" of the process were determined using LCA methodology. The methodology followed the principles established in the ISO 14040 and 14044 standards for CF and 14046 standard for WF.

2.2.1. Goal and scope definition

The main objective of the study is to determine the evolution of eco-efficiency in milk production in Galicia by comparing the outcomes of the analysis with those reported in 2011. To this end, the environmental impacts of a model farm will be analysed to determine which elements are the determining factors in the environmental impact and in the eco-efficiency score. The study was carried out under a "cradle-to-gate" perspective. Figure 1 is a block diagram of an average farm, representative of the set of installations evaluated, in which the limits of the system are identified, as well as the main elements, inputs and outputs. All relevant processes related to milk production, including energy and material consumption during milking and farming activities were considered such as electricity for machinery use and lighting and different cleaning and chemical agents: detergent, sealer, acid solution or disinfectant. In addition, other inputs considered were the production of feed, paper, plastic for silos, containers for chemical products, refrigerant and the management of the waste produced, and transport activities. Gaseous emissions from enteric fermentation, storage of manure and its application as organic fertiliser for crops were estimated.

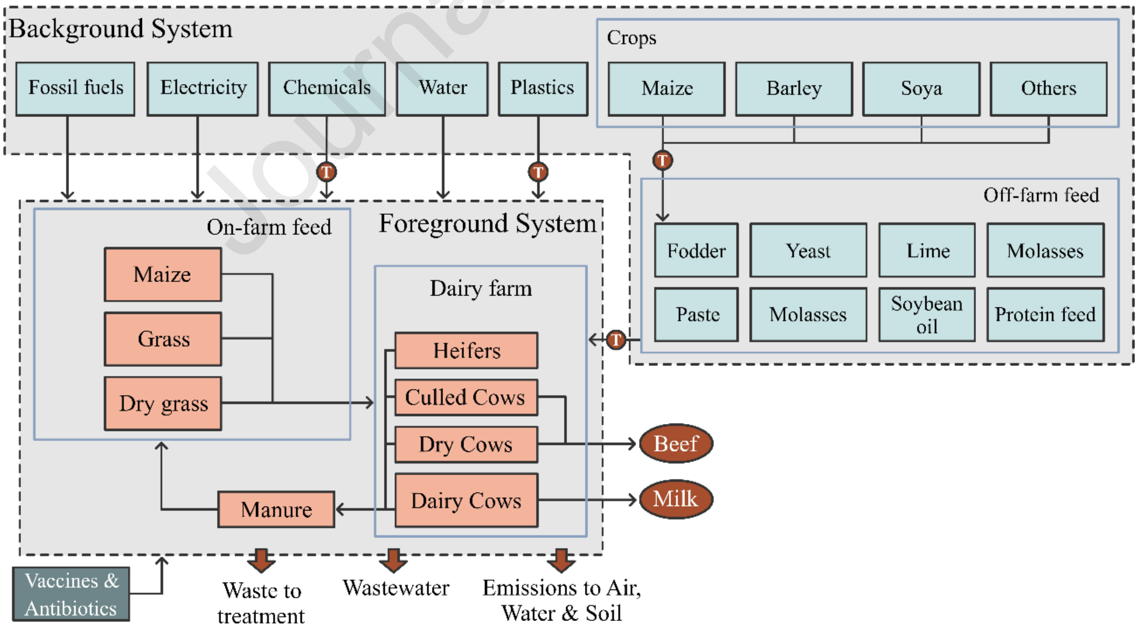


Figure 1. System boundaries for the dairy farm model evaluated in this study. Legend: T: Transport.

2.2.2. Functional Unit (FU) and allocation approach

In the present study, following the guidelines of IDF (2015) when a study is conducted on-farm, the quantity of Fat- and Protein- Corrected Milk (FPCM) produced in one year, corresponding to the campaign Apr18/Mar19, has been taken as the functional unit (FU). To convert the raw milk weight to FPCM, Eq. (1) was followed:

$$FPMC\ (kg/yr) = P\ (kg/yr) * [0.1226*FC\% + 0.0776*PC\% + 0.2534] \quad (1)$$

Where: P: Production; FC: Fat content; PC: Protein content.

In accordance with ISO standards, the allocation of environmental loads should be avoided as much as possible by giving priority to the division of units into subsystems or the expansion of the system boundaries to include other co-production functions. However, since the units assessed are considered to have a multi-output system, allocation is unavoidable. Following the guidelines of IDF (2015), biophysical allocation between the two products produced – milk and meat – has been considered, according to Eq. (2) and Eq. (3):

$$AF_{MILK} = 1 - 6.04 * BMR \quad (2)$$

$$AF_{MEAT} = 1 - AF_{MILK} \quad (3)$$

Where: AF_{MILK} is the allocation factor for milk; BMR is the ratio M_{MEAT}/M_{MILK}; M_{MEAT} is the sum of live weight of all animals sold; and M_{MILK} is the sum of total FPMC.

Section S2 of the Supplementary material shows the economic, mass, and biophysical allocation factors calculated for each farm.

2.2.3. Data collection

The quality of the inventory data is a key element in ensuring the accuracy and reproducibility of LCA studies. A consistent environmental assessment requires high quality baseline data. To ensure this data quality, priority should be given to the use of primary sources, minimising as far as possible the use of secondary data from databases and/or similar sources. In this context, most of the information provided in the life cycle inventory was constructed from primary data collected through questionnaires completed by workers. These questionnaires collect information on all relevant aspects of the farm, such as operational characteristics, general data on location and degree of technology used, number of animals in the farm, feed consumption, use of machinery or production of waste, corresponding to the campaign Apr18/Mar19.

The life cycle inventories of the background system (chemicals, fossil fuels, electricity, water...) were taken from the Ecoinvent® database version 3.5, considering the consumption of each element according to the information collected in the questionnaires. In this way, the processes of electricity production (Spanish electricity mix), cleaning agents, fuels, lubricants, fertilisers pesticides correspond to Ecoinvent inventory data (Althaus et al., 2007; Dones et al., 2007; Hischier, 2007; Spielmann et al., 2007). Regarding livestock feed, two main sources for feed production were considered:

- Concentrate, which is formulated with the same composition as considered in Iribarren et al. (2011). Thus, a content of 30% maize, 26% soybean, 17% rape meal, 12% barley and 2% wheat were considered, as well as a certain amount of chemicals and additives. The production of the background processes was taken from the Ecoinvent database.
- Another source of livestock feed is grass and maize grown by farm owners on the surrounding farmland. These productions were modelled individually considering the primary information provided by the farmers. The fuel consumption for the machinery used on the crops was calculated based on the working capacity of the machinery at each stage (h/ha) and the corresponding fuel consumption (l/h). The activities considered in each of the crops have been the typical stages of any cereal crop: organic fertilisation, land clearing, grading, sowing, irrigation, weed control, mineral fertilisation, harvesting and storage (Noya et al., 2015). In addition, direct emissions related to diesel combustion in agricultural machinery during cultivation activities were also estimated from the Ecoinvent database -*Diesel, burned in agricultural machinery*- (Nemecek and Käggi, 2007). In some cases, the own agricultural production does not meet the requirements for feeding livestock. A common practice among Galician farms in this case is to gain surplus production from nearby farms. In these cases, and given that the production of neighbours can be considered similar, no differentiation was

made between the maize or grass produced but feed transport to the farm was taken into account.

In some cases, farmers allow their cattle to graze for a few hours a day. In addition, those farms did not report any material consumption related to those pastures. According to the information provided by the farmers, in any case, these grazing lands do not require any care or consumption of materials. For this reason, no environmental burdens were specifically attributed to grazing land, though animal emissions with grazing feed intake are fully accounted for within the annual per-head emission factors applied.

Finally, emissions of methane (CH_4), dinitrogen monoxide (N_2O) were obtained following the guidelines established by the Intergovernmental Panel on Climate Change (IPCC, 2006). CH_4 emissions from enteric fermentation as well from manure storage and subsequent field application were calculated by combining the Tier 1 method and primary data collected through questionnaires. Direct nitrogen emissions during manure management and soil application were also calculated, following the Tier 1 approximation due to lack of reliable data. Indirect nitrogen emissions in form of NH_3 and NO_3^- were also estimated (Denier van der Gon and Bleeker, 2005). In more detail, Section S3 of the Supplementary Material lists the procedures followed in accordance with the IPCC guidelines for the estimation of gaseous emissions.

2.2.4. Life cycle inventory

It is important to highlight the significant volume of data handled in this study, corresponding to 96 farms. The inventories were classified according to farm size and total milk production. Thus, small farms with a production below 400 m^3, medium farms between 400 and 1,000 m^3 and large farms for production above 1,000 m^3. In this study, the impacts of the life cycle of a simulated farm were evaluated in detail (Table 1). This simulated farm corresponds to an average farm of all farms included in the medium size. Medium size farms were chosen for this purpose due to this size is the most numerous within the sample evaluated. However, this life cycle environmental impact analysis was carried out for each of the 96 farms evaluated.

Table 1. Life cycle inventory data per functional unit (the quantity of FPCM produced during the campaign Apr18/Mar19)

Inputs from Environment			
Raw materials	**L**	**Land**	**ha**
Water	3,110,141	Crops	48
Inputs from Technosphere			
Animal feed	**kg**	**Crops**	**ha**
Concentrate dairy cow	249,363	Maize	21
Concentrate dry cow	6,507	Grass	27
Concentrate heifer	32,422		**kg**
Straw	62,279	Seeds	1,541
Cleaning agents	**L**	**Plastics**	**kg**
Detergent	2334	Silage plastic	807
Acid solution	98	Bottles	137
Disinfectant	112	**Fossil fuels**	**L**
	kg	Lubricant oil	60
Kraft paper	122		**kg**
Sealer	237	Diesel	2,678
Chemicals	**L**	**Energy**	**kWh**
Refrigerant	1	Electricity	27,645
Pesticide	68		**kg**
	kg	Butane	26
Mineral fertiliser	18,29	**Transport**	**t·km**
Calcium carbonate	26,763	Lorry	28,829
Outputs to Environment			
Air emissions	**kg**	**Water emissions**	**kg**
CH_4-enteric fermentation	10,000	NO_3^--manure management	408
CH_4-manure management	2,100	NO_3^--soil management	8756
N_2O-manure management	29		
NH_3-manure management	1,006		
N_2O-soil management	576		
NH_3-soil management	2,161		
Outputs to Technosphere			
Products	**kg**	**Waste to treatment**	**kg**
FPCM	654,441	Plastics to recycling	944
Beef	3,514.30	Paper to recycling	124
Co-products	**m^3**	Municipal Solid Waste	201
Manure	2,686		**m^3**
		Wastewater	759

2.2.5. Impact assessment

The selected assessment method for the calculation of the environmental impacts of the system was the ReCiPe Midpoint (H) (Huijbregts et al., 2016). In particular, the impact assessment step followed the guidelines established in the ISO standards (ISO 14040, 14044, 14046). ISO 14046 states that, to calculate the water footprint of the system, an environmental study based on ISO 14040 and ISO 14044 standards must be carried out and, in the impact stage, categories related to water consumption must be analysed. Therefore, the environmental results have been presented in terms of Global Warming and Water Consumption impact categories for the estimation of the CF and WF indicators, respectively. The inventories were carried out using Simapro 9.0 software (PRé Consultants, 2017).

2.3. Description and selection of DEA methodology

Data Envelopment Analysis (DEA) is a methodology based on linear programming models. The most widely used models are the slacks-based measure of efficiency (SBM), as it allows efficiency scores to be calculated independently of the units of measurement used for the set of inputs and outputs (Tone, 2011). Another feature of this model is that it follows a non-radial approach, assuming conditions of convexity and scalability to obtain the efficient production frontier (Lozano and Gutiérrez, 2011). In addition, the SBM model provides targets to reduce inputs and/or maximise outputs based on the difference with the efficient production frontier established by the model, so this model is ideal for analysing data from matrices with low or no correlation between their elements (Lijó et al., 2017). The specific DEA model used in this work was an input-oriented SBM model with constant returns to scale (SBM-I_CRS). The same model as that used by Iribarren et al. (2011) was chosen in order to establish a consistent methodological basis on which to compare the results obtained and establish a time trend. The computational implementation of the DEA matrix in the SBM-I model was performed through the DEA-solver Pro software (Cooper et al., 2007).

2.4. LCA + DEA framework

In this study, the five-step LCA + DEA method (Vázquez-Rowe et al., 2012) was selected to assess the eco-efficiency of 96 dairy farms, allocating each farm as one DMU. Is important to note that DEA and LCA input/output elements are not the same. The limits of the LCA are broader than the considered in the DEA. Thus, the selection of the elements included in the DEA was based on the importance in the environmental profile. The DEA matrix was completed in order of priority, from those with the greatest impact on the environmental profile to the elements with least influence. A reasonable number of inputs and outputs that allow the convergence of the model were taken into account considering the total number of DMUs analysed. The DEA matrix was composed of 7 inputs: i) concentrate (kg), ii) grass silage (kWh), iii) maize silage (kg), iv) electricity (kWh), v) diesel (kg), vi) silage plastic (kg) and vii) water (m^3); and 5 outputs, four of them undesirable and one product: i) CH_4 (kg), ii) N_2O (kg), iii) NH_3 (kg), iv) wastewater (m^3) and v) raw milk (m^3). It is important to note that the direct emissions and the wastewater have been modelled as inputs (Lozano et al., 2009). The complete DEA matrix is shown in Section S4 of the supplementary material.

3. Results and discussion

3.1. Carbon and water footprint of an average medium-size dairy farm

Figure 2 shows the distribution of the different elements that contribute to the carbon and water footprints associated with the operation of a dairy farm. The carbon footprint is 1.33 kg CO_2 per kg of FPCM, while the water footprint is 52.5 L per kg of FPCM. To facilitate analysis, some of the inputs were grouped into global elements:

- **Waste treatment:** This category includes both the treatment of solid waste produced on the farm and the treatment of the wastewater generated. Solid waste includes plastic packaging, paper and cardboard waste and municipal solid waste.
- **Fossil fuels:** It includes the production of diesel, lubricating oil and butane. It is important to note that the diesel quantified in this category is different from that used for crops, which is considered in animal feed category. The diesel considered in this category is used for non-feed related activities, such as mixing operations or additional machinery.
- **On-farm emissions:** This element is composed of direct emissions of CH_4, N_2O, NH_3 and NO_3^- directly derived from enteric fermentation, slurry management and soil

application. This category also included emissions derived from diesel consumption in different operations than feeding. It is important to differentiate the environmental impacts from production and combustion of diesel. Environmental burdens of diesel production are quantified in animal feed or fossil fuels categories, depending on diesel use. While gas emissions from diesel combustion are considered within this category.

- **Others:** It includes the rest of the elements inventoried on the farm that are not included in another category, highlighting the production and use of detergent, acid solution, disinfectant, sealant, plastics, refrigerants, etc.

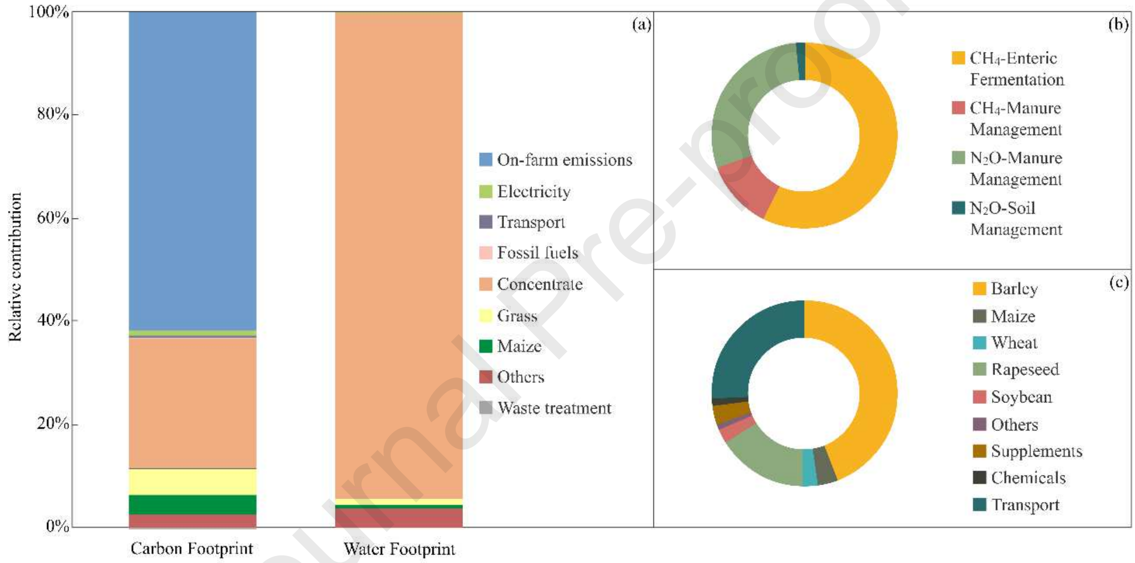


Figure 2. Contribution of the most relevant processes in milk production. (a) Environmental profile and distribution of impacts in terms of carbon and water footprint; (b) Breakdown of carbon footprint of on-farm emissions and (c) breakdown of water footprint of the concentrate.

Most of the contribution of GHG emissions (64.9%) was linked to on-farm emissions, mainly CH_4 and N_2O, from enteric fermentation and manure management (Figure 2.b). In fact, the contribution of enteric fermentation, manure management and feed production stand out in the environmental profile of milk production. This result is in line with other previously published results, which establish these same elements as those with the highest environmental impact in the dairy industry (Famiglietti et al., 2019; Pirlo and Lolli, 2019; Vida and Tedesco, 2017). Other previous studies obtained similar carbon footprint values to those obtained in this study, despite small differences in the system boundaries, the allocation factors and the inventory data used. Thus, Noya et al. (2018) obtained a value of 1.32 kg CO_2 eq per kg of FPCM for a similar sized farm located in Catalonia. Similar values were found in a study conducted in the Netherlands, with values of about 1.4 kg CO_2 per kg of FPCM (Thomassen et al., 2008). However, the CF of this farm was higher than the results of 1.02 kg CO_2 eq per kg of FPCM reported by Aguirre-Villegas et al. (2015) or 1.11 kg CO_2 eq per kg FPCM reported by Vida and Tedesco (2017). These studies, despite the subtle differences in the data inventory used, have in common the use of economic or biologic allocation between milk and meat production.

While other studies using other types of allocation obtained significantly different values, de Léis et al. (2015) reported values of 0.78 kg CO_2 eq per kg of Energy Corrected Milk (ECM) using mass allocation while Castanheira et al. (2010) obtained as result 0.72 kg CO_2 eq per kg of raw milk eq with economic-allocation. These different results from different LCA studies can be compared with caution due to the differences between the specific methodologies and assumptions used, although the general principles may be common (Mc Geough et al., 2012). Most of the studies consulted use as FU the production of a certain amount (usually 1 kg) of FPCM, so is possible to carry out direct comparison with most of the studies.

In terms of water footprint, as observed in Figure 2.c, the impact is practically focused on feed production (90.7%), which is logical since this element encompasses the production of different crops for animal feed (barley, soybean, maize or rapeseed). This relative contribution is in line with a previous study on the calculation of the water footprint in a dairy farm in Catalonia (Noya et al., 2018), in which it was determined that feed production represents 99% of the total water footprint.

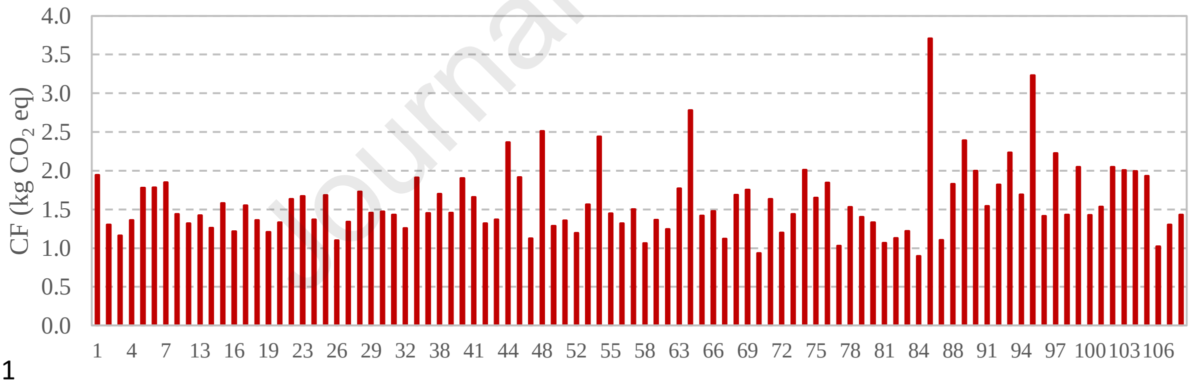
However, comparing the water footprint is an extremely complex task, as there is no standardised method, as there is for the carbon footprint. Although in Noya et al. (2018), the contribution of feed is similar, the water footprint was quantified according to the Water Footprint Network (WFN), which is a completely different methodology to ISO 14046, so the two absolute values cannot be compared. A similar case was reported in Payen et al. (2018), which analysed two farms located in different regions of New Zealand. A system very similar to that of the present study was established, as it included the production of cereals and crops for animal feed, the production of different materials such as fertilisers, pesticides, fuels, etc. However, the abovementioned manuscript reported values of 726 and 537 L per kg FPCM, for the 53 L estimated here. The difference lies mainly in the different methods used, since Payen et al. (2018) use the Available Water Remaining (AWaRe) methodology.

Figure 2 also shows the breakdown of water footprint elements. It can be seen that most of the environmental impact (70%) comes from the cultivation of agricultural products (mainly barley, maize, wheat, rapeseed and soybean). However, it is the barley crop that has the greatest impact on this indicator, mainly because it has a high irrigation rate (0.75 m^3 per kg product) and because it is the majority component of feed within the agricultural products. While the irrigation rate of wheat is similar (0.71 m^3/kg), the proportion in feed is much lower, and the irrigation in maize is practically negligible (only 0.05 m^3/kg). Another remarkable element is the transport of raw materials (mainly those same agricultural products), by transoceanic freight ship. This fact demonstrates the need for a local feed supply that avoids the massive transport of raw materials and products.

3.2. Environmental characterisation of dairy farms

The environmental results obtained for the complete set of farms evaluated are depicted in Figure 3. The results are highly variable, ranging from 0.9 to 3.71 kg CO_2 eq per kg FPCM in the case of carbon footprint and from 18.4 to 96.7 L per kg FPCM in terms of water footprint. The average carbon footprint of the complete sample was 1.6 kg CO_2 eq per kg FPCM, a relatively high value, since the DMUs with the worst environmental results were included within the set. The results obtained for DMUs 85, 95 and 64 are noteworthy, with CF values of 3.71, 3.23 and 2.78 kg CO_2 eq per kg FPCM, respectively. The case of DMU 85 is remarkable since it is a farm with certified organic production that does not use concentrate for animal feed. However, the carbon footprint presents poor results when put in perspective with a low milk production. The average CF result is within the range of 1.1-1.7 kg CO_2 eq per kg of milk quantified in Baldini et al. (2018) and Famiglietti et al. (2019). Once again, the high variability in the determination of the environmental impacts of this productive activity is evident.

Regarding water footprint results, DMUs 104 and 40 stand out with 96.74 and 91.67 L per kg of FPCM, respectively. These results can be linked to concentrate consumption, which is a key factor in the environmental impact of dairy farms in terms of their water footprint. On the opposite, DMUs 70, 85 and 98 can be highlighted for their low water footprint. In fact, these three farms have crop/concentrate feed ratio over 86%, reaching 100% in the DMU 85. Moreover, if a ratio of concentrate/m^3 milk produced is calculated, these DMUs present the lowest values, always below 260 kg of forage per m^3 of raw milk, while the average for the entire sample is 435 kg of forage per m^3 of raw milk. As can be observed in Figure 3, there is no clear relationship between the two indicators used. CF mainly depends on direct emissions, which are related to the livestock and manure produced, while WF depends on 90% of the consumption of feed.



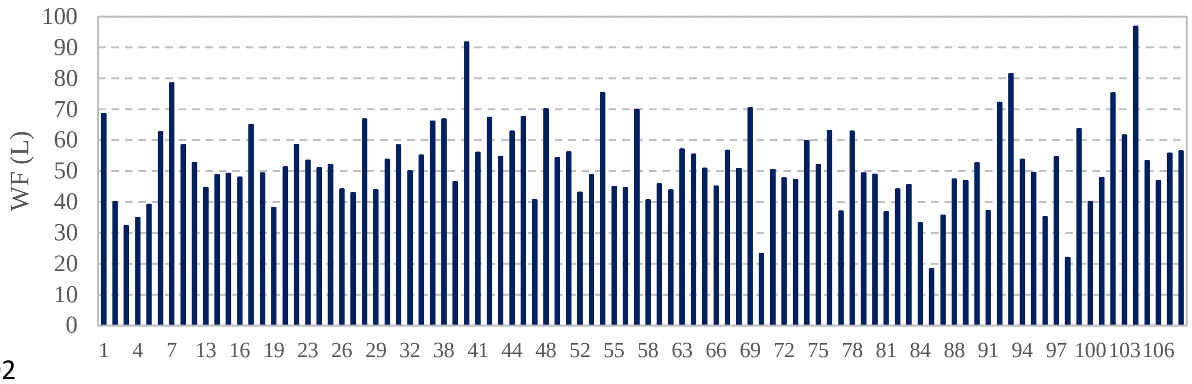


Figure 3. Carbon footprint (top) and water footprint (below) per kg of FPCM produced across the sample dairy farms

3.3. DEA computation and efficiency scores

In order to compute the efficiency scores and the operational benchmarks, the DEA matrix (Table S3 of Supplementary material) was implemented in the optimisation model. Table 2 presents the efficiency scores computed for the dairy farms. Section S4 of Supplementary material presents the target reduction percentages relative to original values for all the inputs considered in the analysis.

Table 2. Efficiency scores (Φ) for the sample of dairy farms

DMU	Φ	DMU	Φ	DMU	Φ	DMU	Φ	DMU	Φ	DMU	Φ
1	0.33	20	0.58	40	0.54	58	1	76	0.33	93	0.29
2	0.68	22	0.70	41	1	59	0.53	77	0.67	94	0.22
3	0.43	23	0.78	42	0.66	62	0.51	78	0.49	95	0.12
4	0.35	24	1	43	1	63	1	79	0.61	96	0.41
5	0.46	25	0.62	44	0.31	64	1	80	0.50	97	0.24
6	0.42	26	0.94	45	0.33	65	0.44	81	1	98	1
7	0.31	27	0.64	46	1	66	0.40	82	0.57	99	0.25
8	0.44	28	0.47	48	0.14	67	1	83	1	100	0.65
12	0.61	29	0.67	50	0.64	68	1	84	1	101	0.57
13	0.51	30	0.65	51	0.35	69	0.27	85	1	102	0.28
14	0.60	31	1	52	1	70	1	86	0.61	103	0.27
15	0.46	32	0.51	53	0.38	71	0.49	88	0.40	104	0.25
16	0.60	34	0.31	54	0.23	72	0.72	89	0.39	105	0.37
17	0.56	35	0.49	55	0.25	73	0.59	90	0.22	106	1
18	1	38	0.39	56	0.45	74	0.24	91	0.43	107	0.58
19	1	39	0.28	57	0.45	75	0.49	92	1	108	0.49

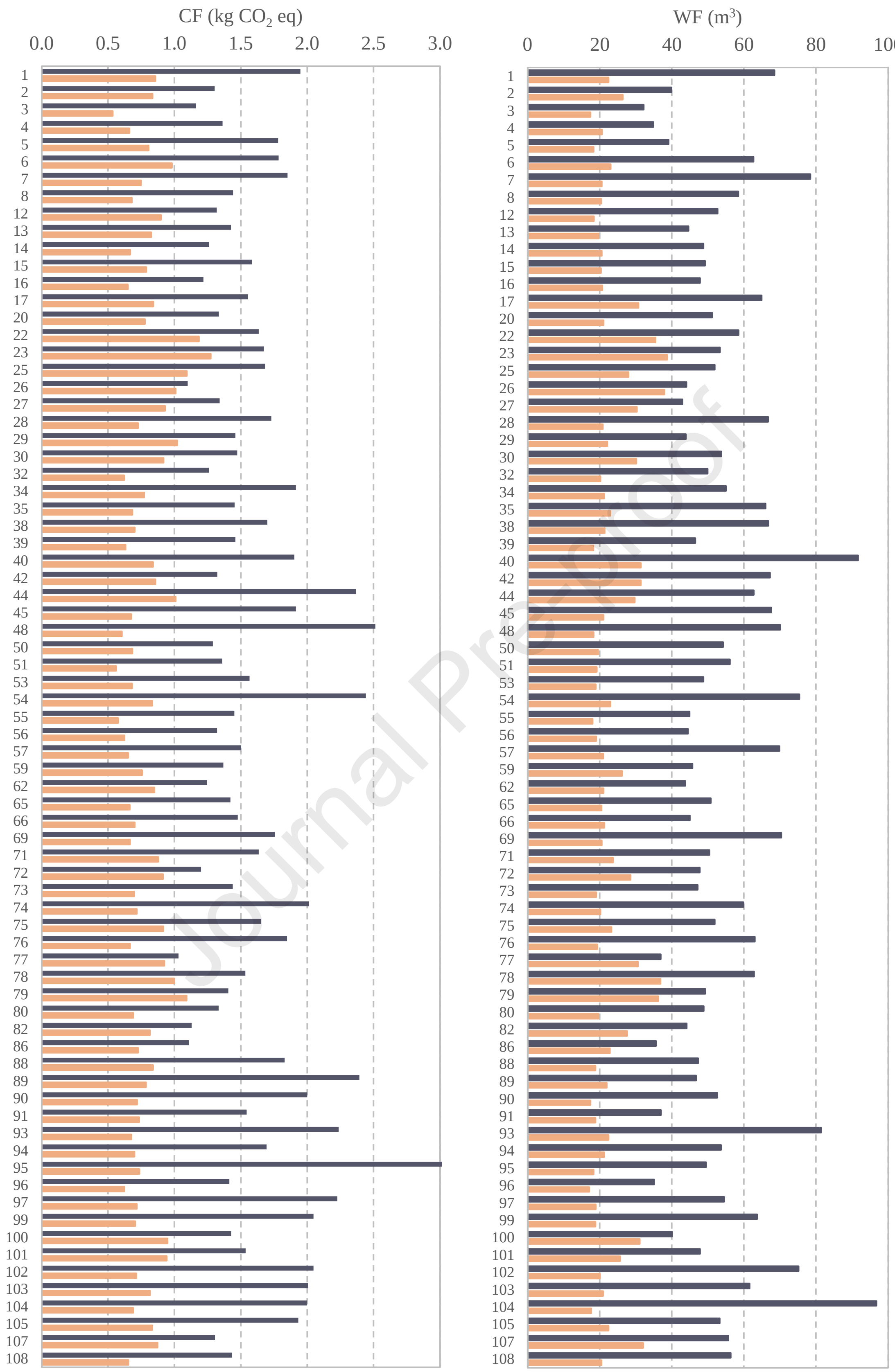
The results show that this methodology is suitable for identifying the link between the operational and environmental performance of multiple similar units. Of all the farms evaluated, just 21 of 96 dairy farms proved to be fully efficient (Φ=1). In fact, the efficiency ratio can be considered acceptable, an average efficiency of 0.58 is achieved in the analysed sample, while only 27 farms present efficiency values below 0.4. For those inefficient farms (Φ<1), important reduction targets are proposed. Thus, average reductions that range from a minimum of 13.6% in maize silage consumption to 53.7% in silage plastic are achieved Section S5 of Supplementary material presents the operational reductions proposed by the model for each one of the inputs considered in the DEA matrix. If these results are considered as the maximum potential for input reduction that can be achieved in milk production, the sample of farms evaluated has a greater margin for improvement than other agricultural and livestock systems previously evaluated (Lozano et al., 2010; Vázquez-Rowe et al., 2012).

3.4. Environmental impact of virtual DMUs

The last stage of the methodology is to analyse the reduction targets set by the SBM-I model, which involves modifying the life cycle inventories of inefficient farms. In this way, a relationship can be established between inefficient operations and environmental impacts by comparing the environmental profile before and after considering the recommendations for reducing impacts (current and virtual dairy farms), depicted in Figure 4.

All environmental profiles of farms with an efficiency value below 1 have improved by applying the DEA recommendations. The average percentage of carbon footprint reduction is around 49% in the set under study. However, it can reach maximum reduction values of 77% in the case of DMU 95. This farm is characterised by a very low efficiency value (0.11), so reductions in material consumption are expected to be significant and, consequently, also a reduction in environmental impacts. This DMU is characterised by a very traditional farm, with a low degree of modernisation, few heads of cattle and, therefore, low milk production. In fact, it is the farm with the lowest productivity, barely reaching 2.8 m^3 of milk production per cow, while the average for the rest of the sample analysed is above 9.3 m^3 per cow. This average production value is within the expected range 8,000-11,000 litres/cow per year according to the last National dairy report carried out by the Ministry of Agriculture and Fisheries, Food and Environment in 2017 (MAPAMA, 2017). In detail, the DMU 95 does not consume concentrate, since the cattle are fed exclusively on the grass of the surrounding land, which means that direct emissions are the greatest "hot spot.

The reduction of environmental impacts is more evident in terms of WF with an average reduction around 55% as this element is 90% dependent on the environmental impacts of feed production. Reductions in this element have a direct positive impact on the environmental performance of the farm. Thus, observing the recommended percentages of reduction in Section S5 of the Supplementary material, the farms with the highest reduction in concentrate are DMUs 104, 48 and 8, with 83.8%, 74.2% and 67.6% respectively, which imply the greatest reduction in their water footprint: 81.7, 73.8 and 73.8% respectively.



452

453 **Figure 4.** Environmental impacts in terms of carbon footprint (left) and water footprint (right)

454 per kg FPCM for real (black) and virtual (orange) farms

3.5. Eco-efficiency evaluation over time

Given that the sample analysed comprises a wide range of livestock farms of different sizes, it is interesting to establish the relationship between farm size and the value of operational efficiency, as reported in Iribarren et al. (2011). Figure 5 shows the efficiency scores against farm size in terms of total raw milk production for 2011 (grey square) and 2019 (orange circle). There is an apparent correlation between farm size and its efficiency score.

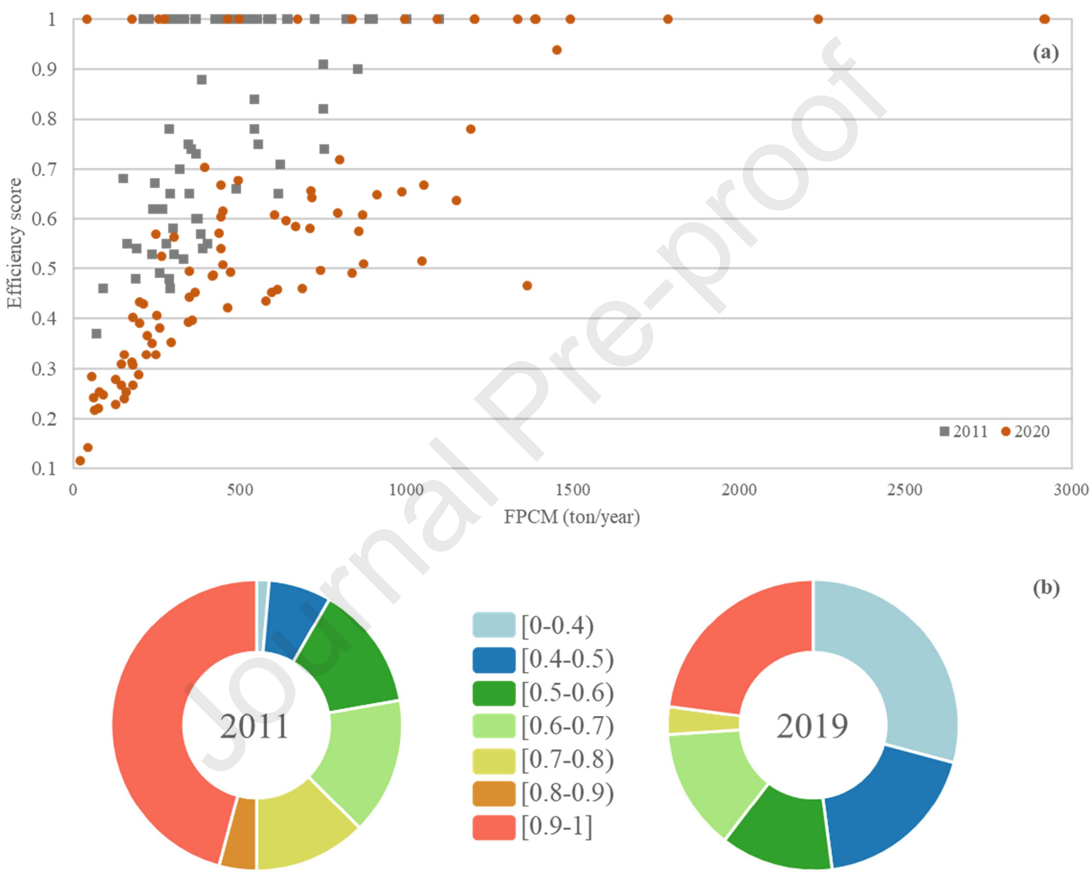


Figure 5. (a): Efficiency scores against raw milk production for 2011 (grey square) and 2019 (orange circle). (b): Relative distribution of dairy farms according to their efficiency score

As shown in Table 2 and Figure 5, almost 22% of dairy farms (21 or 96) were considered efficient (Φ=1). This value is lower than that obtained by Iribarren et al. (2011), where 31 out of 72 farms were considered efficient. This difference can be attributed to the fact that Iribarren et al. (2011) considered fewer elements in the DEA analysis when handling data from a smaller sample. In both studies, two main groups were distinguished in terms of feeding system. On the one hand, import-based feeding refers to feed products that are produced abroad and then imported into the farm (mainly concentrate) and on the other hand, farm-based feeding, where the main feed is composed by maize and grass cultivated in the farm. No relationship was found in any case, only that a high percentage of efficient farms (22 out of 31) used maize and concentrate as the two main feed products in 2011. Anyway, the progression of Galician dairy farms towards a local and sustainable diet, consisting mainly of on-farm feeding and following the principles of the circular economy, is remarkable. Thus, the sample of farms evaluated in this study presents an average percentage of on-farm feeding above 80% and only 6 farms present a percentage below 70%.

In addition, the overall decrease in the average eco-efficiency of inefficient farms in 2019 should be noted. Furthermore, the positive correlation between the farm size and the operational efficiency observed in 2011 is even more evident in this study. This fact has been made possible by an expansion in the total number of farms assessed and their size, pointing out that the Galician dairy sector needs to continue carrying out improvement actions that lead to better operational and environmental performance.

4. Conclusions

The life cycle impact has been evaluated on the basis of the carbon footprint and water footprint of milk production in 96 livestock farms distributed throughout Galicia. Feed production (mainly concentrate and on-farm maize and grass), as well as direct CH_4 and N_2O emissions have been identified as the critical processes of the system. The carbon footprint for an average medium-sized farm has been estimated at 1.33 kg CO_2 per kg of FPCM, a value that is within the range found in similar studies.

However, the range of environmental results found is very wide, which demonstrates the high variability of the operational characteristics of this type of production system. The water footprint according to ISO 14046 is 52.5 L per kg FPCM. The ecoefficiency analysis carried out has shown that of the 96 farms evaluated, 21 are currently fully efficient. This analysis has also made it possible to identify actions that efficient farms should carry out. Thus, reductions in the consumption of silage plastic (-53.7%) and the production of wastewater (-49.9%) stand out as the principal elements to improve the overall efficiency of the analysed farms. It can be stated how the eco-efficiency of milk production has decreased over the last decade, going from an average of 0.64 in 2011 to an average of 0.58 in 2019. This fact marks the path that the Galician dairy sector must follow, seeking to reduce its environmental impacts so that the production of a basic foodstuff such as milk pursue the compliance of international standards, especially in terms of environmental certification.

Acknowledgements

This research was founded by CEPES (118.831059.02). A. Cortés, M.T. Moreira and G. Feijoo belong to the Galician Competitive Research Group GRC (ED431C 2017/29) as well as to CRETUS Strategic Partnership (ED431E 2018/01), co-founded by FEDER (EU).

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- Joint Life Cycle Assessment and Data Envelopment Analysis of 96 Galician dairy farms
- Primary inventory data were managed for all evaluated dairy farms
- Determination of carbon and water footprint per kg of FPCM was carried out
- Efficiency scores suggest a positive correlation with farm size

Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: