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

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8 **Abstract**

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

26 **Keywords**

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

29 **1. Introduction**

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

36 The environmental impacts of the food industry are largely driven by livestock production, which
37 accounts for 3-8% of total energy consumption and emits 14.5% of total anthropogenic GHG
38 emissions worldwide (Eurostat, 2020), associated with emissions of nitrous oxide (N₂O) and
39 methane (CH₄) from enteric fermentation, fertilisation activities and manure storage (Aguirre-
40 Villegas et al., 2015). Despite their relevance, the impacts of this sector on other environmental
41 aspects, such as eutrophication, acidification and water scarcity, should not be ignored (González-
42 García et al., 2013).

43 Today, milk is one of the most widely produced foods in the world (Üçtuğ, 2019), with dairy
44 products being a fundamental pillar of the human diet (Wang et al., 2018). In the context of the
45 European Union, Spain is the seventh largest producer of cow milk, with 5% of the total (Eurostat,
46 2019). In Spain, the dairy sector is the second most important of all the livestock sectors. The
47 latest data published by the Spanish Agrarian Guarantee Fund (FEGA, 2019) show that the
48 Spanish dairy industry processes more than 7 million m³ of milk. Galicia, a region in northwest
49 Spain, produces 38% of the national milk production (MAPA, 2019), making it the ninth largest
50 dairy region in Europe, with a remarkable turnover of 800 million euros and more than 25,000
51 people employed. Given this context, it is desirable to propose strategies for environmental
52 improvement in livestock and milk production.

53 Among the different methods to evaluate the environmental performance of milk production, Life
54 Cycle Assessment (LCA) has been applied in recent years for a wide range of production systems
55 in different countries (Baldini et al., 2020; Berton et al., 2020; Djekic et al., 2019; Egas et al.,
56 2020; Escribano et al., 2020; Famiglietti et al., 2019; Knudsen et al., 2019; Woldegebriel et al.,
57 2017). Noya et al. (2018) evaluated the environmental burdens of milk production in facilities of
58 Northeast Spain. Although a wide range of environmental indicators were calculated, the study
59 focused mainly on the water footprint according to the Water Footprint Network (WFN). The
60 capital importance of feed production in the water footprint was demonstrated due to
61 characterisation factors of agricultural products. Baldini et al. (2018) compared the environmental
62 profile of three Italian dairy farms within two different scenarios. On one side, the direct gaseous
63 emissions were estimated according with the Intergovernmental Panel on Climate Change (IPCC)
64 and European Environmental Agency (EAA) guidelines. On the other hand, emissions measured
65 in other papers were taken as input data to quantify the emissions associated to manure
66 management. The results showed the importance of the emission factors since IPCC equations
67 underestimated manure management emissions while overestimated ammonia related emissions.
68 Pirlo and Lolli (2019) carried out a different comparison, eight conventional and six organic dairy
69 arms from Italy. This study concluded that conventional production is slightly higher than organic
70 (9,004 vs. 7,736 kg/cow per year, respectively). However, the differences in environmental
71 impacts in terms of GWP, ACP and EUP categories were not significant. Other authors focus
72 their research on establishing the environmental performance of milk production based on a single
73 indicator. Thus, numerous papers on carbon footprint (Finnegan et al., 2017; Horrillo et al., 2020;
74 Laca et al., 2020; Morais et al., 2018; Vida and Tedesco, 2017) or water footprint (Lu et al., 2018;
75 Mekonnen et al., 2019; Payen et al., 2018; Usva et al., 2019) were published in recent years.

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

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

98 The first joint use of these two methodologies dates from a scientific publication in which a 3-
99 step procedure was established to determine a relationship between operational efficiency and the
100 environmental impacts of a sample of 62 mussel cultivation racks (Lozano et al., 2009). Over
101 time, other researchers have expanded and improved this methodology to a 5-step method that
102 allows for the environmental assessment of current and virtual DMUs. This 5-steps method has
103 been widely applied in different production systems: WWTPs (Lorenzo-Toja et al., 2015), organic
104 blueberry orchards (Rebolledo-Leiva et al., 2017), grape production (Mohseni et al., 2018),
105 grocery stores (Álvarez-Rodríguez et al., 2019) or farm-scaled biogas plants (Lijó et al., 2017).

106 This methodology was applied to Galician dairy industry in 2011 to evaluate the eco-efficiency
107 of a set of 72 farms (Iribarren et al., 2011). This study demonstrated that farm size had no
108 influence on the efficiency score. However, there was a tendency for small inefficient farms to
109 perform worse than medium and large farms.

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

117 **2. Materials and methods**

118 *2.1. Definition of the case study*

119 Galicia is the leading Spanish autonomous regions in milk production at national level since 2001,
120 with 38% of the total Spanish production. In fact 39% of the Spanish dairy farms are located in
121 the Galician region (MAPA, 2019). The dairy industry is the most important food industry sector
122 in Galicia, followed in terms of turnover by the canning industry (Torres López et al., 2017).
123 Galician dairy farms are characterised, like all agricultural and livestock farms, by a great
124 variability in the consumption of materials and production models (Aguirre-Villegas et al., 2017).
125 Thus, it is necessary to include as many farms as possible in the analysis so that the sample is
126 characteristic of the Galician dairy sector. Taking this premise as a key element in the analysis,
127 96 farms distributed throughout Galicia were considered. All the farms studied have an
128 agricultural area around the farm within a 5 km radius to grow mainly corn and grass, which is
129 subsequently stored in silos and used as cattle feed. This agricultural land is managed by the
130 farmers themselves and was included within the system boundaries. In this way, the processes of
131 grass and maize cultivation were modelled considering the use of machinery, the time of use per
132 hectare, the consumption of diesel and other materials, such as fertilizers or agrochemicals. In

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

137 The size of the different farms is variable; the smallest farm is composed of 13 animals with
138 annual production around 20,000 kg of milk, while the largest farm has 520 animals and produces
139 3,000,000 kg of milk per year. Although milk is the main objective of the farms, meat production
140 should not be neglected. Thus, the production obtained from old cows slaughtered for meat has
141 been considered a co-product of the farms.

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

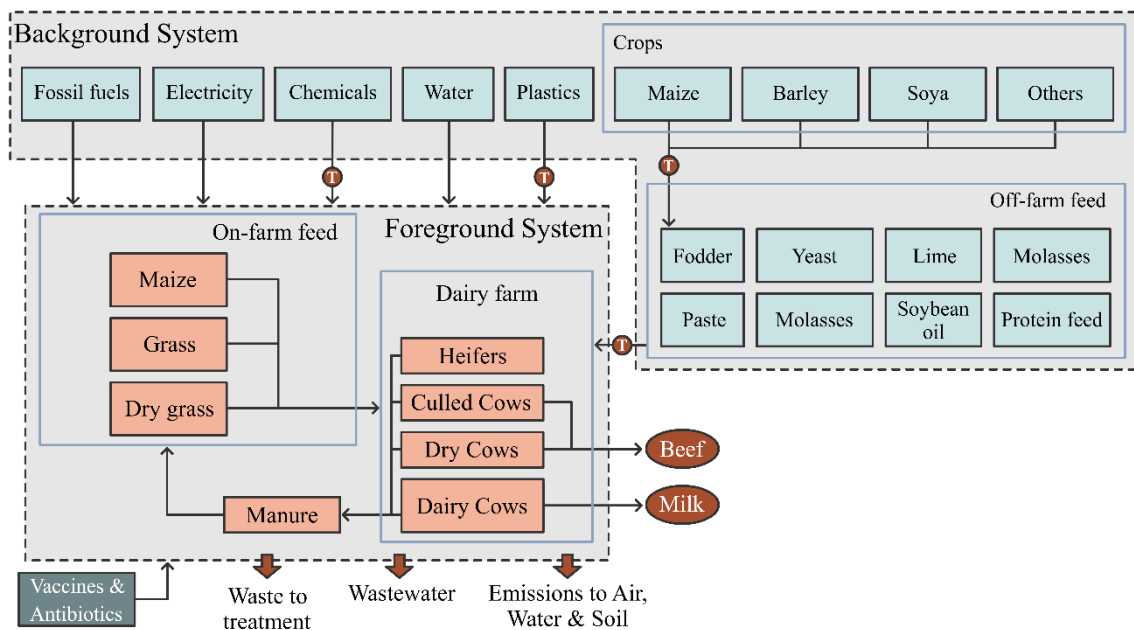
150 *2.2. LCA methodology*

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

156 *2.2.1. Goal and scope definition*

157 The main objective of the study is to determine the evolution of eco-efficiency in milk production
158 in Galicia by comparing the outcomes of the analysis with those reported in 2011. To this end,

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



170

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

173 *2.2.2. Functional Unit (FU) and allocation approach*

174 In the present study, following the guidelines of IDF (2015) when a study is conducted on-farm,
 175 the quantity of Fat- and Protein- Corrected Milk (FPCM) produced in one year, corresponding to

176 the campaign Apr18/Mar19, has been taken as the functional unit (FU). To convert the raw milk
177 weight to FPCM, Eq. (1) was followed:

$$178 \text{ FPCM (kg/yr)} = P \text{ (kg/yr)} * [0.1226*FC\% + 0.0776*PC\% + 0.2534] \quad (1)$$

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

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

$$186 AF_{MILK} = 1 - 6.04 * BMR \quad (2)$$

$$187 AF_{MEAT} = 1 - AF_{MILK} \quad (3)$$

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

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

192 2.2.3. Data collection

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

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

209 - Concentrate, which is formulated with the same composition as considered in Iribarren
210 et al. (2011). Thus, a content of 30% maize, 26% soybean, 17% rape meal, 12% barley
211 and 2% wheat were considered, as well as a certain amount of chemicals and additives.

212 The production of the background processes was taken from the Ecoinvent database.

213 - Another source of livestock feed is grass and maize grown by farm owners on the
214 surrounding farmland. These productions were modelled individually considering the
215 primary information provided by the farmers. The fuel consumption for the machinery
216 used on the crops was calculated based on the working capacity of the machinery at each
217 stage (h/ha) and the corresponding fuel consumption (l/h). The activities considered in
218 each of the crops have been the typical stages of any cereal crop: organic fertilisation,
219 land clearing, grading, sowing, irrigation, weed control, mineral fertilisation, harvesting
220 and storage (Noya et al., 2015). In addition, direct emissions related to diesel combustion
221 in agricultural machinery during cultivation activities were also estimated from the
222 Ecoinvent database -*Diesel, burned in agricultural machinery*- (Nemecek and Käggi,
223 2007). In some cases, the own agricultural production does not meet the requirements for
224 feeding livestock. A common practice among Galician farms in this case is to gain surplus
225 production from nearby farms. In these cases, and given that the production of neighbours
226 can be considered similar, no differentiation was made between the maize or grass
227 produced but feed transport to the farm was taken into account.

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

234 Finally, emissions of methane (CH₄), dinitrogen monoxide (N₂O) were obtained following the
235 guidelines established by the Intergovernmental Panel on Climate Change (IPCC, 2006). CH₄
236 emissions from enteric fermentation as well from manure storage and subsequent field application
237 were calculated by combining the Tier 1 method and primary data collected through
238 questionnaires. Direct nitrogen emissions during manure management and soil application were
239 also calculated, following the Tier 1 approximation due to lack of reliable data. Indirect nitrogen
240 emissions in form of NH₃ and NO₃⁻ were also estimated (Denier van der Gon and Bleeker, 2005).
241 In more detail, Section S3 of the Supplementary Material lists the procedures followed in
242 accordance with the IPCC guidelines for the estimation of gaseous emissions.

243 *2.2.4. Life cycle inventory*

244 It is important to highlight the significant volume of data handled in this study, corresponding to
245 96 farms. The inventories were classified according to farm size and total milk production. Thus,
246 small farms with a production below 400 m³, medium farms between 400 and 1,000 m³ and large
247 farms for production above 1,000 m³. In this study, the impacts of the life cycle of a simulated
248 farm were evaluated in detail (Table 1). This simulated farm corresponds to an average farm of
249 all farms included in the medium size. Medium size farms were chosen for this purpose due to
250 this size is the most numerous within the sample evaluated. However, this life cycle
251 environmental impact analysis was carried out for each of the 96 farms evaluated.

252

253 **Table 1.** Life cycle inventory data per functional unit (the quantity of FPCM produced during the
 254 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 ₂ O-manure management	29		
NH ₃ -manure management	1,006		
N ₂ O-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	m³	Municipal Solid Waste	201
Manure	2,686		m³
		Wastewater	759

255

256 2.2.5. Impact assessment

257 The selected assessment method for the calculation of the environmental impacts of the system
258 was the ReCiPe Midpoint (H) (Huijbregts et al., 2016). In particular, the impact assessment step
259 followed the guidelines established in the ISO standards (ISO 14040, 14044, 14046). ISO 14046
260 states that, to calculate the water footprint of the system, an environmental study based on ISO
261 14040 and ISO 14044 standards must be carried out and, in the impact stage, categories related
262 to water consumption must be analysed. Therefore, the environmental results have been presented
263 in terms of Global Warming and Water Consumption impact categories for the estimation of the
264 CF and WF indicators, respectively. The inventories were carried out using Simapro 9.0 software
265 (PRé Consultants, 2017).

266 *2.3. Description and selection of DEA methodology*

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

281 *2.4. LCA + DEA framework*

282 In this study, the five-step LCA + DEA method (Vázquez-Rowe et al., 2012) was selected to
283 assess the eco-efficiency of 96 dairy farms, allocating each farm as one DMU. Is important to

284 note that DEA and LCA input/output elements are not the same. The limits of the LCA are broader
285 than the considered in the DEA. Thus, the selection of the elements included in the DEA was
286 based on the importance in the environmental profile. The DEA matrix was completed in order
287 of priority, from those with the greatest impact on the environmental profile to the elements with
288 least influence. A reasonable number of inputs and outputs that allow the convergence of the
289 model were taken into account considering the total number of DMUs analysed. The DEA matrix
290 was composed of 7 inputs: i) concentrate (kg), ii) grass silage (kWh), iii) maize silage (kg), iv)
291 electricity (kWh), v) diesel (kg), vi) silage plastic (kg) and vii) water (m³); and 5 outputs, four of
292 them undesirable and one product: i) CH₄ (kg), ii) N₂O (kg), iii) NH₃ (kg), iv) wastewater (m³)
293 and v) raw milk (m³). It is important to note that the direct emissions and the wastewater have
294 been modelled as inputs (Lozano et al., 2009). The complete DEA matrix is shown in Section S4
295 of the supplementary material.

296 **3. Results and discussion**

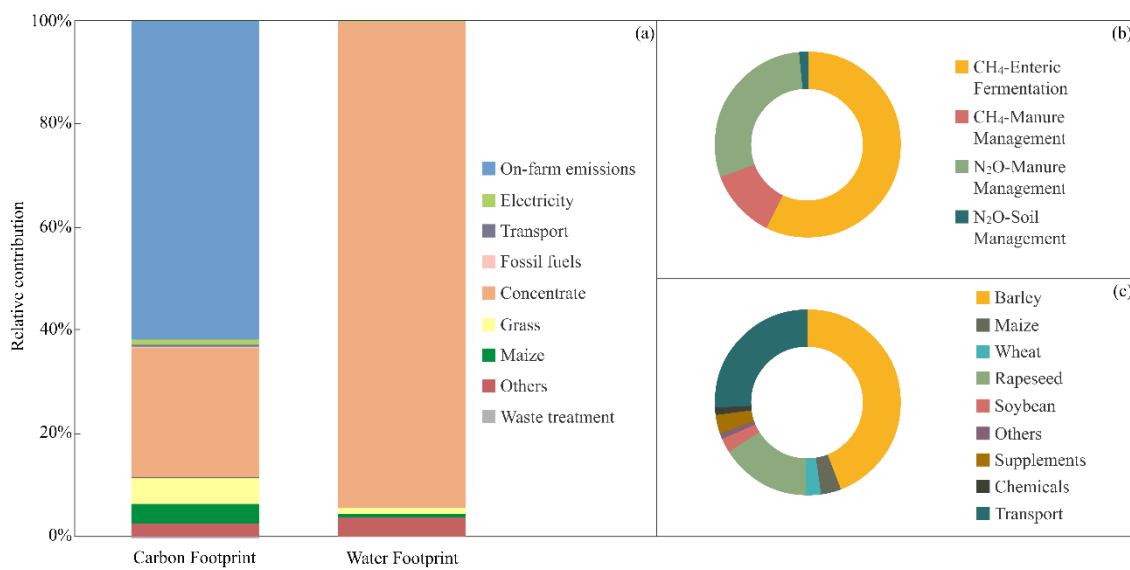
297 *3.1. Carbon and water footprint of an average medium-size dairy farm*

298 Figure 2 shows the distribution of the different elements that contribute to the carbon and water
299 footprints associated with the operation of a dairy farm. The carbon footprint is 1.33 kg CO₂ per
300 kg of FPCM, while the water footprint is 52.5 L per kg of FPCM. To facilitate analysis, some of
301 the inputs were grouped into global elements:

- 302 - **Waste treatment:** This category includes both the treatment of solid waste produced on
303 the farm and the treatment of the wastewater generated. Solid waste includes plastic
304 packaging, paper and cardboard waste and municipal solid waste.
- 305 - **Fossil fuels:** It includes the production of diesel, lubricating oil and butane. It is important
306 to note that the diesel quantified in this category is different from that used for crops, which
307 is considered in animal feed category. The diesel considered in this category is used for non-
308 feed related activities, such as mixing operations or additional machinery.
- 309 - **On-farm emissions:** This element is composed of direct emissions of CH₄, N₂O, NH₃
310 and NO₃⁻ directly derived from enteric fermentation, slurry management and soil application.

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

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



319 **Figure 2.** Contribution of the most relevant processes in milk production. (a) Environmental
 320 profile and distribution of impacts in terms of carbon and water footprint; (b) Breakdown of
 321 carbon footprint of on-farm emissions and (c) breakdown of water footprint of the concentrate.
 322

323 Most of the contribution of GHG emissions (64.9%) was linked to on-farm emissions, mainly
 324 CH₄ and N₂O, from enteric fermentation and manure management (Figure 2.b). In fact, the
 325 contribution of enteric fermentation, manure management and feed production stand out in the
 326 environmental profile of milk production. This result is in line with other previously published
 327 results, which establish these same elements as those with the highest environmental impact in
 328 the dairy industry (Famiglietti et al., 2019; Pirlo and Lolli, 2019; Vida and Tedesco, 2017). Other
 329 previous studies obtained similar carbon footprint values to those obtained in this study, despite

330 small differences in the system boundaries, the allocation factors and the inventory data used.
331 Thus, Noya et al. (2018) obtained a value of 1.32 kg CO₂ eq per kg of FPCM for a similar sized
332 farm located in Catalonia. Similar values were found in a study conducted in the Netherlands,
333 with values of about 1.4 kg CO₂ per kg of FPCM (Thomassen et al., 2008). However, the CF of
334 this farm was higher than the results of 1.02 kg CO₂ eq per kg of FPCM reported by Aguirre-
335 Villegas et al. (2015) or 1.11 kg CO₂ eq per kg FPCM reported by Vida and Tedesco (2017).
336 These studies, despite the subtle differences in the data inventory used, have in common the use
337 of economic or biologic allocation between milk and meat production.

338 While other studies using other types of allocation obtained significantly different values, de Léris
339 et al. (2015) reported values of 0.78 kg CO₂ eq per kg of Energy Corrected Milk (ECM) using
340 mass allocation while Castanheira et al. (2010) obtained as result 0.72 kg CO₂ eq per kg of raw
341 milk eq with economic-allocation. These different results from different LCA studies can be
342 compared with caution due to the differences between the specific methodologies and
343 assumptions used, although the general principles may be common (Mc Geough et al., 2012).
344 Most of the studies consulted use as FU the production of a certain amount (usually 1 kg) of
345 FPCM, so is possible to carry out direct comparison with most of the studies.

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

352 However, comparing the water footprint is an extremely complex task, as there is no standardised
353 method, as there is for the carbon footprint. Although in Noya et al. (2018), the contribution of
354 feed is similar, the water footprint was quantified according to the Water Footprint Network
355 (WFN), which is a completely different methodology to ISO 14046, so the two absolute values
356 cannot be compared. A similar case was reported in Payen et al. (2018), which analysed two farms

357 located in different regions of New Zealand. A system very similar to that of the present study
358 was established, as it included the production of cereals and crops for animal feed, the production
359 of different materials such as fertilisers, pesticides, fuels, etc. However, the abovementioned
360 manuscript reported values of 726 and 537 L per kg FPCM, for the 53 L estimated here. The
361 difference lies mainly in the different methods used, since Payen et al. (2018) use the Available
362 Water Remaining (AWaRe) methodology.

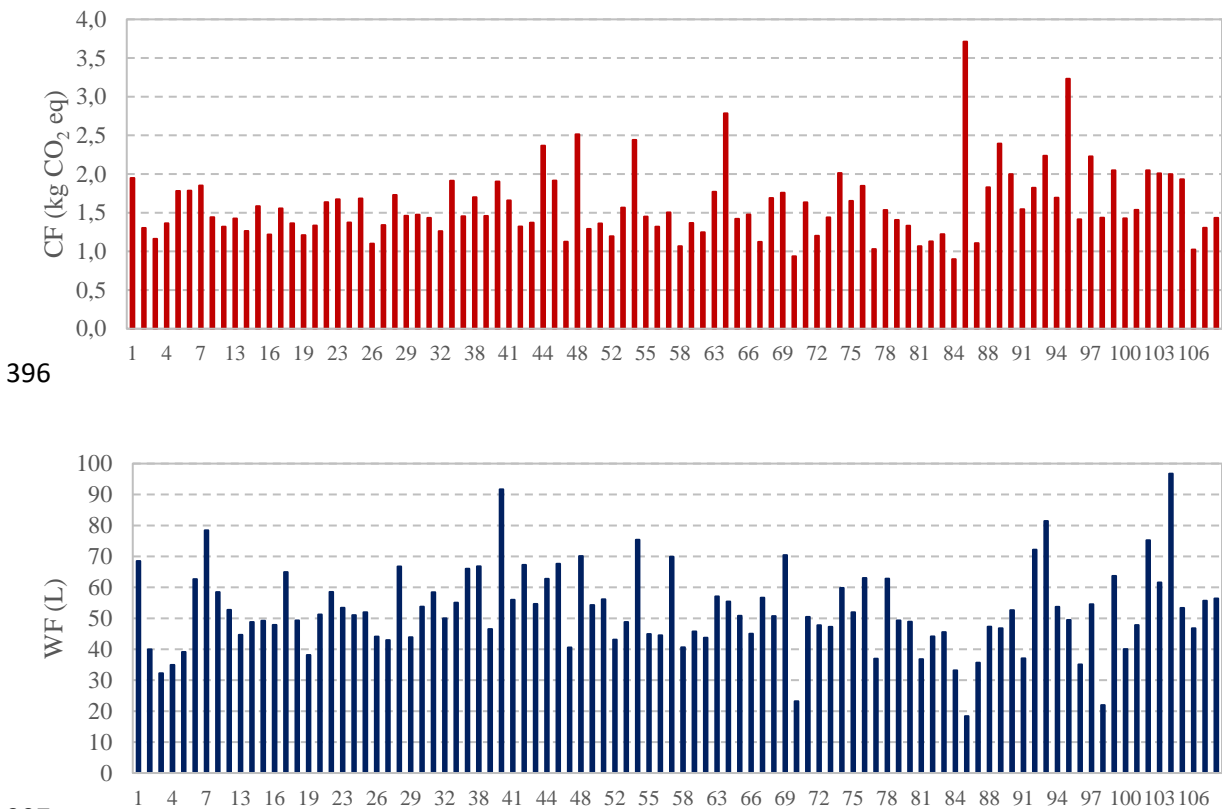
363 Figure 2 also shows the breakdown of water footprint elements. It can be seen that most of the
364 environmental impact (70%) comes from the cultivation of agricultural products (mainly barley,
365 maize, wheat, rapeseed and soybean). However, it is the barley crop that has the greatest impact
366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

373 *3.2. Environmental characterisation of dairy farms*

374 The environmental results obtained for the complete set of farms evaluated are depicted in Figure
375 3. The results are highly variable, ranging from 0.9 to 3.71 kg CO₂ eq per kg FPCM in the case
376 of carbon footprint and from 18.4 to 96.7 L per kg FPCM in terms of water footprint. The average
377 carbon footprint of the complete sample was 1.6 kg CO₂ eq per kg FPCM, a relatively high value,
378 since the DMUs with the worst environmental results were included within the set. The results
379 obtained for DMUs 85, 95 and 64 are noteworthy, with CF values of 3.71, 3.23 and 2.78 kg CO₂
380 eq per kg FPCM, respectively. The case of DMU 85 is remarkable since it is a farm with certified
381 organic production that does not use concentrate for animal feed. However, the carbon footprint
382 presents poor results when put in perspective with a low milk production. The average CF result
383 is within the range of 1.1-1.7 kg CO₂ eq per kg of milk quantified in Baldini et al. (2018) and

384 Famiglietti et al. (2019). Once again, the high variability in the determination of the environmental
385 impacts of this productive activity is evident.

386 Regarding water footprint results, DMUs 104 and 40 stand out with 96.74 and 91.67 L per kg of
387 FPCM, respectively. These results can be linked to concentrate consumption, which is a key factor
388 in the environmental impact of dairy farms in terms of their water footprint. On the opposite,
389 DMUs 70, 85 and 98 can be highlighted for their low water footprint. In fact, these three farms
390 have crop/concentrate feed ratio over 86%, reaching 100% in the DMU 85. Moreover, if a ratio
391 of concentrate/m³ milk produced is calculated, these DMUs present the lowest values, always
392 below 260 kg of forage per m³ of raw milk, while the average for the entire sample is 435 kg of
393 forage per m³ of raw milk. As can be observed in Figure 3, there is no clear relationship between
394 the two indicators used. CF mainly depends on direct emissions, which are related to the livestock
395 and manure produced, while WF depends on 90% of the consumption of feed.



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

400 3.3. DEA computation and efficiency scores

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

406 **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

407

408 The results show that this methodology is suitable for identifying the link between the operational
 409 and environmental performance of multiple similar units. Of all the farms evaluated, just 21 of 96
 410 dairy farms proved to be fully efficient ($\Phi=1$). In fact, the efficiency ratio can be considered
 411 acceptable, an average efficiency of 0.58 is achieved in the analysed sample, while only 27 farms
 412 present efficiency values below 0.4. For those inefficient farms ($\Phi<1$), important reduction targets
 413 are proposed. Thus, average reductions that range from a minimum of 13.6% in maize silage
 414 consumption to 53.7% in silage plastic are achieved Section S5 of Supplementary material

415 presents the operational reductions proposed by the model for each one of the inputs considered
416 in the DEA matrix. If these results are considered as the maximum potential for input reduction
417 that can be achieved in milk production, the sample of farms evaluated has a greater margin for
418 improvement than other agricultural and livestock systems previously evaluated (Lozano et al.,
419 2010; Vázquez-Rowe et al., 2012).

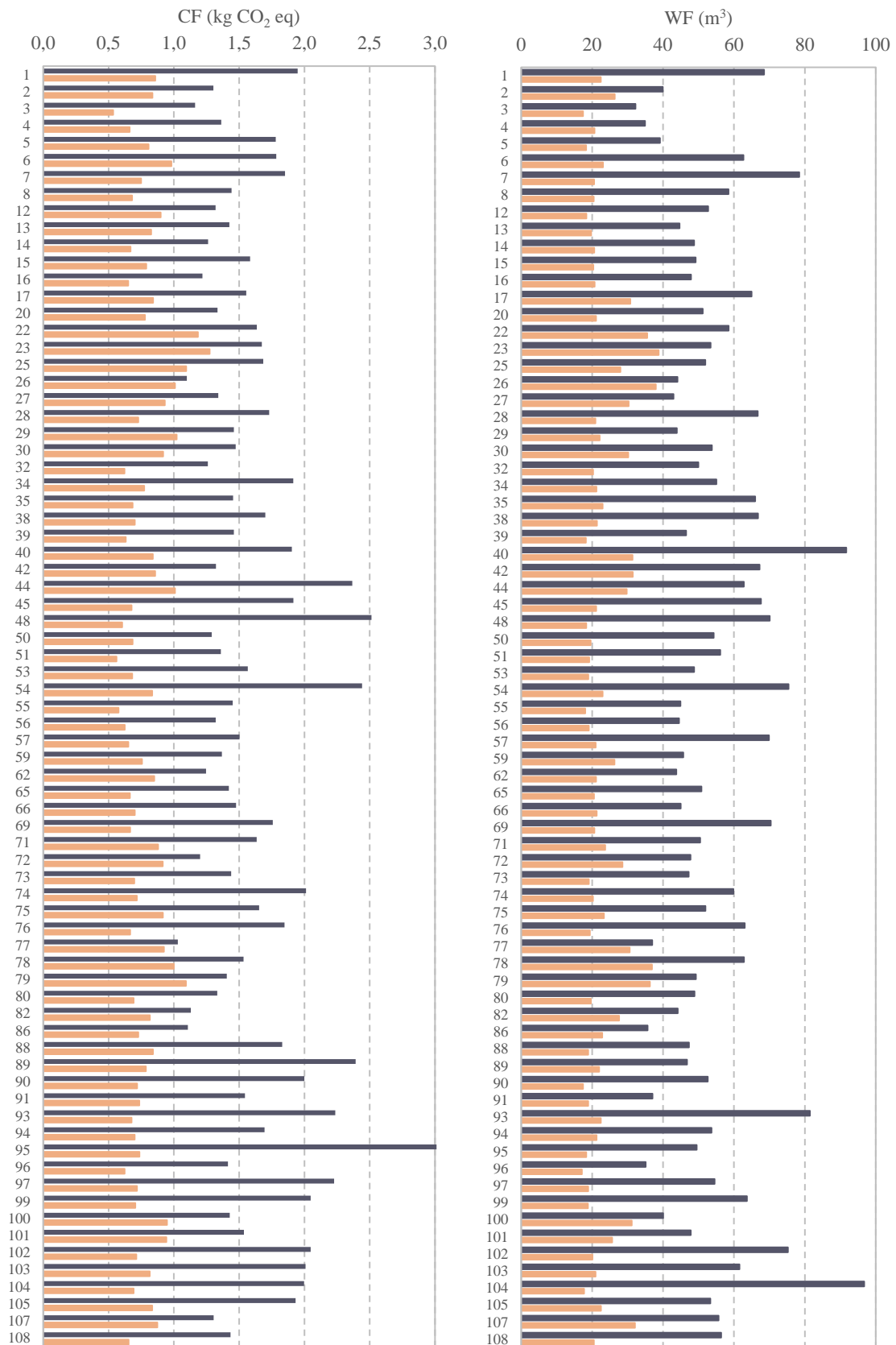
420 *3.4. Environmental impact of virtual DMUs*

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

426 All environmental profiles of farms with an efficiency value below 1 have improved by applying
427 the DEA recommendations. The average percentage of carbon footprint reduction is around 49%
428 in the set under study. However, it can reach maximum reduction values of 77% in the case of
429 DMU 95. This farm is characterised by a very low efficiency value (0.11), so reductions in
430 material consumption are expected to be significant and, consequently, also a reduction in
431 environmental impacts. This DMU is characterised by a very traditional farm, with a low degree
432 of modernisation, few heads of cattle and, therefore, low milk production. In fact, it is the farm
433 with the lowest productivity, barely reaching 2.8 m³ of milk production per cow, while the average
434 for the rest of the sample analysed is above 9.3 m³ per cow. This average production value is
435 within the expected range 8,000-11,000 litres/cow per year according to the last National dairy
436 report carried out by the Ministry of Agriculture and Fisheries, Food and Environment in 2017
437 (MAPAMA, 2017). In detail, the DMU 95 does not consume concentrate, since the cattle are fed
438 exclusively on the grass of the surrounding land, which means that direct emissions are the
439 greatest "hot spot".

440 The reduction of environmental impacts is more evident in terms of WF with an average reduction
441 around 55% as this element is 90% dependent on the environmental impacts of feed production.

442 Reductions in this element have a direct positive impact on the environmental performance of the
443 farm. Thus, observing the recommended percentages of reduction in Section S5 of the
444 Supplementary material, the farms with the highest reduction in concentrate are DMUs 104, 48
445 and 8, with 83.8%, 74.2% and 67.6% respectively, which imply the greatest reduction in their
446 water footprint: 81.7, 73.8 and 73.8% respectively.

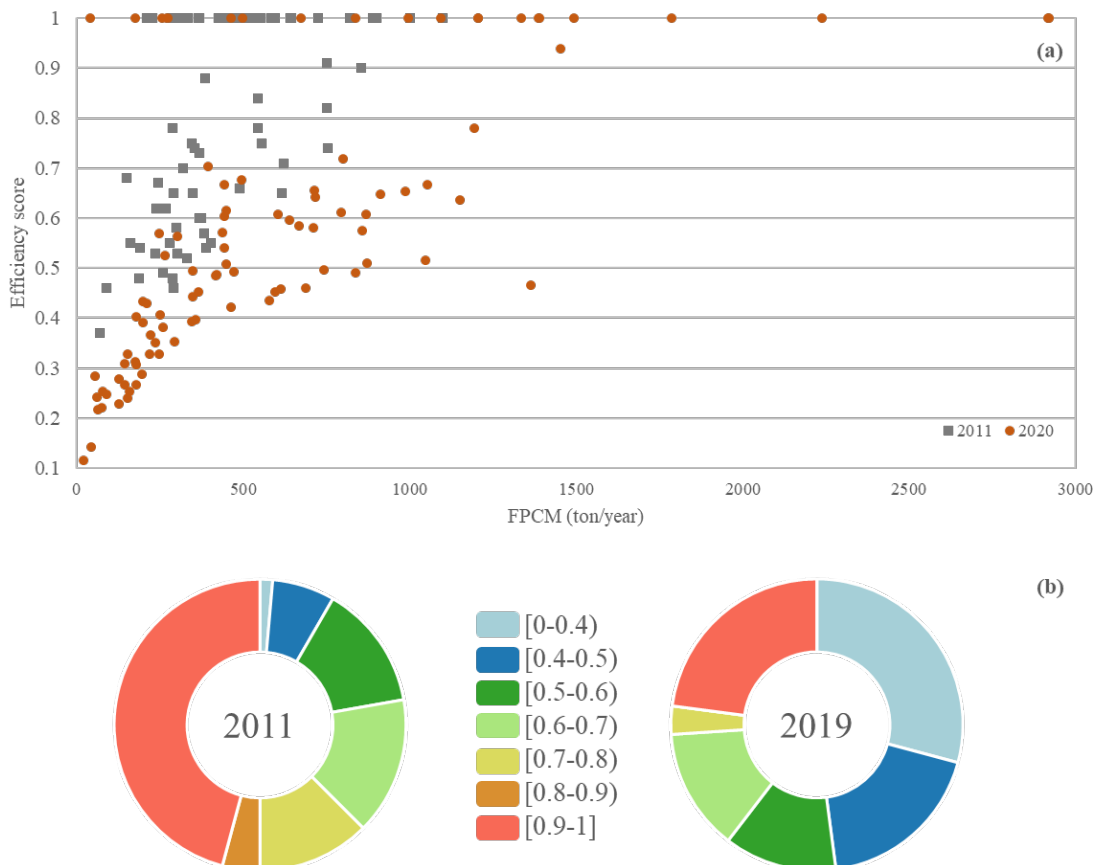


447

448 **Figure 4.** Environmental impacts in terms of carbon footprint (left) and water footprint (right) per
 449 kg FPCM for real (black) and virtual (orange) farms

450 3.5. Eco-efficiency evaluation over time

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



456

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

459 As shown in Table 2 and Figure 5, almost 22% of dairy farms (21 or 96) were considered efficient
 460 ($\Phi=1$). This value is lower than that obtained by Iribarren et al. (2011), where 31 out of 72 farms
 461 were considered efficient. This difference can be attributed to the fact that Iribarren et al. (2011)
 462 considered fewer elements in the DEA analysis when handling data from a smaller sample. In
 463 both studies, two main groups were distinguished in terms of feeding system. On the one hand,

464 import-based feeding refers to feed products that are produced abroad and then imported into the
465 farm (mainly concentrate) and on the other hand, farm-based feeding, where the main feed is
466 composed by maize and grass cultivated in the farm. No relationship was found in any case, only
467 that a high percentage of efficient farms (22 out of 31) used maize and concentrate as the two
468 main feed products in 2011. Anyway, the progression of Galician dairy farms towards a local and
469 sustainable diet, consisting mainly of on-farm feeding and following the principles of the circular
470 economy, is remarkable. Thus, the sample of farms evaluated in this study presents an average
471 percentage of on-farm feeding above 80% and only 6 farms present a percentage below 70%.

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

478 **4. Conclusions**

479 The life cycle impact has been evaluated on the basis of the carbon footprint and water footprint
480 of milk production in 96 livestock farms distributed throughout Galicia. Feed production (mainly
481 concentrate and on-farm maize and grass), as well as direct CH₄ and N₂O emissions have been
482 identified as the critical processes of the system. The carbon footprint for an average medium-
483 sized farm has been estimated at 1.33 kg CO₂ per kg of FPCM, a value that is within the range
484 found in similar studies.

485 However, the range of environmental results found is very wide, which demonstrates the high
486 variability of the operational characteristics of this type of production system. The water footprint
487 according to ISO 14046 is 52.5 L per kg FPCM. The ecoefficiency analysis carried out has shown
488 that of the 96 farms evaluated, 21 are currently fully efficient. This analysis has also made it
489 possible to identify actions that efficient farms should carry out. Thus, reductions in the
490 consumption of silage plastic (-53.7%) and the production of wastewater (-49.9%) stand out as

491 the principal elements to improve the overall efficiency of the analysed farms. It can be stated
492 how the eco-efficiency of milk production has decreased over the last decade, going from an
493 average of 0.64 in 2011 to an average of 0.58 in 2019. This fact marks the path that the Galician
494 dairy sector must follow, seeking to reduce its environmental impacts so that the production of a
495 basic foodstuff such as milk pursue the compliance of international standards, especially in terms
496 of environmental certification.

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501

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