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Environmental sustainability assessment of poultry productions through life cycle approaches: A critical review

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Environmental sustainability assessment of poultry productions through life cycle approaches: a critical review

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Abstract

Background

Poultry production is an important human food pillar and is experiencing continuous growth worldwide. The Life Cycle Assessment (LCA) approach has been increasingly used for providing information on poultry production chains, in particular from the environmental point of view, which has also been coupled with economic or social considerations in some cases.

Scope and approach

This study aimed to undertake a critical review to the state of the art of LCA application to the poultry sector. Attention has been drawn to the different methodological approaches adopted in the literature regarding functional units, system boundaries, inventory data collection and multifunctionality management. In addition to reviewing how this sector was methodologically approached by means of the LCA, this study aimed to summarize the main findings and highlight current shortcomings of the literature.

Key findings and conclusions

Chicken chains were by far the most analyzed. A multiplicity of approaches was implemented to date for the evaluation of these products in a life cycle perspective but the most adopted ones were the mass based functional unit, the cradle-to-farm gate perspective and the economic allocation. As for other animal products, the agricultural phase weighs heavily on the impact of the finished food product, in particular due to feed consumption and manure management. The discussion focuses on the parameters most influencing environmental performance, as well as on possible mitigations, some already widely known while others still partially unexpressed. Finally, some research topics are identified that could increase the understanding and consequently the sustainability of this important supply chain in the future.

Keywords: Life cycle assessment, impact assessment, poultry, chicken meat, eggs

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1. Introduction

Poultry productions have experienced impressive growth in recent decades. In 2017 poultry meat, mostly represented by chicken meat (89%), was the most produced worldwide with about 122 Mt, making up 37% of global meat production (FAOSTAT, 2020). According to OECD-FAO (2019), chicken meat is expected to increase by 40 Mt by 2028, representing about half of the total increase in meat production within that year. In addition, 87 Mt of eggs were produced in 2017, of which 92% from laying hens (FAOSTAT, 2020). Beside this, poultry products play a major role in human nutrition, especially in developing countries, due to several factors including being relatively inexpensive, widely available, unaffected by religious restrictions and with a high nutritional value (FAO, 2013).

Poultry products are recognized, together with milk, as the most environmentally efficient among the main livestock production chains, in particular with regard to the carbon footprint but also resources depletion (e.g., land and energy use) (de Vries & de Boer, 2010; Roma et al., 2015). Nonetheless, these fall into the medium-high impact range products when considering a wider basket of edible fresh food (Clune et al., 2017). It is therefore essential to seek continuous improvement of the sustainability of poultry supply chains.

Life cycle assessment (LCA) is a holistic approach for evaluating the environmental impact during the life cycle of products or processes. LCA has long been used for environmental metrics of food products (Andersson et al., 1994), as well as a decision-making tool for environmental management in the same area (Vázquez-Rowe et al., 2012; Djekic & Tomasevic, 2016; Costantini et al., 2021). It is internationally standardized by ISO 14040:2006 and 14044:2006, which define the four founding pillars (goal and scope definition, inventory, impact assessment and interpretation of results) in order to harmonize as much as possible its use among practitioners. LCA also finds application in Type III certification programs (regulated by ISO 14025:2010) to produce environmental product

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declarations (EPD), which are increasingly being used by enterprises in the agri-food sector for reasons of transparency, marketing and eco-labeling (Cimini & Moresi, 2018). The different certification programs provide sector-specific guidelines, called product category rules (PCR), for the compilation of EPDs (Minkov et al., 2015). The International EDP® System, arguably one of the most internationally adopted certification life cycle programs for agri-food, provides PCR for *Hen eggs in shell, fresh* (CPC 02310) and *Meat of poultry* (CPC 2112). On the contrary, there are currently no Product Environmental Footprint Category Rules (PEFCRs) drawn up by the European Commission dedicated to measuring the life cycle impact of these products. Moreover, FAO has recently published, through the Livestock Environmental Assessment and Performance Partnership (LEAP), a guideline document with the aim of tracing a harmonized international methodology for the environmental assessment of greenhouse gas (GHG) emissions and energy use from poultry supply chains (LEAP, 2016). Most of the methodologies addressed by this document can actually be applied for a wider range of impact categories.

LCA reviews in specific livestock fields have been carried out for milk (Baldini et al*.,* 2017), pig (McAuliffe et al., 2016) and beef (de Vries et al., 2015) production systems, which recapitulated the environmental criticalities of each, also highlighting some limits of the use of the LCA. Up to now, some efforts (mainly published in conference proceedings) were done to review LCA studies focused on poultry. In fact, Skunca et al (2015) analysed 13 studies, Leinonen and Kyriazakis (2016) limited the analysis on UK poultry sector. Finally, the reviews carried out by Vaarst et al (2015) and Rodic et al. (2011) do not specifically focus on LCA application to poultry sector but on a broader concept of "environmental impact". In particular, Vaarst et al (2015) considered the multi-dimensional aspects of "sustainability" and, consequently, analyses also the economic and social performances of poultry production. However, there is a lack of a comprehensive poultry-focused LCA review. Given the crucial importance in agri-food terms of this sector, which is even destined to

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grow further in the future, this study intends to review the current knowledge on its environmental performances. In more detail, the goals of this review are:

- summarize for what purpose and how LCA has been applied to date in the poultry sector;
- systematically compare different LCA-studies of poultry products;
- identify the aspects of the poultry production process (e.g., production factors consumed, emission sources, etc.) mainly responsible for the environmental impact of the sector;
- discuss the effectiveness of possible mitigation solutions.

2. Literature review methodology

To perform the review, scientific manuscripts were retrieved by the "core collection" of Web of Science^{TM} database covering the period 2010 to 2020. This period was selected to reflect the current state of the art and recent development, as well as the application of updated LCA methods. In addition, previous LCA studies have already been discussed in a comprehensive review of several livestock categories (de Vries & de Boer, 2010). The keywords used for the research were "LCA or Life Cycle Assessment & eggs", "LCA or Life Cycle Assessment & poultry", "LCA or Life Cycle Assessment & chicken", “LCA or Life Cycle Assessment & broiler”.

In particular, 155 studies were found. After the analysis of title and the abstract 108 studies were excluded because not in line with the topic of this study. In more detail, the criteria used for selecting the studies were the following:

- the main aim is to analyse, even partially, the performance of the life cycle of poultry products;
- the applied methodology must be clearly stated and explained, and the assessment must be carried out in a life cycle perspective;

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- only studies published in peer-review journals have been included, while conference proceedings, book chapters, Ph.D and Master Thesis have not been taken into consideration;- studies focused exclusively on the management and/or re-use and valorization of any by-product of the poultry production chain (poultry manure, eggshells, various slaughtering by-products, etc.) have been excluded.

Making acritical comparisons between the results of different LCA studies is inadvisable. In fact, in addition to the variability and uncertainty related to activity data themselves, some methodological choices can have significant influence. For this reason, particular attention during the review was also paid to the methodological choices adopted as well as to the assumptions made.

3. Major outcomes

As explained in the previous section, 47 studies were analyzed in depth. **Figure 1** shows the timeline of the reviewed studies and also highlights that more studies have been found in the field of poultry meat (66%) than in that of eggs (34%). Only two studies (Leinonen et al., 2013; Leinonen et al., 2014) concerned both.

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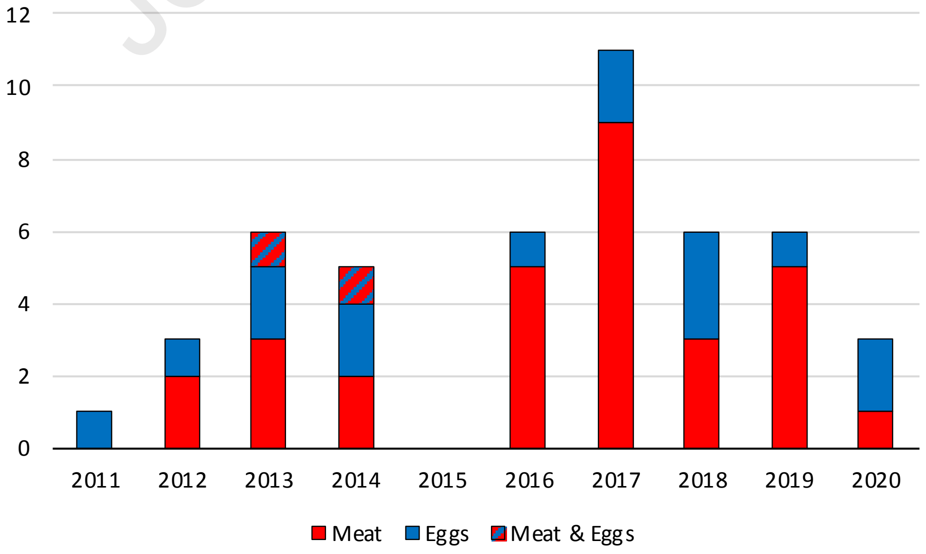

Figure 1 – Timeline of the scientific literature reviewed.

Most studies (89%) focused on chicken, but studies relating to minor productions have also been found, namely turkeys (Leinonen et al., 2016b; Williams et al., 2016; Kheiralipour et al., 2017), geese (Arroyo et al., 2013) and ostriches (Ramedani et al., 2019). Regarding the geographical context, Europe is the most examined continent, with 27 studies. Instead, 9 studies refer to Central-North America, 7 to Asia, 2 to Oceania (represented by Australia only), 3 to South America (represented by Brazil only), and one to Africa (Thévenot et al., 2013; focused on the French overseas department of Réunion). The distribution by country is shown in **Figure 2**. The largest number of publications refer to the United Kingdom (10).

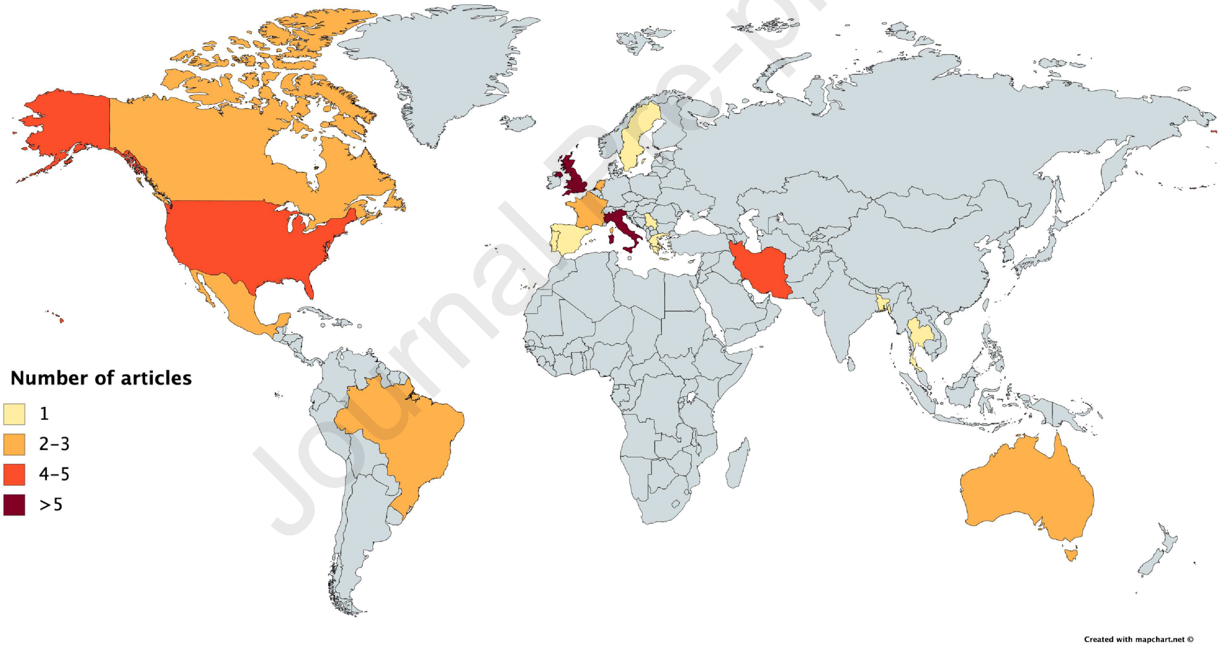

Figure 2 – Geographic distribution of the revised studies.

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As for standardization, the mention of ISO standards that regulate principles and framework, requirements and guidelines of LCA is widespread among the revised studies. On the other hand, LEAP guidelines were mentioned by a limited number of studies (31%) in the years following its publication, i.e. from 2017 onwards. In any case, the reference to certain standards does not necessarily mean that these have been meticulously followed and do not guarantee the reliability of the results. In fact, the approaches used by the various authors in carrying out the studies have been highly variable. The main methodological choices encountered in the revised literature are reported in **Table 1** and **Table 2** respectively for meat and egg production chains and discussed in the following sections.

Table 1 – Schematic review of the main methodological aspects of LCA studies applied to the poultry sector: meat production systems.

Reference	Country	Poultry Species	FU	System boundary		Multi-functionality issue	Impact categories (method)
				Boundary	Land Use Change		
Arroyo et al., 2013	FR	Goose	1 kg of foie gras	Cradle-to-slaughterhouse gate	Not mentioned	Mass and economic	GWP, EP, AP, TEx, PEU, WU, LO (CML2)
Bengtsson & Seddon (2013)	AU	Chicken	1 t roast chicken & 1 t breast fillet	Cradle-to-retail/quick food restaurant gate	Not mentioned	Economic allocation	WEEI (BPIC), GWP, NRERD, WD
Boggia et al. (2019)	IT	Chicken	1 kg live weight	Cradle-to-farm gate	Not mentioned	Not mentioned	11 midpoint indicators (Eco-Indicator 99)
Castellini et al. (2012)	IT	Chicken	1 kg live weight	Cradle-to-farm gate	Not mentioned	No allocation	Endpoint indicator (Eco-Indicator 99)
Cesari et al. (2017)	IT	Chicken	1 kg packed chicken meat	Cradle-to-slaughterhouse gate	Included	No allocation	GWP, AP, EP, TE, NRFEU (CML 2001); CED
Duarte da Silva Lima et al. (2019)	BR	Chicken	1 kg live weight	Cradle-to-farm gate	Not mentioned	No allocation	12 midpoint indicators (CML 2001)
Giannenas et al. (2017)	GR	Chicken	1 kg live weight	Cradle-to-farm gate	Included	No allocation	ADP, AP, EP (CML); POFP, ALO, NLT (ReCiPe 2008 H); CED; GWP; HTPc, HTPnc, FE (USEtox); WDI (Water scarcity)
González-García et al. (2014)	PT	Chicken	1.2 kg packed chicken	Cradle-to-slaughterhouse gate	Not mentioned	No allocation, system expansion for manure	ADP, AP, EP, GWP, POFP, ADP (CML

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Reference	Country	Poultry Species	FU	System boundary		Multi-functionality issue	Impact categories (method)
				Boundary	Land Use Change		
			meat			management	2001); CED
Kheiralipour et al. (2017)	IR	Turkey	1 t live weight	Cradle-to-farm gate	Not mentioned	Not mentioned	11 midpoint indicators (CML 2001)
Leinonen et al. (2012a)	UK	Chicken	1 t expected carcass	Cradle-to-farm gate	Included	Economic allocation (for background processes), system expansion for manure management	GWP, PEU, LO, EP, AP, PU, ARU
Leinonen et al. (2013)	UK	Chicken	1 t expected carcass	Cradle-to-farm gate	Included	Economic allocation (for background processes), system expansion for manure management	GWP, EP, AP
Leinonen et al. (2014)	UK	Chicken	1 t expected carcass	Cradle-to-farm gate	Included	Economic allocation (for background processes), system expansion for manure management	GWP, PEU, EP, AP
Leinonen et al. (2016a)	UK	Chicken	1 t expected carcass	Cradle-to-farm gate	Not included	Economic allocation (for background processes), system expansion for manure management	GWP, PEU, LO, EP, AP, PU, ARU
Leinonen et al. (2016b)	UK	Turkey	1 kg live weight	Cradle-to-farm gate	Included	Economic allocation (for background processes), system expansion for manure management	GWP, EP, AP (CML 2001); PEU
López-Andrés et al. (2018)	MX	Chicken	1 kg carcass weight	Cradle-to-slaughterhouse gate	Not mentioned	Mass, neural network and stepwise regression	15 impact categories (IMPACT 2002)
Martinelli et al. (2020)	BR	Chicken	1 kg live weight	Cradle-to-farm gate	Not mentioned	No allocation	GWP, EP, AP (CML 2001)
Nordborg et al. (2017)	SE	Chicken	1 kg chicken fillet	Cradle-to-household consumption	-	Economic allocation for crop co-products and mass allocation for slaughterhouse co-products	FE (USEtox)

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Reference	Country	Poultry Species	FU	System boundary		Multi-functionality issue	Impact categories (method)
				Boundary	Land Use Change		
Paolotti et al. (2016)	IT	Chicken	1 t live weigh	Cradle-to-farm gate	Not mentioned	System expansion for manuring in the orchard and avoided mowing for free-range in olive orchard	11 midpoint indicators (Eco-Indicator 99)
Payandeh et al. (2017)	IR	Chicken	1 t live weight	Cradle-to-farm gate	Not mentioned	Mass allocation	11 midpoint indicators (CML 2001)
Pishgar-Komleh et al. (2017)	IR	Chicken	1000 chickens at the farm gate / 1 kg live weight	Cradle-to-farm gate	Not mentioned	No allocation	GWP, EUE
Prudêncio da Silva et al. (2014)	FR & BR	Chicken	1 t packed chicken meat / 1000 € of product	Cradle-to-slaughterhouse gate	Included	No allocation	GWP, AP, EP, TE, LO (CML 2001); CED
Putman et al. (2017)	US	Chicken	1 t live weight	Cradle-to-farm gate	Not mentioned	Biophysical allocation	GWP, AP, EP, LO, WU, FEU (TRACI 2.1)
Ramedani et al. (2019)	IR	Chicken	1 t live weight	Cradle-to-farm gate	Not included	Mass allocation	11 midpoint indicators
Rocchi et al. (2019)	IT	Chicken	1 t live weigh	Cradle-to-farm gate	Not mentioned	System expansion for manuring in the orchard and avoided mowing for free-range in olive orchard	5 midpoint indicators (Eco-Indicator 99)
Skunca et al. (2018)	RS	Chicken	1 kg of consumed chicken meat	Cradle-to-household consumption	Not mentioned	Mass allocation	GWP, CED, OLD, AD, EP (Impact 2002 +)
Tallentire et al. (2017)	UK & US	Chicken	1 t live weight	Cradle-to-farm gate	Included	Economic allocation	GWP, AP, EP, ALU; NREU (Impact 2002)
Tallentire et al. (2018)	UK	Chicken	1 bird at 2.2 kg live weight	Cradle-to-farm gate	Included	Economic allocation	GWP, ALU
Tallentire et al. (2019)	Continental Europe	Chicken	1 kg of meat	Farm-to-slaughterhouse gate	-	-	Animal welfare indicators
Thévenot et al. (2013)	FR-RE (Réunion)	Chicken	1 t of packed whole chickens	Cradle-to-slaughterhouse gate	Not mentioned	Economic allocation, system expansion for manure and other organic wastes management	GWP, AP, EP (CML 2001); CED
Usubharatana &	TH	Chicken	A one-day-old chick	Cradle-to-hatchery gate	Not included	Mass allocation (of the feed plant	GWP

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Reference	Country	Poultry Species	FU	System boundary		Multi-functionality issue	Impact categories (method)
				Boundary	Land Use Change		
Phungrassami (2016)						production)	
Wiedemann et al. (2017)	AU	Chicken	1 kg of chilled whole chicken & 1 kg of boneless, skinless chicken portion	Cradle-to-slaughterhouse gate	Included	Economic allocation for slaughterhouse co-products	GWP, NRFEU, WU, SWWU, LO
Williams et al. (2016)	UK	Turkey	1 t live weight	Cradle-to-farm gate	Included	Economic allocation (for background processes), system expansion for manure management and avoided electricity production from conventional combustion technologies	GWP, AP, EP, POFP, Dioxin emission, (CML 2001); PM10 emissions; CED

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Note:

Impact categories: ADP = abiotic depletion potential, ALO = agricultural land occupation, ALU = agricultural land use, AP = acidification potential, ARU = abiotic resource use, CED = cumulative energy demand, EP = eutrophication potential, EUE = energy use efficiency, FE = freshwater ecotoxicity, FEU = fossil energy use, GWP = global warming potential, HTPc = Human Toxicity Potential (cancer effects), HTPnc = Human Toxicity Potential (non-cancer effects), LO = land occupation, NLT = natural land transformation, NRERD = non-renewable energy resource depletion, NREU = non-renewable energy use, NRFEU = non-renewable fossil energy use, OLD = Ozone layer depletion, PEU = Primary energy use, POFP = Photochemical oxidant formation potential, PU = Pesticide use, SWWU = stress-weighted water use, TE = terrestrial ecotoxicity, WD = water depletion, WDI = water depletion index, WEEI = weighted environmental ecopoint impact, WU = water use.

Impact assessment method: BPIC: BPIC, 2010; CED: *Frischknecht et al.,* 2007; CML 2001: *Guinée et al.,* 2002; Eco-Indicator 99: *Goedkoop & Spriensma*, 2001; Impact 2002+: *Jolliet et al.,* 2003; TRACI 2.1: *Bare*, 2012. USEtox (V2): *Fantke et al.,* 2015.

Table 2 – Schematic review of the main methodological aspects of LCA studies applied to the poultry sector: eggs production systems. All studies refer to the breeding of laying hens.

Reference	Country	FU	System boundary		Multi-functionality issue	Impact categories (method)
			Boundary	Land Use Change		
Abín et al. (2018)	ES	A dozen packed eggs / 1 kg packed eggs	Cradle-to-farm gate	Included	System expansion: spent-hens meat is considered as a substitute for broiler meat, constituting an environmental credit for its avoided production	18 midpoint indicators (ReCiPe 2008 H); 3 endpoint indicators (ReCiPe 2008 H); GWP (Greenhouse Gas Protocol V1.01/CO2 eq)
Dekker et al. (2011)	NL	1 kg eggs	Cradle-to-farm gate	Not included	Economic allocation	GWP, EU, LO, FPU, AP, ND, PD, NS, PS
Dekker et al. (2013)	NL	1 kg eggs	Cradle-to-farm gate	Not included	Economic allocation	GWP, EU, LO, FPU, AP, ND, PD, NS, PS
Costantini et al. (2020)	IT	1 kg eggs	Cradle-to-farm gate	Not included	Surplus method, economic and biophysical allocation	12 midpoint indicators (ILCD)
Estrada-González et al. (2020)	MX	1 kg packed eggs	Cradle-to-farm gate	Not mentioned	Not mentioned	18 midpoint indicators (ReCiPe 2008 H)
Ghasempour & Ahmadi (2016)	IR	1 kg eggs	Cradle-to-farm gate	Not mentioned	Not mentioned	11 midpoint indicators (CML 2001)
Leinonen et al. (2012b)	UK	1 t eggs	Cradle-to-farm gate	Included	Economic allocation, system expansion for manure management	GWP, PEU, LO, EP, AP, PU, ARU
Leinonen et al. (2013)	UK	1 t eggs	Cradle-to-farm gate	Included	Economic allocation, system expansion for manure management	GWP, EP, AP
Leinonen et al. (2014)	UK	1 t eggs	Cradle-to-farm gate	Included	Economic allocation, system expansion for manure management	GWP, PEU, EP, AP
Mainali et al. (2017)	BD	10000 eggs	Cradle-to-farm gate	Not included	No allocation (eggs load the full environmental	GWP

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					burden)	
Pelletier et al. (2013)	US	Different for each stage of the supply chain, up to 1 t liquid eggs	Cradle-to-processing facility gate	Not mentioned	Physical allocation (based on gross energy content of co-products)	GWP
Pelletier et al. (2014)	US	1 t eggs	Cradle-to-farm gate	Not mentioned	Physical allocation (based on gross energy content of co-products)	GWP, AP, EP, CED
Pelletier (2017)	CA	Different for each stage of the supply chain, up to 1 t liquid eggs	Cradle-to-processing facility gate	Not included	Physical allocation (based on gross energy content of co-products)	GWP, AP, EP (CML 2001); CED; LU, WU
Pelletier (2018a)	CA	1 t eggs	Cradle-to-farm gate	Not included	Physical allocation (based on gross energy content of co-products)	GWP, AP, EP (CML 2001); CED; LU, WU
Pelletier (2018b)	CA	1000 egg facility worker hours	Farm-to-processing facility gate	-	-	Social indicators, according to UNEP/SETAC (2009)
Taylor et al. (2014)	UK-WLS	1 kg eggs	Cradle-to-farm gate	Not mentioned	Economic allocation	GWP
van Hal et al. (2019)	NL	1 kg eggs	Cradle-to-farm gate	Not included	Economic and Food-based allocation	GWP, EU, LU, LUR (Van Zanten et al., 2015)

Note:

Impact categories: AP = acidification potential, ARU = abiotic resource use, CED = cumulative energy demand, EU = energy use, FPU = fossil phosphorous use, GWP = global warming potential, LO = land occupation, LU = land use, LUR = land use ratio, ND = nitrogen deficit, NS = nitrogen surplus, NRFEU = non-renewable fossil energy use, PEU = primary energy use, PD = phosphorous deficit, PS = phosphorous surplus, PU = pesticide use, WU = water use.

Impact assessment method: CED: *Frischknecht et al.*, 2007; CML 2001: *Guinée et al.*, 2002; ILCD: *Wolf et al.*, 2012; ReCiPe 2008: *Goedkoop et al.*, 2009.

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3.1. Goal and scope

Most of the performed LCA studies aim to describe the environmental performance of poultry systems at different levels of the production chain or comparing different systems (e.g., in terms of housing systems or feeding strategies). All these LCA studies are *attributional* LCA (aLCA) or intende to explore the impact related to physical input and output flows of the system under study. In contrast, *consequential* LCA (cLCA) studies are lacking. This is probably due to the additional inventory data required for system expansion in aLCA. In addition, cLCA studies normally presents more uncertainty as consequential system changes in response to changes in inputs and output flows often have to be largely assumed.

In Pelletier et al. (2014), Putman et al. (2017) and Pelletier (2018a), LCA was used as a tool to carry out a retrospective analysis of the environmental efficiency evolution of the poultry supply chains in the last 50 years in US and Canada. These authors concluded that the environmental impact per unit of product has significantly decreased over time for all evaluated impact categories thanks to improvements in animal performance (due to selecting breeding and genetics; feeding and housing techniques and management; etc.) and in background processes (increase in yields of feed production, greater energy efficiency, changes in the electricity mixes, lower emissions related to transport, etc.). According to Pelletier et al. (2014) and Pelletier (2018) the overall environmental impact of the egg industry has declined in both countries, despite increased production. Putman et al. (2017) instead observed that the absolute impact of chicken meat production in the US has increased, despite the greater environmental efficiency per kg of meat. This difference can be attributed to the increase in chicken meat production.

21% of the studies coupled the LCA with economic assessments on the supply chain (excluding studies that used fixed outputs prices solely to perform economic allocation). Social considerations were included by only 9% of studies, or the following: Castellini et al. (2012) and Rocchi et al. (2019)

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assessed aspects such as workplace safety and animal welfare to perform a multi-criteria analysis of various broiler systems; *Pelletier* (2018b) applied the Guidelines for Social LCA of Products (UNEP/SETAC, 2009; Benoît-Norris et al., 2011) to egg production facilities in Canada in a gate-to-gate perspective; finally, Tallentire et al. (2019) proposed a methodology for inserting an animal welfare indicator in a future integrated social-LCA framework that may be more appropriate for livestock production chains, with a particular case on European broiler production. In fact, the UNEP/SETAC Guidelines currently have limitations in being applied in specific sectors/contexts (Pelletier, 2018b).

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3.1.1. Functional unit

According to ISO 14044, the functional unit (FU) shall be consistent with the goal and scope of the study. At the same time, there must be an agreement between the FU and the system boundaries considered. In this regard, an inconsistency is represented by reporting the results for poultry meat in terms of *expected* carcass weight without loading impacts from the slaughtering phase, considering fixed yield values for slaughter and relating them to the impact up to the farm gate. As pointed out by Wiedemann et al. (2017), this may lead to an underestimation of the impact linked to the carcass production, especially for impact categories affected by energy consumption and for water use.

Despite the adopted FUs are highly heterogeneous across the revised studies, it is noticeable the predominant use of mass-based FUs, both when considering productions at the farm gate and after subsequent processing at different stages of the supply chain. Prudêncio da Silva et al. (2014) used the economic value at the farm gate (1000 € of product) as an additional FU with respect to the mass-based one in comparing broiler production systems between countries (Brazil and France) with different meat markets.

3.1.2. System boundaries

Most of the attention has been paid to the production phase, thus limiting the system boundaries of the study and excluding retail, household and end-of-life phases. This because the production phase, and in particular the agricultural phase, has been highlighted as the most impacting for animal products (Notarnicola et al., 2017). Three main types of system boundaries have been identified in the revised studies: cradle-to-farm gate, which was adopted by 63% of the total studies; cradle-to-slaughterhouse gate, adopted by 22% of studies in the meat field, while the slaughter phase was never considered for spent hens; finally, cradle-to-others various downstream processes (further processing and/or packaging, distribution to retailers, household consumption). An exception is represented by Usubharatana & Phungrassami (2017), who performed an LCA in a cradle-to-hatchery gate perspective.

However, it should be noted that different studies, even when they adopt the same system boundaries, may not consider the same types of input and output flows. For instance, land use change (LUC) inclusion is an aspect that can have a strong influence on results, especially for global warming potential (GWP). Due to the lack of a shared consensus on how to consider and calculate it, this can create distortions in interpretations and comparisons. Ideally, in an LCA study it should be clearly reported whether LUC is included and specify how it was computed. According to MacLeod et al. (2013), LUC would be responsible for 18% of global GHG emissions from chicken supply chains, showing the environmental relevance of this aspect. However, some authors have preferred to explicitly exclude it from the assessment, mainly because of the great uncertainty connected to it, while in some cases it was not even mentioned. In the studies in which it was included, the LUC considered was always the *direct* one, with the exception of Leinonen et al. (2013) which considered both *direct* and *indirect* LUC. As for the presentation of the results, LEAP

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suggests, when including the impact related to LUC, to show them separated from the rest of the analysis, due to the great uncertainty associated with it. Among authors who included LUC in their analysis, this practice was observed only by Wiedemann et al. (2017).

Regarding the common use of manure as an organic fertilizer, system expansion has been frequently practiced, accounting for avoided mineral fertilizers production as an environmental credit for the poultry production system. This is a common practice in LCA studies that include some type of residual handling that bring environmental benefits to the system. However, more clarity and transparency, often absent in the literature, would be needed on how such substitution is assumed to occur (Hanserud et al., 2018).

Variability was also found in the consideration of upstream processes of the poultry production chain. Among these, an important reference flow in the case of poultry supply chains is the production of one-day-old chicks (whether they are intended for future fattening or laying eggs). LEAP guidelines recommend that the system boundaries should at least encompass the production cycle starting from the great-grandparents generation. Actually, studies considering this amount of parental generations are limited (Leinonen et al., 2012a; Leinonen et al., 2012b; Bengtsson & Seddon, 2013; Giannenas et al., 2017) and most authors did not even specify it or only considered breeding parents, which decreases the accuracy of impact estimation throughout the life cycle.

Also, a wide range of approaches can be observed in the consideration of capital goods and infrastructures. Their inclusion (although not always explicit) in upstream processes starting from raw materials extraction is common to most studies, for instance with regard to transport operations, fuels and electricity consumption, agricultural machines involved in feed production. This is done by means of background data from life cycle inventory databases. On the other hand, virtual consumption and maintenance of capital goods related to the rearing (animal housing infrastructures, warehouses, silos, tanks, etc.) and processing (slaughterhouse infrastructures, etc.)

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phases has almost always been excluded. Cleaning materials were included only sporadically within system boundaries (e.g., by Aubín et al., 2018), while veterinary products were always excluded.

3.1.3. Allocation

In the case of poultry meat production, the main allocation issue concerns the carcass and secondary slaughtering products (inedible organs, head, feet, blood, feathers, etc.), necessary to be addressed for LCA studies which include the impacts relating to the slaughter phase. The studies concerned can be mainly divided between those who considered secondary slaughter products as residual product (i.e., a product with a possible subsequent use but zero economic value, LEAP, 2016), thus without loading any impact on them, and those who regarded them as a co-product, practicing economic allocation. However, the value of these products is generally low, causing only a small variation of meat environmental results when considered. Wiedemann et al. (2017) found that the economic value of carcass weight represented 98.5-99.2% of the total slaughterhouse outputs.

The egg production system always produces at least two co-products, namely eggs and spent hens meat. LEAP guidelines recommend handling this co-production with the 'biophysical' method, that is, based on energy requirements for growth and egg production (LEAP, 2016). However, this method was applied only by Putman et al. (2017) and tested in a sensitivity analysis by Costantini et al. (2020). Other cases where a physical relationship between the co-products was considered were Pelletier et al. (2013), Pelletier et al. (2014), Pelletier (2017) and Pelletier (2018a), who considered the mass-adjusted gross energy content of the various co-products, both between eggs and meat and in the upstream crop production processes. The economic allocation was the most used type of allocation instead. This confirms that economic allocation, despite its limitations, currently appears to be the most consistently applicable method for quantifying the co-products relationships in complex agricultural systems (Mackenzie et al., 2017). Anyway, spent hen meat represents a

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minimal part of the system's co-production, both in terms of quantity and value. In fact, Dekker et al. (2011), Leinonen et al. (2012b) and Costantini et al. (2020) showed that economic allocation for spent hens entails limited changes (in the order of 1%) in the environmental results of egg production. Abín et al. (2018) practiced a system expansion, considering the spent hens meat produced as an environmental credit for the replacement of the same amount of broiler meat specifically produced. Although avoiding allocation through system expansion is theoretically a priority practice according to the ISO 14044 standard, in this case it involves the assumption that spent hens meat is an equal replacement for broiler meat, which is not actually the case given the significant differences in physicochemical characteristics and nutritional properties between these two products (Chen et al., 2016). Van Hal et al. (2019) made a comparison between the application of two allocation methods to the feed used: an economic 'standard' and a method that instead rewards the use of low-opportunity-cost feedstuff (crop residues and by-products). In this way, the authors intended to weight the avoidance of the competition between feed and food production, which is normally not taken into account by the common LCA indicators even if it represents a criticality of livestock production systems, in particular for monogastric animals (Van Zanten et al., 2018). With regard to the management of the poultry manure generated during the rearing cycle, the main trend in revised studies is to consider it as a residual with zero economic value but with a subsequent use (as fertilizer), therefore not receiving any allocation burden.

A good practice should be to verify the influence that different allocation choices can have on environmental results with sensitivity approaches within individual studies (LEAP, 2016; Baldini et al., 2017). However, only few studies have tested more than one type of allocation (Arroyo et al., 2013; López-Andrés et al., 2018; Van Hal et al., 2019; Costantini et al., 2020).

3.2. Inventory data

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In all studies, the inventory was made up of the integration of primary and secondary data. Primary data were derived from personal communication and interviews with stakeholders involved in the productive chain at different stages or from databases representative of certain territories (e.g. regional/national or international inventories). Secondary data include both literature data (i.e. from previous studies), model-based estimates, and so-called background data, which are normally present on specific databases. Of the latter, Ecoinvent (Frischknecht et al., 2005; Wernet et al., 2016) was the most cited, but several others were also employed, such as Agri-footprint (Blonk Consultants, 2014), Feedprint (Vellinga et al., 2013), AgriBalyse (AgriBalyse, 2017), Carbon Trust (Carbon Trust, 2010), AustLCI (Life Cycle Strategies, 2015), etc.

In general, a good practice should be reporting detailed and transparent information when exposing the inventory analysis. Collection of data for setting up LCA studies on the poultry sector should be as accurate as possible especially for all factors concerning the feed (origin, composition, consumption, possibly digestibility), which in turn influence even the characteristics and quantity of manure produced (LEAP, 2016). The management of the latter is also fundamental to consider.

With regard to animal-related emissions, most of the studies adopt the emission factors proposed by the IPCC. However, these only concern manure-related emissions and do not provide for enteric fermentation due to *insufficient data for calculation*. In fact, the vast majority of the revised studies take methane emitted from enteric fermentations to be negligible, the only exceptions represented by Taylor et al. (2013) and Giannenas et al. (2017), who included it among the system outputs. In the first, the contribution of poultry enteric methane on the overall carbon footprint of the system (free-range egg production) was actually limited to 0.6%, while in the second its contribution is not specified. Nevertheless, LEAP guidelines urge the inclusion in LCA inventories of enteric methane emission factors reported in the literature. In particular, reference is made to Wang & Huang (2005) and Yusuf et al. (2012), according to which poultry would emit from 0.015 to 2 g of enteric

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methane/head/year. Hydrogen sulphide (H_2S) emissions from manure were found to be explicitly considered only by Ramedani et al. (2019).

3.3. Impact assessment

Variability was found with regard to the impact coverage. The most widely studied category is the GWP, considered in almost all studies, some of which (9% of the total) focused exclusively on this impact category. **Figures 3** and **4** show the GWP results of the literature for meat and egg production respectively.

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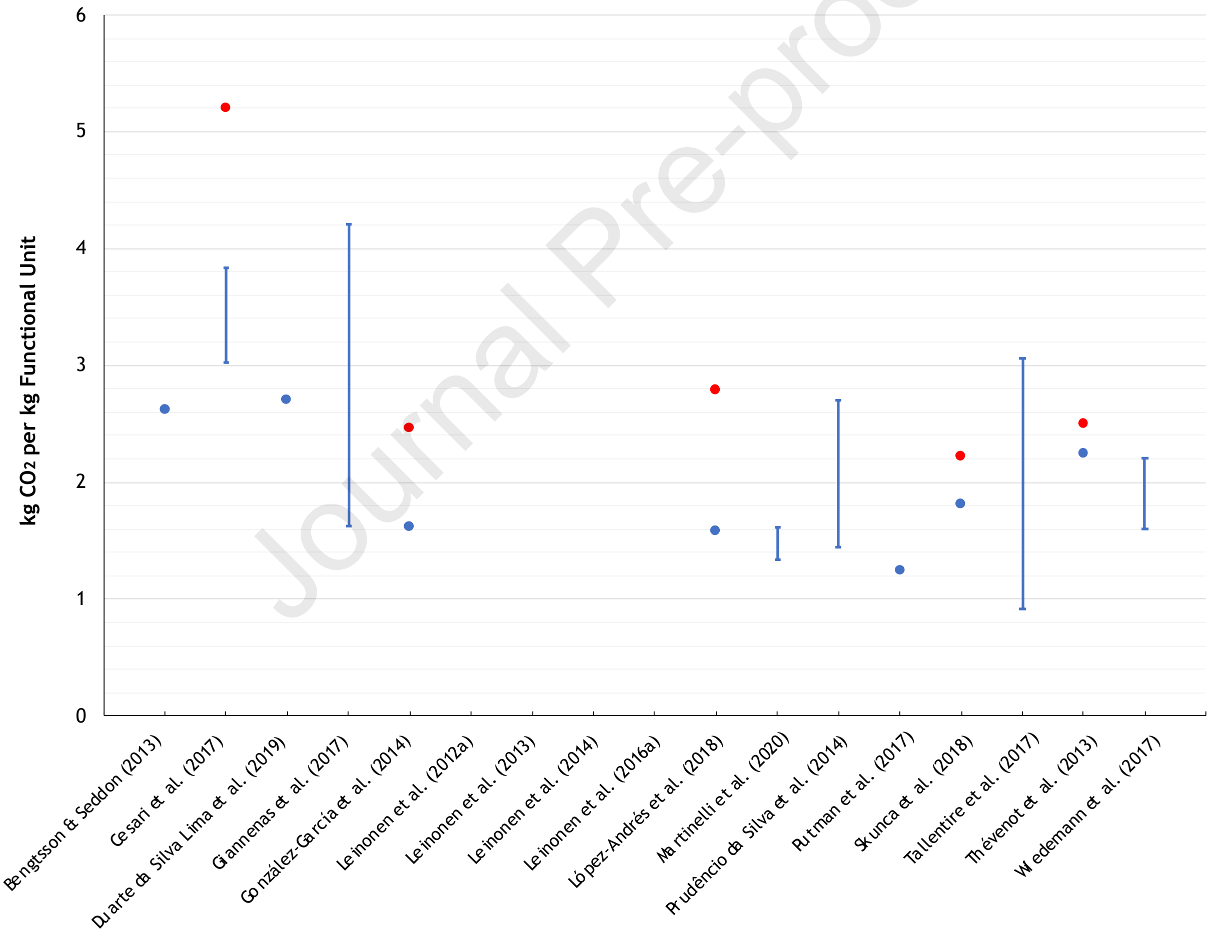

Figure 3 - Comparison between the GWP results per kg of live weight (farm gate), in blue, and per kg of carcass weight (slaughterhouse gate), in red, of the different LCA studies focused on chicken meat production.

Some studies may present multiple GWP values due to the consideration of different rearing systems for comparisons. In these cases, bars have been reported showing the minimum and maximum values achieved. For the meat chain, results are reported to the farm gate (kg CO_2 eq · [kg Live Weight]$^{-1}$) and, where available, to the slaughterhouse gate (kg CO_2 eq · [kg carcass]$^{-1}$). For eggs, on the other hand, results refer to the production of 1 kg of eggs at the farm gate. The observed variability includes both that due to methodological differences, as explained in the previous sections, and that linked to different production contexts, management choices (feed used, rearing system adopted, etc.) and animal performances.

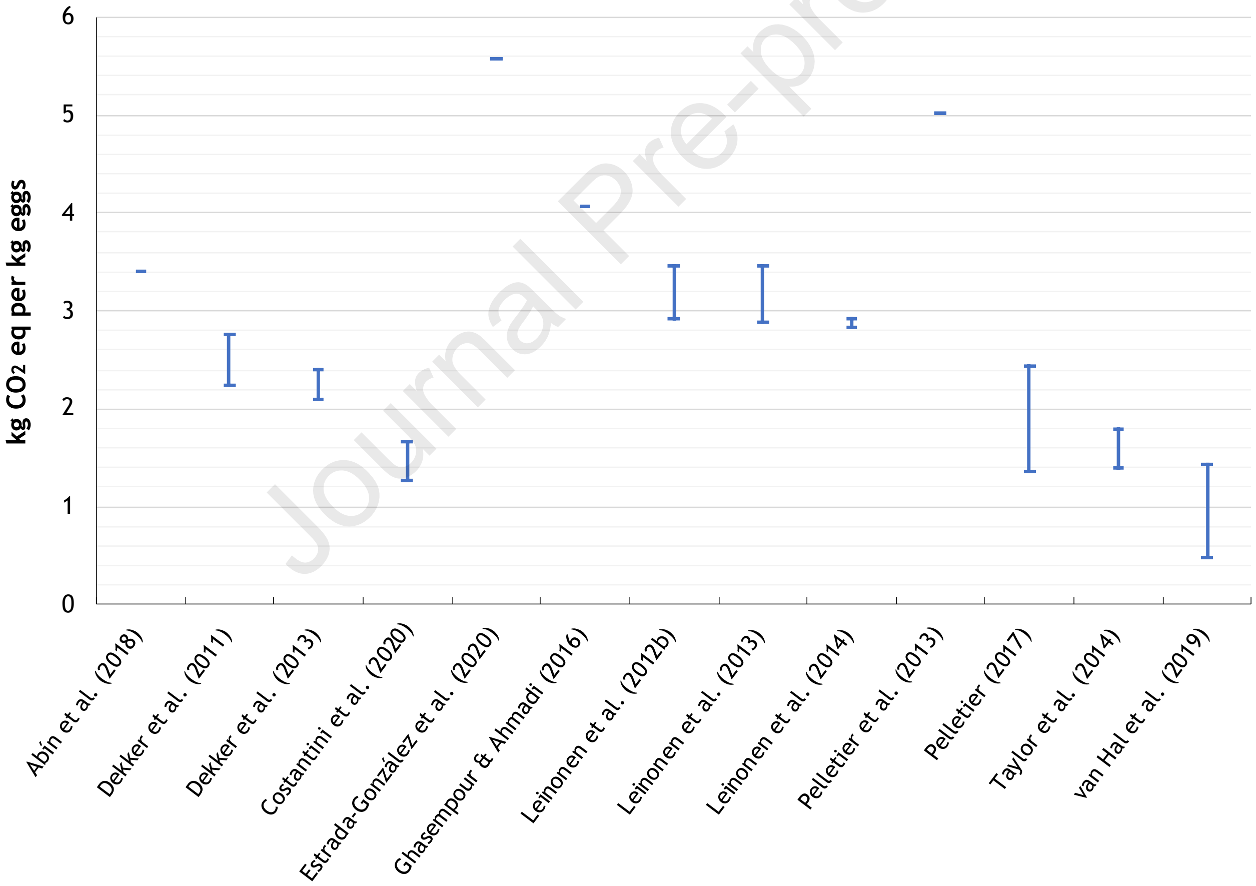

Figure 4 - Comparison between GWP results for kg of eggs of different LCA studies.

The only study that did not include the GWP impact focused on freshwater ecotoxicity in a comparison between different food products, including chicken fillet, in Sweden (Nordborg et al.,

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2017). Other emission-related categories widely analyzed were eutrophication and acidification potentials (EP, AP), while the resource-related categories mainly taken into consideration were energy use, water use and land occupation. For energy use assessment, the Cumulative Energy Demand (CED) was the most common method. The impact assessment methods were also highly variable.

3.4. Key trends identified

In all studies, feed production and supply were found to be major contributors to the impact of poultry production for both GWP, AP and EP. Even if a wide variety of feed and feed components is used, in the different LCA studies reviewed, the protein feeds are the most impacting one, both for GWP (mainly due to LUC) than for the other environmental impact categories such as AP, EP and particulate matter (mainly due to the emissions of nitrogen and phosphorous compounds during cultivation). Soybean and its derived products are the feeds more frequently identified as environmental hotspots even because they are the main source of protein. For organic production in EU, the impact of soybean and derived products on GWP is usually lower because genetically modified crops are not allowed and, consequently, feedstock locally produced are used instead of imported one (usually cultivate in South America where LUC is not negligible).

Animal feeding is the main responsible of the environmental impact independently by the different rearing systems (cage and non-cage; conventional and organic). In fact, the animal performances linked to the feed, especially feed intake, daily weight gain or hen day egg production and, consequently, the feed conversion ratio (FCR), have been identified as highly influencing factors on the environmental impact of the final products of the supply chains. Therefore, the search for the continuous on-farm improvement of all these parameters is always remarked as the first aspect to pursue in order to obtain a more sustainable production. Nevertheless, by aggregating the GWP

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from all the studies in which the FCR was explicitly expressed, low correlation was found between these (Tables S1 and S2, Supplementary materials). For broiler meat, the environmental results are deeply affected by the age at slaughter (Tallentire et al., 2017). In addition to animal-related parameters, Thévenot et al. (2013) also demonstrated that quality of buildings and equipment and other farm characteristics partially influence the variability of environmental poultry performances.

As for poultry meat, the slaughtering, processing and packaging stages were found to have a limited impact on most of impact categories except than for cumulative energy demand for which they normally have a weight in the order of 10-15%. Seeking continuous improvement also in these areas (e.g. by means of greater efficiencies in energy consumption, proper management of waste and wastewater, adoption of recyclable packaging) can play a role in making the supply chain more sustainable but it is clear that the priority mitigation must be sought on the agricultural phase, as it would be the most incisive.

Mitigation scenarios with respect to existing systems have been widely evaluated in literature. Most of these have been addressed to the feed area in various aspects, both feed production and diet formulation. In this regard, some authors have focused their research exclusively on achieving sustainable poultry feed production (e.g., Nguyen et al., 2012), while more frequently the variation given from the use of several feeds have been explored on the finished poultry product.

The close relationship between the current global poultry production and soybean supply has been discussed in the last years. In most European LCA studies, soybean products are environmental hotspot due to its import from South America and to the cultivation. Regarding soybean cultivation, the main concerns are related to LUC and massive use of pesticides. According to Tallentire et al. (2018), there is no evidence that the efficiency of protein utilization has changed as a result of selective breeding on broiler chickens. Therefore, mitigation interventions linked to the protein requirements must be carried out on diet formulation and/or on the protein source itself to have

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the greatest influence. According to Leinonen et al. (2016), the partial soybean replacement (both at feasible and extreme levels) in the diet of broiler and laying hens with other protein crops (bean, pea and sunflower) results in a GWP reduction trends even if with a great uncertainty. This uncertainty is due to the LUC accounting methods and the diets changes (i.e., to maintain the energy and nutrient balance, the replacement of soybean with other protein crops often requires a greater inclusion in the diets of synthetic amino acids or vegetable oils, which involve relatively high unitary GHG emissions).

Beyond the environmental impact, the poultry sector consumes more soybean than all other livestock systems in Europe, and low self-sufficiency for this protein source exposes the continent to serious food security risks (Tallentire et al., 2018). The use of *alternative protein sources* is currently very little widespread for large-scale animal feeding, and it is still partially or totally limited by the regulations in force in many countries. However, Tallentire et al. (2018) indicated novel ingredients such as microalgae, yeast protein concentrate, bacterial protein meal, leaf protein concentrate and insect meal valid solutions to contain both GWP and agricultural land occupation related to conventional broiler diets, although they may cause increased nitrogen excretion. Earthworm meal was also indicated as a possible ingredient capable of improving the sustainability of poultry systems (Kahn et al., 2018; Parolini et al., 2020). Further research is needed on these ingredients which present good prospects but, beyond regulatory barriers, do not yet have characteristics and efficiency (economic and environmental) such as to justify their large-scale diffusion on the feed market, especially if considered in competition with soybean.

Manure management is another important environmental hotspot, very influential on AP and EP, in particular for the volatilization of ammonia, which affects every phase of manure management (housing stage, storage, handling, field spreading), and for the loss of nutrients, nitrates and phosphates above all, in surface and groundwater that occurs after the field application. The energy

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valorization of poultry manure was explored as a mitigation option both as feedstock for anaerobic digestion (Thévenot et al., 2013; Mainali et al., 2017) and fuel for biomass-burning power stations (Williams et al., 2016). Indeed, under certain digestion conditions, poultry manure is known to have a high biogas production potential, yet it is currently under-exploited in this sense. As for the use of poultry litter as a fuel, Williams et al. (2016) have highlighted how this can bring environmental benefits especially for AP, EP and energy demand, while for the GWP it is only slightly mitigated, considering that the loss of soil organic carbon given by the non-spreading of litter on land counterbalances the environmental benefit from the production of renewable energy. The emission of combustion gases from burning plants is also an environmental trade-off of this practice.

As for the comparison between different farming systems, it is difficult to draw unambiguous conclusions. Regarding eggs, conventional systems presented lower environmental burdens than organic in the comparative LCA studies conducted by Dekker et al. (2011) and Leinonen et al. (2012b). For GWP, the cage farming system appeared less impacting, while the difference between organic, barn and free-range systems is lower and, according to Leinonen et al. (2012b), not statistically significant. In both studies, organic production also showed higher land use per kg of eggs than conventional systems. Pelletier (2017), in Canada, obtained completely opposite results, due to the use of animal derived products as feed components in conventional systems . With regard to chicken meat, conventional rearing systems were found to have slightly less impact on GWP than organic by both Leinonen et al. (2012a) and Martinelli (2020). The difference is more marked with the standard indoor system, while free-range system is on the middle between the latter and the organic one (Leinonen et al., 2012a). AP, EP and land use impacts are significantly higher for organic systems, especially due to a greater feed consumption and manure production linked to a longer cycle duration.

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The variation under different stocking densities, evaluated by Leinonen et al. (2014) and by Cesari et al. (2017), has a minor role on the environmental performance of the system. This is interesting considering that in many developed countries the poultry industry is increasingly moving towards systems with lower stocking densities to meet customers' expectations for animal welfare. Indeed, this is regarded as a possible indicator for social LCA (Tallentire et al., 2019).

3.5. Future perspectives

This review highlighted broad aspects related to the environmental impact of poultry farming, and in particular of its evaluation using the LCA approach. Despite the attention that poultry sector received in this regard over the last ten years, many gaps are still to be filled. The main critical points on which it is possible to set up future research activities are the following:

- There is a need to further unify the application of the LCA method as some methodological choices. These mainly concern the system boundaries (e.g., consideration of manure management with system expansion or not; LUC inclusion within system boundaries and its accounting method), which in any case should always be clearly defined and present concordance with the FU adopted, and the allocation of environmental burdens.
- Future studies should take into greater consideration the adoption of more food-oriented functional units, e.g. by considering the nutritional value of products. The selection of FUs based on mass (or volume) is a debated issue regarding agri-food LCA studies. These are easily understandable and comparable, but do not reflect the true function of food commodities, which is to provide human nutrition (McAuliffe et al., 2020). For this reason, FUs should also keep quality and not just quantitative aspects into account to avoid misinterpretations and allow consistent comparisons with other food products. Only a few of the reviewed studies made considerations beyond the mass of animals or food produced

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- The poultry sector is very dynamic and multifunctional; productions are continuously evolving and growing, and associated by-products and waste streams are expected to increase as well. This sector should be explored also by means of consequential LCA, which would allow to understand the environmental impact of the poultry in a broader cause-effect chain perspective.
- In the revised literature, the LCA approach has been used mainly to investigate the life cycle from an environmental point of view. This tool should be more frequently coupled with economic considerations, because these are necessary in order to implement feasible mitigation strategies. Moreover, social aspects of sustainability, including the macro-topic of animal welfare, appear almost totally neglected by current LCA studies. As sustainability is a multi-layered concept, the integration between these different aspects should be greater in the future.
- There are important shortcomings in the current literature geographical coverage. Asia is the largest producer (in particular China) of both eggs and poultry meat (FAOSTAT, 2020), but studies are relatively few and not representative of large areas. Furthermore, continental Africa is not addressed by any study despite the fact that this sector is experiencing a development in the continent, slowly passing from being mainly family-run towards more organized and intensive structures (Mattiello et al., 2018).
- The potential of using alternative protein sources as an environmental mitigation strategy for poultry production is still poorly documented compared to the expected yet unexpressed potential mentioned in the literature.
- Competition between feed and food ingredients in poultry diets should be increasingly considered and weighed from an environmental perspective.

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Finally, it is important to underline that some environmental effects related to poultry farming still remain almost completely unexplored by the LCA studies carried out to date. Among these, it is important to mention the odor impact (Conti et al., 2020), consequences on biodiversity (Crenna et al., 2019) and also those given by antimicrobials, estrogens and heavy metals release through manure (Hu et al., 2017). Each of these has methodological limits and ongoing debates on its accounting, but the fact remains that they represent serious environmental concerns for livestock productions, including poultry.

This study did not deepen the possible valorization pathways of by-products of the poultry production chain. These, which have recently been reviewed by Kanani et al. (2020), would deserve a separate environmental assessment review study.

4. Conclusions

A literature review was performed with the aim of analyzing the state of art of LCA applied to the poultry sector. There have been several studies focused on this sector in the last decade. Most of the studies focused on the agricultural phase (i.e. cradle-to-farm gate perspective), for which feed consumption was consistently found as an environmental hotspot. Studies that also included egg or meat processing show that such processes have little influence on the total impact for most categories. The results variability found in the literature has been large; greater unification should be needed in methodological choices. In general, the possibilities of reducing the environmental impact of this sector are still wide and, in this regard, many mitigation strategies have been explored in the literature, including the efficient management of the supply chain and above all of the poultry housing conditions and rearing parameters, diet formulation and feeding strategies, among which particular interest and perspectives cover the use of alternative protein sources and feeds that do not involve food competition, reduced age at slaughter for poultry meat and best

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management of manure, possibly also enhanced energetically. However, more research is needed as understanding of the environmental performance of this sector is still limited in some respects, which were highlighted in the discussion. Also, economic and social aspects will have to be increasingly taken into consideration in the life cycle perspective.

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Highlights

- The review focuses on the environmental impact of poultry productions
- 155 LCA (Life Cycle Assessment) studies were identified, 47 reviewed in detail
- Functional unit, system boundary and multifunctionality management were identified
- The agricultural phase weighs heavily on the impact of the finished food product
- Feed consumption and manure management are the main impact contributors

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