Contribution of Feeding Processes to the Environmental Impact of Broiler Chicken Production

Nikolett Éva Kiss[1], János Tamás[1], Attila Nagy[1]

[1]University of Debrecen, Faculty of Agricultural and Food Sciences and Environmental Management, Institute of Water and Environmental Management. 138. Böszörményi str. Debrecen, Hungary

Abstract

The environmental impact of broiler chicken production was evaluated in this study utilizing life cycle analysis (LCA). The research examined at 11 different impact categories (abiotic depletion potential for elements (ADPe); abiotic depletion potential of fossil fuels (ADPf); acidification potential (AP); eutrophication potential (EP); global warming potential (GWP); ozone layer depletion potential (ODP); photochemical oxidation potential (POP); human toxicity potential (HTP); fresh water aquatic ecotoxicity potential (FAETP); marine aquatic ecotoxicity potential (MAETP); terrestrial ecotoxicity potential (TETP)). The goal of the study was to determine the environmental critical points in broiler production for each impact category, as well as the contribution of feed and related processes to the environmental burden when compared to transportation, natural gas and electricity consumption, and other chicken house processes.

The results show that feed and related activities were the largest contributors to the environmental burden in the case of 8 out of 11 impact categories (ADPe, AP, EP, GWP, POP, FAETP, HTP, TETP). In fact, animal feeding contributed more than 80% to five of these impact categories (AP, EP, POP, FAETP, and TETP). Natural gas consumption and transportation processes were the main contributing activities for the ADPf and ODP impact categories, whereas electricity consumption was the main contributing activity for MAETP.

Keywords: broiler chicken production, environmental impacts, feed and related processes, life cycle assessment

1. Introduction

Since the 1990s, the number of broiler chickens raised worldwide has doubled. While in 2000 there were 14.4 billion chickens worldwide, in 2019 there were nearly 26 billion. This intensive growth is mostly due to population growth, as chicken meat is a very important and rapidly produced source of protein, thus quickly satisfying consumer demand [1, 2]. Poultry farming and the livestock sector in general are very important for the economy in addition to the food supply. They contribute, for example, to job and income creation, asset savings, economic performance and taxes.

Due to a fast rising population that is expected to reach or possibly exceed 10 billion by 2050, the livestock sector is currently experiencing one of its greatest challenges [3, 4]. Increasing production capacity is not easy, taking into account land and water use restrictions and regulations that limit producers. Thus, in the livestock sector, sustainability is a crucial concern, i.e., how to maximize production without jeopardizing future usage of natural resources while also attempting to meet the nutritional demands of the population and animals [5]. Generally speaking, livestock production systems have a significant impact on the environment and their polluting effects require increasing attention to environmental protection [6]. The sector also has an impact on climate change, nitrogen and

---

* Corresponding author: Nikolett Éva Kiss
Email: kiss.nikolett@agr.unideb.hu

phosphorus cycling, and biodiversity loss due to changes in land use patterns, among others [7-14].

Greenpeace has released a report [15] stating that industrial poultry farming is a major source of ammonia pollution in the air, soil, and water, and urging the European Commission to stop subsidizing giant farms in favor of more sustainable methods and practices. In the poultry industry, efforts are underway to reduce the use of antimicrobials and their environmental impact. But when viewed from the perspective of a holistic approach to health and welfare, it is clear that a comprehensive approach is required to make the poultry industry more sustainable and animal-friendly while maintaining its economic viability.

Animal feed and related operations, according to several authors, are the sector's top emitters, and these activities are the main contributors to the environmental burden. Da Silva et al. [16] who researched a French and a Brazilian broiler chicken farm, agree. Another study conducted by Bengtsson and Seddon [17] in Australia came to the same conclusion: feed production and processing are the major contributors to broiler chicken farming's environmental impact. According to Pelletier's [5] research, feed production accounts for 45 to 82.4% of greenhouse gas emissions in the United States.

Broiler chicken production was dominated by processes related to feed production and emissions from on-farm operations in a research by Gonzalez-Garcia et al. [18] in Portugal.

Life Cycle Assessment (LCA) (ISO 14040:2006) is an environmental management tool for assessing environmental pressures. LCA can help companies and economies to become more sustainable and make better decisions. Because there hasn't been a study on the environmental consequences of broiler chicken farm in Hungary, the environmental impacts of a hungarian farm were analyzed using the LCA in this study.

2. Materials and methods

Based on the ISO14040:2006 the four main steps of the life cycle assessment are the following:

1. Definition of the goal and scope,
2. Life cycle inventory analysis,
3. Life cycle impact assessment,
4. Interpretation of LCA results.

Figure 1 summarizes the relationship between the 4 steps.

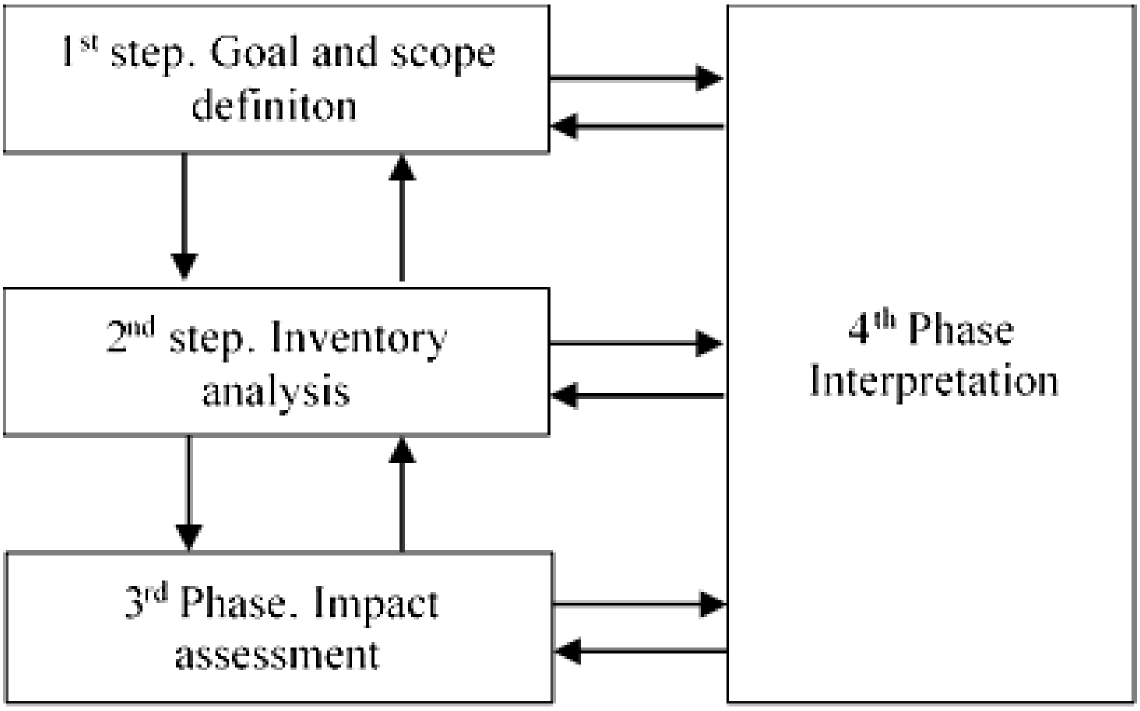

Figure 1. Steps of life cycle assessment (ISO14040:2006)

2.1. Definition of the goal and scope

The first step in a life cycle assessment is to define the goal, the system boundaries and the functional unit. In the current assessment, the goal was to identify the critical points of production in broiler chicken breeding. This life cycle assessment of broiler chicken production considered the production on the farm and the transport of day-old chicks and feed to the farm.

Because the functional unit is 1 tonne live weight of broiler chickens, the results reflect the environmental impact of producing 1 tonne of broiler chicken.

2.2. Life cycle inventory analysis

In intensive poultry production, the flows involved in the process include day-old chicks, feed, drinking water, litter, energy for ventilation and feed distribution, gas for heating. It also includes the amount of water needed to clean the poultry house at the end of the rotation. The input and output material and energy flows involved in broiler chicken production are summarized in Table 1. The data were provided by the company. The analysis was based on the average of 10 winter (October to March) and 9 summer (April to September) rotations.

Table 1. The input and output material and energy flows in broiler chicken production

	winter	summer
Input material and energy flows		
Day-old chicks (pcs)	256 000	256 000
Feed (t)	872.6	1169.4
Vitamins (kg)	98.5	128.0
Water (t)	3 841.5	8 689.4
Litter (t)	24.7	23.9
Electricity (kWh)	39 844.2	66 275.1
Heat, natural gas (m^3)	69 665.0	16 538.8
Output material and energy flows		
Chicken to slaughterhouse (pcs)	244 473.1	243 189.7
Chicken to slaughterhouse (t)	619.41	610.57
Manure (t)	102.1	111.5
Wastewater (t)	102.9	104.0
Emission to air:		
NH_3 (t)	3.77	3.71
CH_4 (t)	0.53	0.52
N_2O (t)	4.04	3.98
NOx (t)	0.04	0.04

2.3. Life cycle impact assessment

In practice, software is used to carry out life cycle assessments. For the current assessment, the OpenLCA software was chosen, as it provides the complete material and energy flows required for all levels of this analysis. The software is free to download and use [19].

The analyses were carried out in the Agribalyse database, which contains a large amount of data for all the necessary analyses [20-22].

In this study, the CML IA baseline impact assessment method was used, which is an internationally accepted and very widely used impact assessment method [23].

The environmental impacts of the production were illustrated with the following impact categories [24, 25]:

1. Abiotic depletion potential for elements (kg Sb-eq) (ADPe): refers to the extent of the use of non-renewable sources and minerals.
2. Abiotic depletion potential for fossil fuels (MJ) (ADPf): shown in megajoules, instead of unit antimony equivalents (kg Sb-eq) of the resource.
3. Acidification potential (kg SO_2-eq) (AP): refers to compounds that cause acid rain (SO_2, NO_x, NO, and N_2O).
4. Eutrophication potential (kg PO_4-eq) (EP): refers to the effects of over-fertilization or an excess supply of nutrients on terrestrial and aquatic environments, with a focus on the two most important nutrients, nitrogen (N) and phosphorus (P).

5. Global warming potential (kg CO_2-eq) (GWP): it is an index improved by the impact of the comparison of different gases on the atmosphere.
6. Ozone layer depletion potential (kg CFC-11-eq) (ODP): to describe the emissions of all ozone-depleting substances the CFC-11 equivalent is used.
7. Photochemical oxidation potential (kg C_2H_4-eq) (POP): describes the ethylene equivalent emissions from photochemical oxidation due to a high NO_x concentration.
8. Fresh water aquatic ecotoxicity potential (kg 1.4-DB-eq) (FAETP): the amount of contaminants in freshwater that have an impact on aquatic life pollution.
9. Human toxicity potential (kg 1.4-DB-eq) (HTP): the maximum concentration of compounds that are hazardous to humans.
10. Marine aquatic ecotoxicity potential (kg 1.4-DB-eq) (MAETP): shows the effects of different chlorine compounds in the atmosphere on marine life and aquatic environments.
11. Terrestrial ecotoxicity potential (kg 1.4-DB-eq) (TETP): shows the impact of various chlorine compounds on the environment and on humans.

2.4. Interpretation of LCA results

The forth phase of the LCA is a systematic technique to identify, quantify, check and evaluate information from the results of the life cycle inventory and the life cycle impact assessment phases. The Results and discussion chapter will explain these findings.

3. Results and discussion

The environmental impact of farming 1 tons live weight of broilers is presented in Table 2, with separate values for summer and winter for each impact category.

The results showed that there was no substantial difference between the environmental pressures in summer and winter for most effect categories (ADPe, AP, EP, POP, HTP, FAETP, MAETP, TETP). The difference in environmental pressures between summer and winter rotations was less than 10% for these impact categories.

Table 2. LCA results of the broiler chicken production

Impact categories	Winter	Summer
ADPe (kg Sb-eq)	0.0046	0.0045
ADPf (MJ)	16 536	13 186
AP (kg SO_2-eq)	15.82	15.47
EP (kg PO_4-eq)	11.76	11.65
GWP (kg CO_2-eq)	2 374	2 132
ODP (kg CFC-11-eq)	0.00019	0.00017
POP (kg C_2H_4-eq)	1.29	1.25
FAETP (kg 1.4-DB-eq)	1 436	1 430
HTP (kg 1.4-DB-eq)	639.9	621.7
MAETP (kg 1.4-DB-eq)	649 257	667 572
TETP (kg 1.4-DB-eq)	520.5	513.2

The largest difference between summer and winter rotations were found in three impact categories: ADPf (20%), GWP (10%), and ODP (10%). Environmental pressures were higher in these impact categories in winter rotations.

Figure 2 shows which processes contribute the most to environmental pressures within each impact category. The contributing operations were divided into five categories: (1) animal feeding, (2) transportation processes, (3) natural gas consumption, (4) electricity consumption, and (5) other processes.

The feed-related operations are the most complexed, extending from the cultivation and processing of feed crops (maize, wheat, soya, rapeseed), to the acquisition and transportation of additional minerals and vitamins, to the final feed mix manufacture in the feed mixing facility. In this study, the transport processes are those other than feeding, which include transporting day-old chicks and feed to the stables. The use of natural gas and electricity in the sheds is mostly for temperature control and feed distribution. And other processes are a category that includes operations like waste management or the use of cleaning and disinfection chemicals that have a minor impact on the impact category or only appear in one or two impact categories.

The feeding processes, which comprised nutrient replenishment, i.e. fertilizers and the raw materials needed to create them, were the most environmentally detrimental operations in the case of ADPe, whether in the case of summer (0.0045 kg Sb-equivalent) or winter (0.0046 kg Sb-equivalent) rotations. Even in the stables, housing-related emissions were high at ADPe, accounting for around 21% of emissions in the winter and roughly 30% in the summer. Gianneas et al. [26] observed 0.0015 kg Sb-equivalent per 1 t live weight of broiler chickens, Lima et al. [27] 8.6*10-5 kg Sb-equivalent, and Ramedani et al. [28] 0.0173 kg Sb-equivalent per 1 t live weight of broiler chickens.

Natural gas usage is the largest contribution to the ADPf. Of course, natural gas heating is more essential in the winter, accounting for around 65 % of emissions in winter rotations and about 35 % in summer rotations. The relatively high natural gas consumption in the summer can also be explained by the fact that the rotations from April to September were taken into account for the summer period, and that the stables had to be heated at the start of the rearing period to reach the optimum temperature in the cooler months. Emissions from transportation activities account for a major portion of ADPf's emissions, around 28%. Feed-related processes account for around 23% of the total ADPf in the summer, but only 3% in the winter. While the ADPf during rotations in the current study was 13 186 MJ in the summer and 16 536 MJ in the winter, Lima et al. [27] computed just 150 MJ and Ramedani et al. [28] already calculated 184 000 MJ per 1 t living weight. Lima et al. [27] conclude that the largest contributors to both ADPe and ADPf impact categories are the energy required to produce feed and the use of fossil fuels and minerals. For ADPe, similar conclusions can be drawn based on the present results, but for ADPf, natural gas consumption and transport processes also played a major role in this research.

The contribution of feed-related processes to the environmental burden was higher than 80% for AP, EP, POP, FAETP and TETP. For AP, feed-related processes accounted for 83 and 81% of the 15.47 (summer) and 15.82 (winter) kg SO2 eq. and transport-related processes for about 12%. The remaining 1% is accounted for by electricity consumption and other operations in summer rotations, while for the winter rotations, the remaining 7% was accounted for by natural gas and electricity consumption and other processes. AP has been studied by several researchers. The values found in the present study were closest to the 15.8 and 17 kg SO_2-equivalents measured by Pelletier [5] and Martinelli et al. [29]. Da Silva et al. [16] compared a French and a Brazilian broiler chicken farm, for the former 28.7 and for the latter

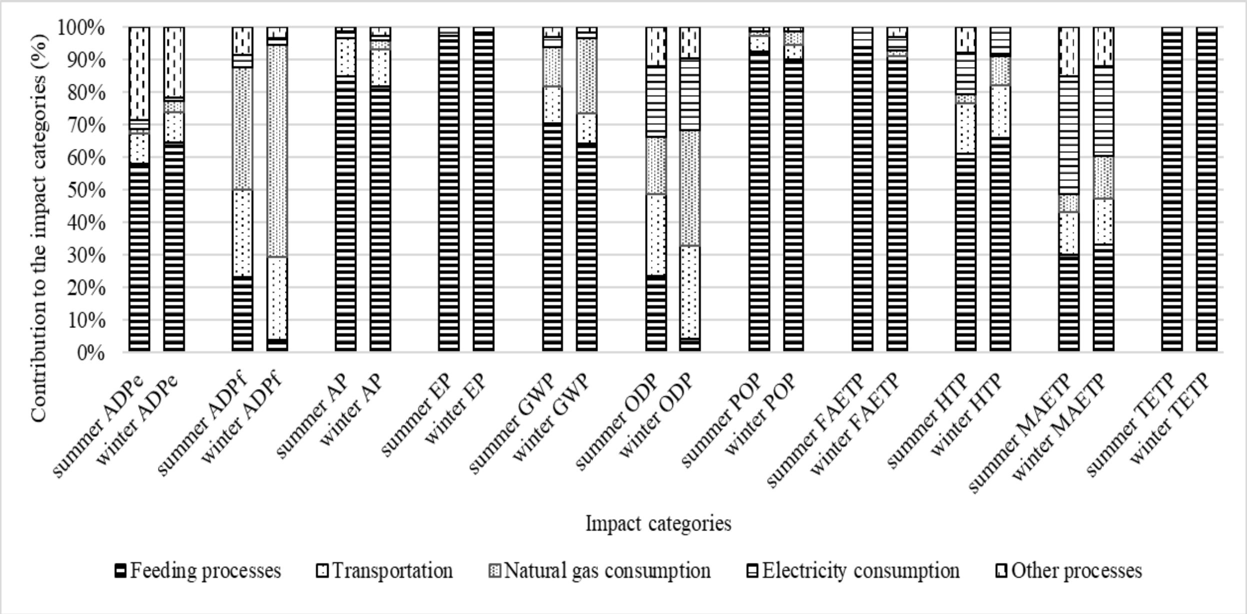

Figure 2. The contribution of processes to the emissions of the broiler chicken sector

31.4 kg SO^2-equivalents were the AP. Kalhor et al. [30] also examined emissions from summer and winter rotations, finding that summer emissions were 29.58 kg SO2-equivalents and winter emissions were 41.75 kg SO2-equivalents. AP ranged from 25.9 to 66.7 kg SO2-equivalent for other authors [26-28, 31-36]. Most researchers have also found that feed-related processes, as well as obsolete waste management technology, are the leading causes of AP.

Regardless of the period, EP's environmental impact is almost entirely reflected by feed-related processes. While EP was 11.65 kg PO_4-equivalents in summer and 15.82 kg PO4-equivalents in winter rotations in this study, these two values were 11.02 and 14.69 kg PO_4-equivalents in a similar comparison by Kalhor et al. [30]. In a comparison of French and Brazilian colonies, Da Silva et al. [16] reported values ranging from 13.8 to 19.3 kg PO_4-equivalents. Among the authors already mentioned, the lowest eutrophication potential was observed by Pelletier [5], who measured 3.9 kg PO_4-equivalents in the USA, while the highest was recorded by Ramedani et al. [28], with 78.4 kg PO_4-equivalents.

For both POP and FAETP, the contribution of feeding processes is around 90%.

The remaining 10% or so for POPs were accounted for by transport processes and natural gas consumption, and for FAETP by electricity consumption and, in winter, natural gas consumption. The 1.25 kg C_2H_4-equivalent in summer and 1.29 kg C_2H_4-equivalent in winter at POP are similar to the 1.237 and 1.34 kg C_2H_4-equivalent measured by Payandeh et al. [34] and Lima et al. [27], respectively.

Feed-related processes are responsible for over 70% of the estimated GWP in the summer and 63 percent in the winter. The remaining emissions are largely linked to natural gas usage and transportation, with electricity consumption and the other processes coming in second and third. The most researched impact category is GWP, which has a wide range of recorded values in CO2 equivalents. While the current analysis predicted 2132 kg CO_2-equivalent emissions in the summer and 2374 kg CO_2-equivalent emissions in the winter, GWPs determined by various authors range from 1395 kg to 5782 kg CO_2-equivalent per 1 ton of live weight (Table 3).

Table 3. GWP values of broiler chicken production in other life cycle assessment studies

GWP value (kg CO_2-eq.)	References
1395	Pelletier [5]
1450 – 2700	Da Silva et al. [16]
4210	Giannenas et al. [26]
2700	Lima et al. [27]
4350	Ramedani et al. [28]
1488	Martinelli et al. [29]
1390 – 2932	Kalhor et al. [30]
2079	Katajajuuri et al. [31]
1800	Williams et al. [32]
3087	Leinonen et al. [33]
5782	Payandeh et al. [34]
1226	Putman et al. [35]

The majority of researchers concluded in GWP that feed-related procedures and outmoded manure management methods are the main contributions to emissions from broiler production. The lower emissions in this study could be explained by the farm's technology, which includes modern manure removal system, optimized ventilation, and covered manure storage.

TETP is entirely contributed by processes related to animal nutrition, including land use and crop production. The summer and winter results of 513.2 and 520.5 kg 1,4-DB-equivalents, respectively, are close to the 598 kg 1,4-DB equivalents measured by Ramedani et al. [28]. Lima et al. [27] found a 1,4-DB equivalent of 800 kg, and Payandeh et al. [34] found a very high value of 1952.126 kg 1,4-DB equivalent.

For ODP, the contribution of forage is not significant in winter, around 4%, and around 23% in summer. Natural gas usage is the most important factor in the winter, followed by emissions from transportation processes, electricity consumption, and other processes. In the summer, transportation processes contribute about the same to environmental burden as feed-related emissions, followed by electricity and natural gas usage, and other processes. The ODP values determined by different authors also differ significantly. For all summer and winter rotations, Kalhor et al. [30] recorded 0.001 kg CFC-11-equivalents, Lima et al. [27] measured 9.6*10-7 kg CFC-11-equivalents, and Ramedani et al. [28] discovered 0.00204 kg CFC-11-equivalents.

Feeding accounts for around half of the HTP, with the remaining half accounted for by transportation, electricity consumption, the use of cleaning and disinfecting agents, and other processes, i.e. processes associated to agricultural activities. The summer 1,4-DB-equivalent of 621.7 kg and 639.9 kg in winter measured in the present study is close to the summer 1,4-DB-equivalent of 655.33 kg measured by Kalhor et al. [30]. For the winter rotation, the authors measured already 996.36 kg 1,4-DB-equivalent. Other authors have reported HTP of around 1080 and 6300 kg 1,4-DB-equivalents [27-28].

In addition to the ADPf and ODP impact categories, MAETP is the third impact category where non-feeding processes are the largest contributors to environmental pressures.

Electricity consumption is the most significant contributor to MAETP, accounting for roughly 37% in the summer and 28% in the winter. Feeding accounts for roughly the same percentage of the environmental load as transportation and other operations, with natural gas consumption coming in last. The MAETP has been estimated by other authors to be between 100440 and 955000 kg 1,4-DB-equivalents [27-28,30], compared to this study's values of 667572 (summer) and 649257 (winter) kg 1,4-DB-equivalents.

4. Conclusions

The goal of this study was to determine the environmental critical points in broiler chicken production, with a particular focus on the environmental impact of the feeding operations.

Feed-related operations, transportation processes, electricity consumption, natural gas consumption, and other processes were the five categories in which the processes that contribute the most to emissions are classified. The results reveal that feeding and related processes contribute to the greatest extent for 8 of the 11 effect categories (ADPe, AP, EP, GWP, POP, FAETP, HTP, TETP) to the environmental burden. Animal feeding produces more than 80% of the environmental burden in the AP, EP, POP, FAETP, and TETP impact categories, while it contributes more than 60% in the most often used environmental indicator, GWP.

To reduce the environmental impact and make farming as sustainable as possible, fertilizer use and pesticides need to be reduced, but emissions would be significantly improved also if more modern machinery and equipment were used for field operations. Of course, the installation of modern technologies and the creation of state-of-the-art infrastructure is very costly and, in most cases, can only be financed through grant aid. Another solution could be the introduction of reduced tillage systems and the use of single-tillage operations, which would reduce the use of fossil fuels and greenhouse gas emissions.

Acknowledgements

This research was supported by EU grant to Hungary GINOP 2.2.1.-15-2017-00043.

Project no. TKP2021-NKTA-32 has been implemented with the support provided from the National Research, Development and Innovation Fund of Hungary, financed under the TKP2021-NKTA funding scheme.

References

1. Chia, S.Y., Tanga, C. M., Van Loon, J. J., Dicke, M., Insects for sustainable animal feed: inclusive business models involving smallholder farmers, Current Opinion in Environmental Sustainability, 2019, 41, 23-30. 2. Nalunga, A., Komakech, A.J., Jjagwe, J., Magala, H., Lederer, J., Growth characteristics and meat quality of broiler chickens fed earthworm meal from Eudrilus eugeniae as a protein source, Livestock Science, 2021, 245, 104394.

3. Lutz, W., Samir, K. C., Dimensions of global population projections: what do we know about future population trends and structures? Philosophical Transactions of the Roya Society B., 2010, 27, 365, 2779-2791.

4. https://sdg.iisd.org/news/world-population-to-reach-9-9-billion-by-2050/

5. Pelletier, N., Tyedmers, P., Forecasting potential global environmental costs of livestock production 2000–2050, Proceedings of the National Academy of Sciences of the United States of America, 2010, 107, 43, 18371-8374.

6. Starme, E., Environmental and Health Problems in Livestock Production: Pollution in the Food System, American Journal of Public Health, 2011, 94, 10, 1703-09.

7.Sala, O.E., Human-induced perturbations on biodiversity. In: Mooney, H. A., Cushman, J. H., Medina, E., Sala, O. E.: Biodiversity and ecosystem function: Basic principles. In: Heywood, V. H.: Global biodiversity assessment. Cambridge University Press. Section 5, 1995.

8. Tilman, D., Fargione, J., Wolff, B., D'Antonio, C., Dobson, A., Howarth, R., Schindler, D., Schlesinger, W. H., Simberloff, D., Swackhamer, D., Forecasting Agriculturally Driven Global Environmental Change, Science (Washington), 2001, 292, 281-284.

9. Margulis, S., Causes of Deforestation of the Brazilian Rainforest. Washington: World Bank Publications, 2003.

10. Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Avery, K. B., Tignor, M., Miller, H. L., Couplings Between Changes in the Climate System and Biogeochemistry. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, 2007.

11. Rockstrom, J., Steffen, W., Noone, K., Persson, A., Chapin, F. S., Lambin, E. F., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H. J., Nykvist, B., De Wit, C. A., Hughes, T., Van Der Leeuw, S., Rodhe, H., Sorlin, S., Snyder, P. K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R. W., Fabry, V. J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., Foley, J. A., A safe operatingspace for humanity, Nature, 2009, 461, 472-475.

12. Arima, E. Y., Richards, P., Walker, R., Caldas, M.M., Statistical confirmation of indirect land use change in the Brazilian Amazon, Environmental Research Letters, 2011, 6, 10-17.

13. Carpenter, S.R., Bennett, E.M., Reconsideration of the planetary boundary for phosphorus. Environmental Research Letters, 2011,

14. Bellarby, J., Tirado, R., Leip, A., Weiss, F., Lesschen, J. P., Smith, P., Livestock greenhouse gas emissions and mitigation potential in Europe, Global Change Biology, 2012, 19, 1, 3-18.

15.https://www.greenpeace.org/static/planet4-international-stateless/2018/03/698c4c4a-summary_greenpeace-livestock-vision-towards-2050.pdf

16. Da Silva, P. V., Van Der Werf, H. M. G., Soares, S. R., Corson, M. S., Environmental impacts of French and Brazilian broiler chicken production scenarios: An LCA approach, Journal of Environmental Management, 2014, 133, 222–231.

17. Bengtsson, J., Seddon, J., 2013, Cradle to retailer or quick service restaurant gate life cycle assessment of chicken products in Australia, Journal of Cleaner Production, 2013, 41, 291–300.

18. González-García, S., Belo, S., Dias, A. C., Rodrigues, J. V., Da Costa, R. R., Ferreira, A., De Andrade, L. P., Arroja, L., Life cycle assessment of pigmeat production: Portuguese case studyand proposal of improvement options, Journal of Cleaner Production, 2015, 100, 126-139.

19. HOSOYA & CO. (1996): Hosoya Manure Fermentation System. Hoyosa & Co., 412 Fukaya, Ayase-Shi, Kanagawa-ken 252, Japan. http://www.k-hosoya.co.jp/en/product/

20. Colomb, V., Amar, S. A., Mens, C. B., Gac, A., Gaillard, G., Koch, P., Mousset, J., Salou, T., Tailleur, A., Van Der Werf, H. M. G., AGRIBALYSE®, the French LCI Database for agricultural products: high quality data for producers and environmental labelling, Oilseeds and fats, Crops and Lipids, 2015, 22.

21. Salou, T., AGRIBALYSE®: Methodology, Agricultural stage – Version 3.0. Ed ADAME, Angers, France, 2020.

22. Asselin-Balençon, A., Broekema, R., Teulon, H., Gastaldi, G., Houssier, J., Moutia, A., Rousseau, V., Wermeille, A., Colomb, V., AGRIBALYSE v3.0: the French agricultural and food LCI database. Methodology for the food products. Ed. ADEME, 2020.

23. Gabathuler, H., The CML Story: How Environmental Sciences Entered the Debate on LCA. The International Journal of Life Cycle Assessment, 2006, 11, 127-132. 1

24. Guinée, J. B., Gorree, M., Heijungs, R., Huppes, G., Renekleijn – De Koning, A., Van Oers, L., Sleeswijk, A. W., Suh, S., Udo De Haes, H.A., De Bruijn, H., Van duin, R., Huijbregts, M. A. J., Lindeijer, E., Roorda, A. A. H., Van Der Ven, B. L., Weidema, B. P., Handbook on Life Cycle Assessment - Operational Guide to the ISO Standards. Kluwer Academic Publisher, New York, Boston, Dordrecht, London, Moscow, 2002.

25. Geyer, R., Kuczenski, B., Zink, T., Henderson, A., Common misconceptions about recycling, Journal of Industrial Ecology, 2015, 20, 5, 1010–1017.

26. Giannenas, I., Bonos, E., Anestis, V., Filioussis, G., Papanastasiou, D. K., Bartzanas, T., Papaioannou, N., Tzora, A., Skoufos, I., Effects of Protease Addition and Replacement of Soybean Meal by Corn Gluten Meal on the Growth of Broilers and on the Environmental Performances of a Broiler Production System in Greece. PLoS ONE, 2017, 12, 1, e0169511.

27. Lima, N. D. D. S., Nääs, I. D. A., Garcia, R. G., De Moura, D. J., Environmental impact of Brazilian broiler production process: Evaluation using life cycle assessment, Journal of Cleaner Production, 2019, 117752.

28. Ramedani, Z., Alimohammadian, L., Kheialipour, K., Delpisheh, P., Abbasi, Z., Comparing energy state

and environmental impacts in ostrich and chicken production systems, Environmental Science and Pollution Research, 2019, 26, 27, 28284-293.

29. Martinelli, G.d.C., Vogel, E., Decian, M., Farinha, M. J. U. S., Assessing the eco-efficiency of different poltry systems: an approach using life cycle assessment and economic value added, Sustainable Production and Consumption, 2020, 24, 181-193.

30. Kalhor, T., Rajabipour, A., Akram, A., Sharifi, M., Environmental impact assessment of chicken meat production using life cycle assessment, Information Processing in Agriculture, 2016, 3, 4.

31. Katajajuuri, J.M., Grönroos, J., Usva, K., Environmental impacts and related improvement options of supply chain of chicken meat. 6th International Conference on LCA in the Agri-food Sector. Zürich, Switzerland, 2008.

32. Williams, A.G., Audsley, E., Sandars, D.L., A lifecycle approach to reducing the environmental impacts of poultry production. 17th European Symposium on Poultry Nutrition. Edinburgh, UK, 2009.https://www.cabdirect.org/cabdirect/abstract/20103247175

33. Leinonen, I., Williams, A. G., Wiseman, J., Guy, J., Kyriazakis, I., Predicting the environmental impacts of chicken systems in the United Kingdom through a life cycle assessment: Broiler production systems, Poutlry Sciences, 2012, 91, 8-25.

34. Payandeh, Z., Kheiralipour, K., Karimi, M., Khoshnevisan, B., Joint data envelopment analysis and life cycle assessment for environmental impact reduction in broiler production systems, Energy, 2017, 127, 768–774.

35. Putman, B., Thoma, G., Burek, J., Matlock, M., A retrospective analysis of the United States poultry industry: 1965 compared with 2010. Agricultural Systems, 2017, 157, 107–117.

36. Impacts of poultry production. 17th European Symposium on Poultry Nutrition. Edinburgh, UK, 2009.

37. Leinonen, I., Williams, A. G., Wiseman, J., Guy, J., Kyriazakis, I., Predicting the environmental impacts of chicken systems in the United Kingdom through a life cycle assessment: Broiler production systems. Poutlry Sciences, 2012, 91, 8-25.

38. Payandeh, Z., Kheiralipour, K., Karimi, M., Khoshnevisan, B., Joint data envelopment analysis and life cycle assessment for environmental impact reduction in broiler production systems, Energy, 2017, 127, 768–774.

39. Putman, B., Thoma, G., Burek, J., Matlock, M., A retrospective analysis of the United States poultry industry: 1965 compared with 2010. Agricultural Systems, 2017, 157, 107–117.