BURLEIGH DODDS SERIES IN AGRICULTURAL SCIENCE

Improving poultry meat safety and sustainability

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E-CHAPTER FROM THIS BOOK

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SCIENCE PUBLISHING

Life cycle assessment (LCA) of poultry meat production

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1 Introduction

Livestock farming has been recognized as producing significant environmental impacts. These include a significant role in global warming through greenhouse gas (GHG) emissions, substantial resource utilization, including land use change, nutrient leakage, water use and impacts on biodiversity (Steinfeld et al. 2006, FAO 2006, 2020, Gerber et al. 2013). Emissions and impacts from agriculture arise from diverse direct and indirect sources and can be challenging to address effectively. For instance, ruminant production generates substantial direct methane emissions (via enteric fermentation) and necessitates vast areas of grazing land which then contribute to global warming via deforestation.

Non-ruminant systems, like poultry and pig production, also have their own environmental issues. In general, poultry production has been suggested to be more environmentally sustainable than many other livestock systems, according to assessments based on several environmental indicators (Williams et al. 2006; de Vries and de Boer 2010). Nonetheless, challenges concerning environmental sustainability also persist within non-ruminant systems (Eriksson

http://dx.doi.org/10.19103/AS.2024.0146.16

Chapter taken from: Ricke, S. C. (ed.), Improving poultry meat safety and sustainability, Burleigh Dodds Science Publishing, Cambridge, UK, 2025, (ISBN: 978 1 80146 789 6; www.bdspublishing.com)

et al. 2005, van der Werf et al. 2005; Pelletier 2008). These systems rely heavily on external feed production, especially protein sources like soya, the production of which is limited to specific regions and has its own environmental impacts. Some regions producing soya and other feeds are linked to land use changes, such as deforestation, which strongly contribute to global greenhouse gas emissions (Opio et al. 2013) and biodiversity loss (Kyttä et al. 2023). Additionally, poultry systems, in particular, exhibit distinctive characteristics requiring attention in terms of their environmental impacts, including nitrogen emissions, most notably the emissions of ammonia to the air, nitrous oxide emissions contributing to global warming, and nitrate leaching leading to eutrophication (Usva et al. 2023).

A fundamental prerequisite for enhancing the environmental sustainability of poultry production is the availability of systematic tools capable of comprehensively quantifying the range of environmental impacts originating from the production chain. Such tools should also be capable of pinpointing potential areas for improvement. Currently, the consensus leans toward the use of a method known as life cycle assessment (LCA) for quantifying the environmental impacts in agricultural production systems (MacLeod et al. 2013, FAO 2016). In this context, recent studies on the environmental sustainability of poultry production are reviewed here, focusing on those applying the LCA framework to demonstrate the contributions of different subsystems of poultry production (feed production, emissions from housing, breeding activities, etc.) to overall environmental impacts. These studies also suggest measures that could make poultry production more ecologically sustainable.

2 Background and principles of the life cycle assessment framework

The overall environmental sustainability of agricultural production is a result of a combination of direct and indirect environmental impacts. Direct emissions include so-called Scope 1 and Scope 2 greenhouse gas (GHG) emissions defined by the Greenhous Gas Protocol, the most widely accepted accounting standards for GHG emissions (https://ghgprotocol.org/). These might include reducing energy consumption on farms or reducing other emissions directly released from the farms to the environment, such as ammonia and methane from animal housing or fields (MacLeod 2013, Leinonen et al. 2014, FAO 2016).

However, a substantial proportion of the overall environmental impacts related to livestock production are actually produced by indirect activities (including so-called Scope 3 GHGs). For instance, producing feed for animals requires cultivation of feed crops. This process generates emissions for example through energy consumption of field operations, the use of fertilizers, and energy consumption in production of those fertilizers. Additional emissions are generated by processing and blending feed ingredients, and transporting them, sometimes across considerable distances (Hietala et al. 2023, Usva et al. 2023).

Moreover, the environmental impacts arising from both direct and indirect sources can lead to complex interactions. Enhancing the environmental sustainability of one sub-system of production might inadvertently result in detrimental indirect consequences on other links within the production chain. Furthermore, certain actions in livestock production can simultaneously yield environmental benefits and drawbacks. For instance, altering the composition of livestock feed simultaneously impacts nutrient emissions from manure and the environmental impacts connected to feed production, but can also have impact on animal performance and production efficiency (Huuskonen et al. 2023). Furthermore, employing livestock manure as fertilizer could mitigate the environmental impacts linked to manufacturing fertilizers, yet it could simultaneously elevate nutrient leaching and emissions into the atmosphere.

Navigating such intricate interactions and trade-offs demands a systematic, quantitative, and comprehensive approach to assess environmental impacts within agricultural systems. In recent times, system-based LCA models have been designed specifically for agricultural production (Williams et al. 2010, Leinonen et al. 2012a, 2012b, 2016, Hietala et al. 2023, Usva et al. 2023). Following the general principles of LCA modelling (BSI 2006), these methods encompass all environmental burdens across the production cycle, from raw material extraction to final products. However, a distinctive aspect of this systems-based methodology is its fusion of structural models of agricultural industries with crop and livestock production models, which sometimes can be based on rather complex, process-based approaches. This fusion is designed to effectively manage interactions between different subsystems. Within the systems models, quantities of inputs and outputs are intricately connected to other subsystems. For instance, producing a certain quantity of broiler meat requires a defined number of living animals which, in turn, necessitates a specific number of parent birds and a certain amount of feed and other inputs to production. All these interactions need to be quantified through model calculations.

As an outcome, an LCA model typically assesses emissions into the environment, together with the consumption of resources, and quantifies them in relation to a specifically selected “functional unit.” The determination of the functional unit is dependent on the intended use of the assessment, and it is especially critical for achieving comparability between different products or services being analyzed. For example, if the aim is to compare one broiler meat production system to another broiler system, the functional unit can be simply ‘1 kg of broiler meat delivered to consumer’. However, especially in food production systems, mass- or volume-based functional units rarely provide sufficient comparability between food products, the actual functioning of which can strongly differ from each other. For example, it is not meaningful to compare 1 kg broiler meat to 1 kg of milk or 1 kg of bread, as the nutritional composition and intended use of these quantities differ strongly from each other.

In food products, therefore, it would be useful to specify the function of different items, for example based on their nutritional properties. As an example, the concentration and quality of protein has been used for formulation of so called "nutritional functional units" for food products (e.g. McAuliffe et al. 2023). However, challenges arise in creating an indicator covering comprehensively the nutritional values of a product and therefore these kinds of LCA studies are still rare (McLaren et al. 2021).

3 LCA environmental impact categories

When all the resources use and material flows (including emissions to the environment) related to the production system have been quantified, they can be aggregated into environmentally functional impact categories (e.g., Guinée et al. 2002, Leinonen et al. 2012a, Hietala et al. 2021, 2023, Usva et al. 2023). Several impact assessment methods exist to define the mathematical formulas used to produce the result of the impact category indicator from the input data, e.g. ReCiPe (Huijbregts et al. 2016) and IMPACT World+ (Bulle et al. 2019). There are two types of indicators: midpoint indicators measure the potential impact on certain environmental problem (e.g. climate change) and endpoint indicators measure the overall impact on certain area of protection summing up several midpoint indicators.

Probably the most widely used environmental impact category is the global warming potential (GWP), or "carbon footprint.". This indicator measures the climate change impact in terms of greenhouse gas emissions released into the atmosphere, and technically should also quantify the amount of greenhouses gases possibly removed from the atmosphere. Key sources of these emissions in poultry production include:

- carbon dioxide (CO_2) from fossil fuels and land use change (LUC)
- nitrous oxide (N_2O), and methane (CH_4) from feed crop production and animal farming

In LCA models, the partial losses of ecosystem carbon storage resulting from land use conversion must be included in CO_2 emissions (so called Land Use and Land Use Change, or LULUC emissions), thereby affecting the global warming potential of the system (IPCC 2006, BSI 2011).

Eutrophication potential is a metric used to evaluate the excessive supply of nutrients, often termed as unnatural fertilization, which occurs when

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these nutrients find their way into water systems through leaching, run-off, or atmospheric deposition. The main contributors to this potential are the leaching of nitrate (NO^{3-}) and phosphate (PO_4^{3-}) into water bodies, as well as the emission of ammonia (NH_3) into the air. The eutrophication potential is sometimes divided to marine eutrophication, which is driven by nitrogen, and freshwater eutrophication, which is driven by phosphorus.

Acidification potential predominantly serves as an indicator of the potential decline in soil pH. The primary sources of this potential include ammonia emissions and sulfur dioxide (SO_2) stemming from the combustion of fossil fuels. Furthermore, in poultry production ammonia (NH_3) is also a significant source of acidification.

In addition to assessing emissions into the environment, LCA can gauge the utilization of various resources linked to the production of the specific functional unit under examination. These resources encompass elements like primary energy consumption, water usage, and land occupation. These factors are quantified in terms of the cumulative utilization of resources, including diverse energy sources (which include also the energy necessary for their extraction and distribution), such as gas, oil, coal, nuclear, and renewable energy.

Similarly, resource consumption can also be measured in terms of fresh water withdrawn by humans. Water scarcity impact is used to assess the contribution of water consumption in the product chain to the local water scarcity. The indicator (Boulay et al. 2018) refers to the share of the consumed water to the local freshwater resource after the necessary water needs of ecosystems and humans are fulfilled.

Land occupation describes the area of the land required to produce a unit of the product. In the case of poultry production, this mainly consists of the arable land for producing crops for feed. Closely related to land occupation is also the impact on biodiversity. In addition to the area of occupied land, this indicator can also take into account the land use changes and the location, type, and management of the occupied land (Kyttä et al. 2023).

4 Assessing the environmental impacts of different stages of the poultry production chain

The type and the magnitude of environmental impacts of poultry meat products differ between the life cycle stages. These separate stages include for example production of animal feed and other inputs to poultry system, animal farming, slaughtering and manufacturing the products, logistics, and consumer's actions. Systems-based LCA models for poultry production chains have been applied by several authors, to understand the magnitude of environmental impacts of the overall production systems and specifically the impacts of these different stages

(Costantini et al. 2021, Martinelli et al. 2020, Skunca et al. 2018, Gonzáles-García et al. 2014, Cesari et al. 2017, Prudêncio da Silva et al. 2014, Leinonen et al. 2012a, b). These studies have also given insight into the possibilities of improving the environmental sustainability in the entire poultry production chain.

By far the biggest direct impacts within the production cycle of poultry meat are related to primary production, i.e. production of feed and animal farming. Probably the most comprehensive, national scale study in this area was produced recently by Usva et al. (2023), who published an LCA study on Finnish broiler meat with detailed production data provided by the poultry industry and individual farms, covering almost 90% of broiler chicken production in Finland. The research focused on the animal farming and feed production stages of the Finnish broiler production chain and studied climate and water scarcity impacts.

Even though the direct impacts of slaughtering and meat processing, mainly arising from energy and water consumption, are relatively small (e.g. Costantini et al. 2021), the efficiency of the material flow in terms of utilized portion of the bird's live weight determines the number of birds needed to produce the required amount of meat and, therefore, also the quantities of inputs and emissions related to production. The yield of meat is affected both by the slaughtering process and by the genetics of the bird and by farming practices like the slaughtering age.

In addition to the various stages of production of poultry meat, the use (consumption) stage also has both direct and indirect impacts on the sustainability of poultry systems. Whether poultry meat is consumed in the restaurant or at home affects impacts from activities such as cooking, cleaning, and the logistics related to purchasing. However, in terms of environmental impacts, the relative share of these actions is low compared to the production of meat. Furthermore, consumer actions hardly ever focus solely on any specific food item such as poultry meat since, in most cases, meals consist of several food items. Any environmental assessment of human food consumption should therefore focus on the meal or on diet, rather than looking at single food ingredients alone. In general, although the use stage produces relatively low direct emissions, aggregate consumer choices have a major global environmental impact (e.g. for higher meat consumption) as well as the proportion of total food produced food that is actually consumed relative to the proportion wasted (given that the retail and consumption stages in agrifood supply chains can be responsible for up to 30% of food produced being wasted). It should be kept in mind therefore that the demand and preferences of consumers have a significant impact on overall food production chains, including the production of poultry meat.

4.1 The environmental impacts of feed production

When considering primary production, the findings of e.g. Usva et al. (2023) and Leinonen et al. (2012a, 2012b) found that, in all broiler production systems, feed production is the primary component responsible for several environmental impact categories, including global warming, eutrophication, acidification and water scarcity potentials. Feed production encompasses activities such as cultivating feed crops and processing and transporting ingredients and feed. In intensive broiler production systems in Finland, the contribution of feed production without land use change accounted for over 70% of the climate emissions of primary production, and this figure was nearly 80% when land use change was included (Usva et al. 2023). This is consistent with other recent studies. According to previous research, the significant role of feed in the climate change impact of broiler meat has been demonstrated by e.g. Martinelli et al. (2020), Skunca et al. (2018), Cesari et al. (2017), Kalhor et al. (2016), Prudêncio da Silva et al. (2014), González-García et al. (2014), Leinonen et al. (2012a), and Pelletier (2008).

The GHG emissions arising from poultry feed production originate mainly from the use of fossil energy in fertilizer manufacturing, consumption of fossil fuels in field operations in crop cultivation (e.g. from operating equipment such as tractors), direct (mainly nitrogen) emissions from fertilizer application and, to a smaller extent, transport and processing of feed (Leinonen et al. 2012a, 2012b, Hietala et al. 2023, Usva et al. 2023). In addition to direct and indirect N_2O emissions resulting from the cultivation of feed crops (significantly contributing to the global warming potential), nutrient leaching also affects the eutrophication potential (Leinonen et al. 2012a, 2012b; Hietala et al. 2022a).

Land use change (LUC) and related GHG emissions are strongly associated with feed production, and especially with the production of soya and palm oil in South America and South Asia (Leinonen et al. 2012a, 2012b, 2013).The magnitude of the climate change impact due to land use change depends on the diet of poultry and origin of the feeds, and can be significant. For example, LUC emissions account for 23% of all climate change impacts of primary production of Finnish broiler meat (Usva et al. 2023). Within the LCA framework, LUC emissions are generally considered an important indicator to include when assessing the climate change impacts of livestock production, and they are also included in commonly applied LCA guidelines such as the European Commission Product Environmental Footprint (PEF) framework (European Commission 2021). In addition to CO_2 emissions arising from the land use and management changes, it would be also possible to take into account the carbon sequestration (negative CO_2 emissions) obtained, for example as a result of improved farming practices. However, due to uncertainties associated with the method and the lack of data on the assessment of such LUC effects, carbon uptake is often recommended to be reported separately (e.g. European Commission 2021).

The loss of biodiversity associated with diets consumed in Finland was studied by Kyttä et al. (2023). Their main conclusion was that the majority of the biodiversity impacts arose from land-use change. Poultry has a relatively high biodiversity impact due to the consumption of soy feed and, for this reason, broiler meat was found to be one of the most significant drivers of biodiversity loss associated with food consumption in Finland (Kyttä et al. 2023).

4.2 The environmental impacts of poultry farming

In addition to the emissions related to feed production, other significant environmental impacts arise from animal farming and its inputs, including production of chicks, manure management at farms, and the consumption of other inputs such as energy and water on farms. These other sources account for about 20% of the climate and water scarcity impacts represented by each slaughtered broiler, when looking at broiler meat production chain from cradle to slaughterhouse in Finland (Usva 2023).

Direct emissions resulting from housing and manure management play a role in contributing to both eutrophication potential and acidification potential in broiler production systems (Leinonen et al. 2012a, 2012b). The primary factor behind this impact is the release of ammonia, which contributes to both eutrophication and acidification potentials. Additionally, nitrate leaching following land application affects eutrophication potential. Furthermore, housing and manure management also contribute to the global warming potential, primarily due to direct and indirect nitrous oxide emissions. However, the share of manure management in broiler production is less than 10% of the overall global warming potential (Usva et al. 2023). According to recent studies, this is smaller share than, for example, in beef or pork production (13–15% for beef and 17% for pork, Hietala et al. 2021, Hietala, Submitted) due to overall efficiency of intensive broiler production and relatively low amount of excreted nitrogen compared to the amount of meat produced. Improved feed efficiency as a result of breeding has reduced the amount of nitrogen excreted by the birds and, over decades, this has reduced the global warming, eutrophication and acidification caused by poultry production. This aspect is further discussed below.

Despite the substantial emissions, poultry manure offers some environmental benefits. When used in agricultural crop production, it can replace a portion of manufactured fertilizers, thereby partially offsetting the greenhouse gas emissions resulting from poultry production (Leinonen et al. 2012a, 2012b).

Farm energy consumption is often considered a key target in reducing the overall environmental impact of poultry meat production. Historically, it made a significant contribution to the GHG emissions related to poultry production. (Leinonen et al. 2012a). However, over the last decades, the energy efficiency of poultry farming has increased considerably. In addition, the electricity used (especially for ventilation, lighting and feeding in broiler farms) is becoming progressively "greener" in some countries. As a result, the contribution of direct farm energy use is currently very small in many countries compared to other components of the environmental impacts of poultry production. As an example, in Finland energy use at farm level was less than 4% of overall emissions, mainly because of the overall shift to renewable energy sources in Finland (Usva et al. 2023). In the case of eutrophication and acidification potential or water scarcity, the contribution of farm energy is even lower.

Water is consumed at poultry farms for both drinking and washing. This direct water consumption is the most visible part of the total water consumption, but it contributes only to about 2% to the total water scarcity impact of poultry production (Usva et al. 2023), with the major contribution to the water scarcity arising from feed production. The magnitude of the water scarcity impact depends strongly on the region where the water is withdrawn and what the water availability is in that location. This means that there is huge variation in the magnitude of the water scarcity impact in poultry production systems all over the globe due to local conditions both at poultry farms and the sites of feed crop cultivation. The volume of irrigation water used for feed crop production can be high. However, in the Finnish broiler production system, e.g. most locally produced feeds originate from the rain-fed cultivation systems (Usva et al. 2023). As an example, even though the share of imported, irrigated maize is less than 2% in an average diet for broilers in Finland, the contribution of maize to the total water scarcity impact of an average industrial feed mixture is about 15% (Usva et al. 2023). This example illustrates the significance of the cultivation system in terms of the water scarcity impact.

4.3 Comparing intensive and extensive systems

The intensity of the production has also a major role in environmental sustainability. Leinonen et al. (2012a, 2012b) conducted a comparative analysis of different broiler production systems, which included intensive indoor production, free-range, and organic production. Their findings revealed that the variations in environmental impacts were largely associated with the resource efficiency of each system. The study observed a consistent trend: less intensive poultry systems tended to have higher environmental impacts than more intensive systems, though there was significant variation between farms within each system (Leinonen et al. 2012a, 2012b). These differences were largely associated with the differences in the bird genotypes, their growth rate and associated feed efficiency. This is further discussed in Section 5.

The lower efficiency of organic systems, both in the production of organic feed crops and in animal production itself (feed efficiency), is a significant factor affecting the differences between the organic and conventional poultry systems. For example, it was found that the energy use in organic arable farming is 10–30% and in organic vegetable farming 40–50% higher than in their respective conventional counterparts. Therefore, the GHG emissions in organic arable and vegetable farming were estimated to be 0–15% and 35–40% higher, respectively (Bos et al. 2014).

However, it is essential to acknowledge that the relatively low productivity and high emissions of organic and other extensive systems can be partially offset by the lower input of resources required for these systems, including for example fertilizer inputs to organic feed crop production. While studies like Leinonen et al. (2012a, 2012b) have reported higher acidification potential and eutrophication potential in organic poultry systems compared to other systems, contradictory results have also been observed. Some studies indicate that extensive forms of livestock production can reduce the use of fossil fuels, fertilizers, and other inputs (Haas et al. 2001, Basset-Mens et al. 2009, Boggia et al. 2010) or have lower emissions from housing (Dekker et al. 2011). Additionally, organic production's requirement for certified feed sources allows for the avoidance of crops from "unsustainable" origins, thus potentially partially reducing GHG emissions related to direct land use change (LUC) and, consequently, the global warming potential.

5 Options to improve the environmental sustainability of poultry production

Given the importance of its range of environmental impacts, this section focuses first on improvements relating to the role of feed in poultry production. It then looks at ways of addressing non feed-related environmental impacts.

5.1 Addressing feed-related environmental impacts

As discussed in the above section, the direct influence of feed consumption per unit of produced poultry meat dominates overall environmental impacts across different poultry systems (Leinonen et al. 2012a, 2012b, 2016, Williams et al. 2006, Usva et al. 2023), and therefore, feed-related activities should also be the primary target in improving the environmental sustainability of broiler production. The significance of enhancing feed efficiency becomes evident, as this single component holds the potential to notably decrease GHG emissions attributed to poultry production; the processes related to feed production itself also offer further opportunities for reducing impacts.

As discussed above, the majority of the feed-related GHG emissions are related to the cultivation, processing and transportation of feed (Hietala et al. 2022a, Usva et al. 2023). Amongst these activities, the burning of fossil fuels is a major contributor to emissions, both in the production process of fertilizers, and also in the farming activities related to crop cultivation. Following the international agreements on the reduction of GHG emissions, it can be expected that the proportion of renewable energy used both in the fertilizer production and farming of feed crops will increase in the future, and this will lead to considerable reduction of the feed-related emissions. Therefore, it is likely that the relative role of the "non-fossil" components of feed production emissions, namely the nitrous oxide emissions from fertilizer application together the LUC emissions, will become even more significant and will be the major target in reduction of the feed production emissions in the future.

In addition to its influence on global warming potential, the quantity and composition of feed has a substantial influence on the eutrophication and acidification potentials related to poultry production, both directly and indirectly. The production of feed crops is tied to diverse direct emissions, including nitrate leaching into water and ammonia emissions into the atmosphere. Indirect effects related to feeding include emissions from poultry housing and manure management, similarly contributing to the eutrophication and acidification potential in poultry production. The scale of these emissions directly hinges on the nitrogen content in the manure which, in turn, is contingent upon the birds' nitrogen conversion efficiency, namely the proportion of nitrogen retained in the bird's body or eggs (in the form of protein) divided by the nitrogen acquired from the feed (also in the form of protein). A significant portion of this surplus nitrogen is released into the environment through various emissions, although some can be utilized as crop nutrients if the manure is employed as fertilizer on fields. Therefore, it is obvious that improved feed efficiency has multiple effects on the environmental performance of poultry production. Reduced feed consumption can simultaneously reduce the climate effects and other impacts of feed production and the emissions arising from housing and manure management.

It is important to keep in mind that some environmental impacts have a strong regional dimension. For example, in terms of biodiversity and water scarcity, the magnitude of the impact depends not only on the resource consumed (land use, water consumption) but also on the characteristics of the site. For example the water scarcity impact of poultry meat is strongly dependent on the geographical locations where feeds are produced, resulting in differences in impacts between poultry production systems. To improve environmental performance, it is important to trace the geographic origin of all feed ingredients and other inputs to quantify the actual impact of these materials.

Globally, soya bean meal serves as a primary protein source in poultry diets due to its favorable amino acid composition. However, this choice brings about challenges beyond the conventional environmental impacts associated with feed production. Notably, a considerable portion of the soya bean utilized for animal feed in the Europe is sourced from South America, where recent large-scale land use changes (LUC) have taken place. As mentioned earlier, these land use changes must be factored in when assessing the overall greenhouse gas emissions and biodiversity impact linked to crop production and its subsequent use as animal feed. Currently, soya production in Europe is unable to cover the demand from the European poultry sector. This situation is likely to be exacerbated by unstable conditions due to climate change, e.g. droughts and heat waves, which increase food insecurity, This suggests that e.g. novel plant breeding techniques solutions, including gene editing, should be further studied for their potential to produce more resilient crop varieties.

The significance of LUC emissions in broiler production was demonstrated e.g. by Usva et al. (2023), who reported 23% of the Finnish broiler chickens' global warming potential originating from feed crop production-related LUC. The impact was mainly generated in soya bean production in South America. Although South American soya bean meal accounted for only part of the soya bean meal in broiler chicken diets, its impact was notable. Besides South American soya bean meal, soya from other sources with much lower LUC can be utilized in broiler production. While the shift to different sources of soya bean can aid in reducing LUC emissions from the production, it was noted by Usva et al. (2023) that a trade-off was occurring with other environmental impacts, most notably with increased water scarcity impacts, e.g., due to irrigation and use of other inputs.

This example demonstrates a common strategy to mitigate the feed-related environmental impacts in poultry production through selecting feed ingredients with lower environmental footprints during their production phase. In addition to aiming for sustainable sources of soya bean meal, another approach towards more environmentally sustainable livestock diets involves substituting at least some of the soya bean meal with other, preferably local, protein sources (Leinonen et al. 2013). It is now becoming clear that alternative protein sources such as potato protein, corn gluten meal, rapeseed meal, sunflower meal and by-products of animal production, together with use of synthetic amino acid supplements (to improve nutrient use efficiency), have the potential to replace soya bean meal in commercial poultry diets (Leinonen et al. submitted).

It is also important to notice that even if the change of the origin of soya or the use of alternative protein sources can reduce direct LUC emissions of a particular broiler production system, the 'traditional' use of LCA may not capture all indirect LUC effects occurring globally. It can be argued that any use of agricultural crops will increase global land use pressure and thus contribute to LUC. It has therefore been suggested that these indirect LUC effects should also be included in LCAs for animal products (e.g. Audsley et al. 2009). In general, a completely different LCA approach, so called consequential LCA, may be needed to take into account all globally occurring changes in environmental impacts resulting from large scale system changes (e.g. Ekvall and Weidema 2004).

Considering alternative ‘environmentally friendly’ ingredients in poultry diets also requires evaluating their potential effects on poultry performance, including growth rate and feed efficiency. One requirement for high feed efficiency is am optimally balanced nutrient profile. Such a profile enables birds to efficiently utilize a substantial portion of their dietary nutrient intake, thereby reducing nitrogen and phosphorus excretion and also reducing overall feed consumption. Any changes in performance could significantly alter environmental outcomes. For instance, poorer feed conversion efficiency would increase environmental impacts per unit of product due to higher resource requirements, and such an effect has also been demonstrated for beef by Huuskonen et al. (2023) and dairy by Hietala et al. (2023). Similar effects would occur with increased mortality, as it would reduce the amount of output. As mentioned above, changes in bird performance would also impact manure management, with poorer efficiency leading to more nitrogen excretion, consequently affecting emissions to the environment.

In general, improving feed utilization through dietary optimization is an efficient way to gain positive environmental effects. In poultry production, optimal diets would decrease environmental impacts from both feed production and manure management. In addition to selecting optimal combination of feed ingredients, one way to achieve this is through feed processing techniques or additives like enzymes, to enhance digestion. For protein digestion in particular, improving efficiency is vital, as excessive protein use has various environmental consequences, as discussed above. One promising strategy to achieve this is to add the enzyme protease to feed to enhance protein utilization (Oxenboll et al. 2011, Leinonen and Williams 2015).

In addition to altering feeding strategies, genetic selection aimed at improving feed efficiency has been found to play a significant role in mitigating the environmental impacts of livestock production (Neeteson-van Nieuwenhoven et al. 2013, Hietala et al. 2022b, 2022c, Mehtiö et al. 2023). In broiler production, increased growth rate has been a prominent genetic trend over recent decades, resulting in reduced time to reach slaughter weight (Laughlin 2007). This trend leads to more metabolizable energy being retained as body protein and lipid, while less is released as heat. In practical terms, this is observed as reduced feed consumption by birds (de Beer et al. 2011; Laughlin 2007; Mussini 2012, Tallentire et al. 2016, 2018, Zuidhof et al. 2014).

Studies suggest that these genetic changes, especially the decrease in feed consumption, have substantially lowered greenhouse gas, ammonia, and nitrate emissions from poultry production (Defra 2008, Pelletier 2010). A recent study by Leinonen (submitted) compared a wide range of modern fast-growing and slow-growing broiler genotypes to quantify their global warming potential. It was found that the climate impact of the fastest-growing genotypes was significantly smaller than the impact of the slowest-growing genotypes. This was mainly a result of the fact that a faster growth rate reduces the time to reach slaughter weight, and therefore less energy is lost as heat during the whole growth cycle and less feed is also needed to reach slaughter weight.

In addition to improved feed energy efficiency as a result of faster growth, differences in the body composition (protein vs. lipid content) of modern broilers also have an effect on energy consumption of birds and on the corresponding global warming potential. However, this effect is much smaller than the effect of the high growth rate (Leinonen, submitted).

Although, in theory, reducing the protein concentration of the diet may reduce the GWP through reducing the inclusion of some high-emission ingredients, this effect is also dependent on the differences between the genotypes. In fast-growing genotypes, low feed protein concentration can cause adverse effects on the growth rate of the birds which can then increase environmental impacts. This effect is not as strong in slower-growing genotypes. It can be concluded that, in terms of environmental sustainability, it may be more beneficial to use low-protein diets for slow-growing birds than for fast-growing ones (Leinonen, submitted).

While conventional poultry systems have been able to improve their environmental performance due to their efficiency, where the main driver is the fast growth rate and short production cycles (Leinonen et al. 2012a, 2012b), modern poultry production aims not only for efficiency but also places significant emphasis on improving bird welfare. A commonly increasing trend, at least in some countries in Europe, is to favor slow-growing bird genotypes in broiler meat production (Chodova et al. 2021, Dal Bosco et al. 2014, Devatkal et al. 2019, Fanatico et al. 2007, 2008). As already discussed, the necessary consequence of this practice is lower feed efficiency, and the need to produce more feed to obtain a certain amount of meat which, in turn, increases various environmental impacts. As a result, when moving from conventional production to alternative options where slow-growing birds are used, it is even more important to find additional ways to reduce feed-related impacts. Options for this might be diets with lower protein content and more sustainable protein sources (Leinonen, submitted).

5.2 Addressing non-feed-related environmental impacts

Changes in animal housing can also promote improved welfare, but they can also have consequences on the environmental performance of production. Leinonen et al. (2014) quantified the environmental consequences of some new welfare-enhancing production systems introduced in the EU for broiler and

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egg production. Their conclusion was that high environmental performance can also be achieved in modern, less intensive production systems.

The impacts arising from direct electricity consumption in broiler farms have been significantly reduced in several countries, including Finland, as a result of selecting sustainable energy sources and the general reduction of the emissions intensity in national generation of electricity. However, in many countries, the energy consumption in farms still makes a major contribution to the overall environmental impacts of poultry production. Therefore, improving the energy efficiency of broiler housing, together with increased use of sustainable energy, will remain a major target in improving the environmental sustainability of poultry production.

As previously discussed, a significant portion of eutrophication and especially acidification in poultry systems stems from housing and manure management. While improvements in feed efficiency can reduce these emissions, as discussed above, it is also reasonable to expect that direct measures focused on enhancing manure management at both the farm and end-use stages could contribute to emission reduction. In several countries a common practice involves spreading manure directly onto fields as fertilizer. While this practice offers certain environmental benefits, such as decreasing the need for synthetic fertilizers and increasing soil carbon storage (resulting in CO_2 removal from the atmosphere), a major drawback is the substantial release of ammonia and nitrate into the environment. Hence, alternative strategies for manure management are being explored (Lynch et al. 2013; Huang et al. 2015).

As one option, the use of poultry litter as an energy source has been suggested. In an early study, Williams et al. (2016) evaluated the environmental consequences of utilization of poultry litter as a fuel source for electricity generation at power stations, using the LCA framework. Another option is to apply anaerobic digestion for poultry litter and utilize the bioenergy and digestate. According to an LCA study by Beausang et al. (2020), this option can potentially provide considerable environmental benefits.

As shown in above examples, the options for improving the environmental sustainability of broiler meat production may differ between systems. However, only a minority of global poultry meat is produced in extensive systems while intensive specialized broiler systems cover 81% of the global production (MacLeod 2013). The poultry industry is largely run by few multinational enterprises, and the best practices are spread widely around the world. The largest poultry meat-producing companies are often vertically integrated and located in North and South America and in Eastern and South-Eastern Asia (Windhorst 2017).

Differences in options for improving the environmental performance of broiler systems may not always be related to the production system itself but, rather, to the specific inputs used in production. Examples of such differences include the regional production patterns of protein crops used in feed, or the country-specific energy generation systems, affecting the emission arising from the energy used in the production.

6 Conclusion

In general, LCA is a strong method to assess the environmental performance of current poultry systems and potential improvement options. As a system-based method, in assessing future scenarios LCA can identify true improvements in the environmental performance, instead of just shifting emissions one stage of the production chain to another. However, some LCA methods still need to be further improved. For example, methods to assess impacts on water scarcity and eutrophication are not as developed as climate impact, and especially the biodiversity impact category is undeveloped. The inclusion of the indirect LUC emissions may also need further development, as discussed above. In addition, LCA is a data intensive method, and the lack of data may be a challenge in case general level LCA is conducted. The existing LCA results are not always comparable or usable in other assessments due to different scopes and modelling solutions. If the aim of an LCA study is to improve environmental performance of a specific production chains, the primary data may be more easily available, and the study can provide results that support the improvement in the chains.

Addressing the environmental sustainability of livestock systems is a multidimensional challenge that requires a comprehensive understanding of interconnected factors. Systems modeling-based LCA offers a valuable approach to systematically navigate these intricate interactions, helping to pinpoint areas where significant enhancements in the sustainability of livestock systems can be achieved.

Although poultry production is generally deemed more environmentally sustainable compared to many other livestock commodities, it still contributes to environmental impacts such as global warming, eutrophication, acidification, water use, and biodiversity. Therefore, there remain opportunities to mitigate these impacts through a combination of strategies, including altering feeding practices, optimizing feed composition, genetic selection, animal housing, and energy use.

Among the various stages within the poultry production chain, the production of feed stands out as the primary contributor to the global warming potential of poultry systems. Exploring alternative feed ingredients, such as locally sourced protein crops, holds promise for improving multiple environmental impact categories, provided that these new feeding strategies do not negatively impact bird performance.

Improving feed efficiency emerges as a pivotal approach to reducing environmental impacts. Especially, genetic selection has shown the potential to decrease resource demands in broiler production, particularly feed consumption. Fast and slow growing broiler genotypes provide somewhat different potential solutions for improving their environmental performance. Fast growth itself improves feed efficiency and reduces the impacts related to feed production. On the other hand, slow-growing birds may be able to better utilize "climate-friendly" feed ingredients for example in the form of low-protein diets.

7 Where to look for further information

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