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## A review on life cycle assessment of broiler production systems

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### Abstract

This research synthesizes findings from life cycle assessment (LCA) studies on broiler production systems, providing a comprehensive analysis of the environmental impacts associated with this industry. Various system boundaries, including cradle to farm gate, cradle to slaughterhouse, and cradle to grave approaches, were employed, alongside different functional units such as 1kg of live weight broiler chicken and 1kg of consumed chicken meat. The life cycle inventory analysis (LCI) incorporated primary and secondary data on inputs and outputs throughout the broiler production process. Key findings identified feed production, particularly soybean cultivation, as a major environmental burden, significantly contributing to global warming, acidification, eutrophication, and cumulative energy demand. Other notable impacts arose from energy use, waste management, and transportation. The studies explored the potential of low-protein diets and alternative production systems, such as organic or positive pressure systems, in reducing environmental impacts. Sensitivity and scenario analyses emphasized the importance of variables like feed intake, slaughter weight, and emissions from feed and soybean production. Strategies including litter composting, litter incineration, and energy-efficient systems were suggested for further impact reduction. Allocation methods such as mass and economic allocation facilitated precise distribution of environmental burdens across different production stages. The research highlights critical areas for improvement and informs sustainable practices within broiler production, calling for continued investigation into the long-term sustainability of alternative systems and effectiveness of improvement strategies.

**Keywords:** Broiler production, LCA, LCI

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### Introduction

As the world's population continues to increase there is a need to meet the increasing demand for food in order to ensure food security. According to a report by USDA, poultry products is the most consumed livestock commodity in the world with increasing demands from developing countries due to limited production. It is also expected to remain the world's largest imported livestock over the next 10 years. The demand for poultry meat has risen by 86% from 2001-2021, from 69 million metric tons to 128 million metric tons.

The US is also the world's largest producer of poultry products with Brazil being the biggest exporters. (Ritchie *et al.*, 2023) <sup>[12]</sup>. According to Statista.com broilers have the highest per capita meat consumption in the US among poultry products and this value is set to increase even more. In terms of consumption, the US is highest consumer of poultry products followed by China, Brazil and European union (Shahbandeh, 2023) <sup>[13]</sup>.

Global poultry products imported by Middle east, Saudi Arabia, Latin America and Caribbean, Mexico, European Union, Russia, China, Hong Kong, and East Asia is set to increase by 27% between 2021 – 2031 while exports by Brazil, US, Asia, Latin America, Thailand, Former Soviet Union and European Union is set to increase by 25% within this same time period (Miller *et al.*, 2022) <sup>[8]</sup>.

With all these increase in demands, imports, and exports, which has led to increase production of poultry products, it is important to understand the impacts that this huge industry has on the environments. How much impact does this industry really have on the environment? And are there better ways to go about production to reduce its impacts?

Life cycle assessment is a practice of evaluating the environmental effects of a commercial product, process, or service at each stage of its life cycle. In the case of poultry production, environmental impacts of the various processes involved can be assessed from the production of feed used, through broiler production, slaughterhouse, processing, consumption and finally disposal of bones.

Several life cycle assessment (LCA) studies have been conducted to understand the environmental impacts of poultry production/products in various countries. Authors have also adopted various approaches to determine the impacts of this industry on the environment. Their reports include the following:

- System Boundaries
- Functional Unit
- Life Cycle Inventory Analysis
- Impact Assessment
- Sensitivity and Scenario Analysis
- Allocation Method

In the following sections, I look at these various approaches and their findings.

### System Boundaries

The system boundaries determine which unit processes to be included in the LCA study.

Azmi *et al.* conducted a LCA of the chicken meat agroindustry in Indonesia using a cradle to grave approach. In their study they considered feed production, broiler production, carcass production in the slaughterhouse, distribution of the finished product and consumption (Azmi *et al.*, 2023) <sup>[1]</sup>. Ogino *et al.* studied the LCA of broiler production in Japan and compared conventional production systems to systems that use low-protein diet and/or litter incineration. Their system boundaries included feed production, feed transport, broiler housing, broiler production and manure management (Ogino *et al.*, 2021) <sup>[10]</sup>. Martinelli's study on the eco-efficiency of different poultry production system in Brazil used a cradle to farm gate approach. This approach covers the stages of feed production up to deliver of live chicken by slaughter weight but did not include steps for transporting the inputs and poultry to the slaughterhouse. In their study, they compared the

conventional poultry production systems with positive pressure production systems, dark house production systems and organic systems (Martinelli *et al.*, 2020) <sup>[7]</sup>.

Skunca *et al.* researched on the life cycle assessment of the chicken meat chain in Serbia using a cradle to grave approach. Their paper covered five subsystems which included the chicken farm – involving the breeding of chicken, slaughterhouse, meat processing – involving cleaning and processing the carcass, retail subsystem – involving storage and chilling of finished product and household use – storage and preparation of meat (Skunca *et al.*, 2018) <sup>[14]</sup>. This system is similar to that used by Azmi, which also included five subsystem which were feed production, chicken farm, slaughterhouse, supplier and consumer use subsystem. Although Skunca did not state feed production as a subsystem in their work, they considered it during their input calculations and also considered fresh water, electricity, fossil fuels, packaging materials and cleaning agents as inputs in their system.

Usva *et al.* took a different approach in their study of broiler chicken production in Finland and considered a cradle to slaughter boundary. Their system covered feed production including transportation, broiler chicken parents, egg laying, hatching, and fattening under chicken farm and the slaughter process. Using a cradle to slaughter process is not common as most authors consider a cradle to grave approach or a cradle to farm gate approach. It is also not consistent with the European Commission's Product Environmental Footprint (PEF) guidelines which was a basis their analysis (Usva *et al.*, 2023) <sup>[15]</sup>.

Mostert *et al.* conducted an analysis on broiler production systems in Netherlands. In their approach, convention production systems was compared with Dutch Retail Broiler (DRB) and Better Life one Star (BLS) production system, which were systems introduced to improve broiler welfare. A deterministic, spread sheet-based model was built to analyze the systems for a cradle to farm gate approach (Mostert *et al.*, 2022) <sup>[9]</sup>. Kalhor *et al.* studied the LCA of chicken meat production in Iran using a cradle to farm gate and cradle to slaughterhouse approach. Their study was comparative as they compared the production of chicken meat in summer with production of chicken meat in winter (Kalhor *et al.*, 2016) <sup>[4]</sup>. Leinonen *et al.* built a model to understand the effects of dietary protease on nitrogen emissions from broiler production system in the UK. The subsystems modelled included crop production, non-crop nutrient production, feed processing, breeding, broiler production (including farm energy and water use and gaseous emissions from housing) and manure and general waste management. Two scenarios were compared in their study - diets without protease with standard protein content and diets with protease combined with reduced protein content (Leinonen & Williams, 2015) <sup>[5]</sup>.

González-García LCA of broiler chicken production in Portugal was from a cradle to slaughterhouse perspective with the aim of identifying the environmental hotspots of the system (González-García *et al.*, 2014) <sup>[2]</sup>. Prudêncio da Silva studied the impacts of French and Brazilian broiler chicken production using a cradle to slaughterhouse gate approach with the aim of comparing them. From the two countries, four scenarios were made (two from each) which are the France Standard system, France High Quality System ("Label Rouge"), Brazil large-scale system, and Brazil small-scale system (Prudencio da Silva *et al.*, 2014) <sup>[11]</sup>. Leinonen in his

study on LCA of broiler production systems in the UK, used a structural model to predict environmental impacts. Using a comparative analysis, three broiler production systems in the UK were compared – standard indoor, free range and organic using a cradle to gate approach (Leinonen *et al.*, 2012) [6].

The above literatures have shown a variety of LCA done in several countries including UK, Indonesia, Iran, Brazil, Portugal, France, Netherlands, Finland, Serbia and Japan. These literatures show the various system boundaries used which include cradle to farm gate, cradle to grave and cradle to slaughterhouse approach. For cradle to gate, it considers all the processes involved from feed production to breeding of broilers until maturity. This approach stops at the point where the broilers are ready to be taken to the slaughterhouse and does not go beyond this point. Cradle to slaughterhouse include the process of slaughtering and preparing the broilers for the market. Some authors also include storage and chilling of the carcasses in this process. For, cradle to grave approach, this considers the entirety of the process from feed production to consumer use (after the broiler has been eaten and the waste disposed). Using these various approaches would lead to different environmental impacts since the boundary conditions are different. Many of these studies adopted a comparative analysis perspective, comparing different production systems, dietary approaches, or environmental impacts across countries. However, a few studies employed an attributional analysis to delve into specific aspects of the production process.

### Functional Unit

A functional unit describes a quantity of a product or product system on the basis of the performance it delivers in its end-use application. It is the value delivered at the end of the process or cycle.

Azmi *et al.* in their paper which took a cradle to grave approach used a functional unit of 1kg of fried chicken consumed. This is similar to the functional unit used by Skunca *et al.* who also considered used the same system boundary as Azmi *et al.* and used a functional unit of 1kg of consumed chicken meat (Azmi *et al.*, 2023; Skunca *et al.*, 2018) [1, 14]. A few papers which considered the cradle to gate (farm gate) system boundaries used a functional unit of 1kg of liveweight of broiler chicken (Martinelli *et al.*, 2020; Mostert *et al.*, 2022; Ogino *et al.*, 2021) [7, 9, 10].

Usva *et al.* used a cradle to slaughter approach and considered a functional unit of 1kg of carcass weight (Usva *et al.*, 2023) [15]. Kalhor considered two approaches in his study, cradle to farm gate and cradle to slaughterhouse gate. For both approaches, different functional units were considered – 1 ton of live weight (LW) broiler for cradle to farm gate and 1 ton of chicken meat at slaughterhouse gate (Kalhor *et al.*, 2016) [4]. In Leinonen's study which considered the effects of dietary protease on nitrogen emissions from broiler production, LCA was carried out on two alternative systems. Feed production chain whose system boundary was at the feed mill gate and had a functional unit of 1000kg of broiler feed and Broiler production chain with a functional unit of 1000kg of *expected* carcass weight at the farm gate. The functional unit used for the broiler production chain was not consistent with other paper who considered the live weight of the broiler rather than the carcass weight, however they assumed that there was a constant relationship between

carcass weight and live weight based on the data from the UK broiler industry, hence the reason for using 1000kg of *expected* carcass weight (Leinonen & Williams, 2015) [5].

González-García in his study, although used a cradle to slaughterhouse approach, used a functional unit of 1.2kg of broiler chicken ready to be distributed for sale. Their reason for using this was because that amount (1.2kg) contains the recommended daily protein for an average family (4 people) and because that is the average weight of broiler chicken in the Portuguese market (González-García *et al.*, 2014) [2]. In Prudêncio da Silva paper that compared French and Brazilian broiler chicken production, the main functional unit adopted was 1 tonne of cooled and packaged chicken. Although their results were based on 1 kg of live weight broiler chicken which corresponds to the cradle to gate system boundary (Prudêncio da Silva *et al.*, 2014) [11].

Leinonen's study of broiler production systems in the UK considered a functional unit of 1000kg of *expected* edible carcass weight using a cradle to farmgate approach. Again this functional unit is not consistent with other authors who used a cradle to farmgate system boundary, however the carcass weight used was defined as live weight × the killing-out percentage (excluding feather, gut, feet, and so on, or edible organs, such as the liver). This explains why the functional unit was stated as 1000kg of *expected* carcass weight, since their process did not consider the actual burdens of slaughter or processes or any losses that occurred between the farm gate and the end of the processing line (Leinonen *et al.*, 2012) [6].

The above literatures have reported the various functional units adopted by different authors. We see a relationship between the system boundary considered and the functional unit used. For a cradle to gate approach, most authors used 1kg of liveweight (LW) broiler chicken, for a cradle to slaughter house approach, 1kg of carcass weight was used while for a cradle to grave, 1 kg of fried chicken consumed was used by Azmi. A few authors, like considered 1000 kg of carcass weight in his study, while others like Kalhor and Prudêncio da Silva used 1 ton of live weight (LW) broiler chicken and 1 ton of cooled, packaged chicken respectively. Only González-García considered 1.2 kg of broiler chicken at slaughterhouse and gave his justification for this.

### Life Cycle Inventory Analysis

The ISO defines life cycle analysis (LCI) as the stage of life cycle assessment that includes gathering and quantifying inputs and outputs for a product over the course of its life cycle. The inventory is a list of all the different environmental inputs and outputs that are involved in a product's life cycle. This process basically involves the collection and calculation of all data inputs and outputs.

Azmi in his report on LCA for chicken meat agroindustry in Indonesia, which was a cradle to grave approach collected primary data from the producers at the chicken farm, slaughterhouse and supplier as well as a fast food restaurant for the consumer use data. Secondary data was used for production of fertilizers, feed ingredients, electricity, diesel, natural gas, refrigerants, packaging materials, and cooking oil and was gotten from Ecoinvent 3 and Agrifoot-print 5 databases in SimaPro software (Azmi *et al.*, 2023) [1].

**Table 1:** A summary of studies on LCA in broiler production with the location, system boundaries and functional unit

Study	Location	System Boundary	Functional Unit
Azmi <i>et al.</i> , 2023 <sup>[1]</sup>	Indonesia	Cradle to grave	1kg of fried chicken consumed
Ogino <i>et al.</i> , 2021 <sup>[10]</sup>	Japan	Cradle to gate	1kg of liveweight broiler chicken
Martinelli <i>et al.</i> , 2020 <sup>[7]</sup>	Brazil	Cradle to farm gate	1kg of live chicken
Skunca <i>et al.</i> , 2018 <sup>[14]</sup>	Serbia	Cradle to grave	1kg of consumed chicken meat
Usva <i>et al.</i> , 2023 <sup>[15]</sup>	Finland	Cradle to Slaughter	1kg of Carcass weight
Mostert <i>et al.</i> , 2022 <sup>[9]</sup>	Netherlands	Cradle to farm gate	1kg of liveweight chicken
Kalhor <i>et al.</i> , 2016 <sup>[4]</sup>	Iran	Cradle to farm gate	1 ton of live weight (LW) broiler
Kalhor <i>et al.</i> , 2016 <sup>[4]</sup>	Iran	Cradle to slaughterhouse	1 ton of chicken meat at slaughterhouse gate
Leinonen <i>et al.</i> , 2015 <sup>[5]</sup>	UK	Cradle to feed mill gate	1000kg of broiler feed
Leinonen <i>et al.</i> , 2015 <sup>[5]</sup>	UK	Cradle to farmgate	1000kg of expected carcass weight
González-García <i>et al.</i> , 2014 <sup>[2]</sup>	Portugal	Cradle to Slaughterhouse	1.2kg of broiler chicken ready for distribution
Prudêncio da Silva <i>et al.</i> , 2013	France and Brazil	Cradle to slaughterhouse	1 tonne of cooled and packaged chicken
Leinonen <i>et al.</i> , 2011	UK	Cradle to farmgate	1000kg of expected edible carcass weight

Unlike Azmi who used just one chicken farm, one slaughterhouse and one supplier for his data, Skunca who considered the same system boundary used data from 20 farms, nine slaughterhouses, 8 meat processing plants, 82 retail stores and 500 households consisting of 2011 consumers. Environmental data such as consumption of water, cleaning agents, feed, energy, and waste treatment were calculated on an annual basis and divided by the total annual quantity of produced live weight (farm), carcass weight (slaughterhouse), processed chicken meat (meat processing plant), sold chicken meat and chicken meat products (retail) and consumed chicken meat and chicken meat products (household use). Ecoinvent v3 database and SimaPro 8.2.3 software was used to process their inventories (Skunca *et al.*, 2018) <sup>[14]</sup>.

Ogino's paper on the effects of low-protein diet and litter incineration on LCA, which was a cradle to gate approach, collected primary data from the producers for the different scenarios considered. Environmental data was obtained from MiLCA software database to calculate the consumption of electricity, fossil fuels, production of materials and transportation (Ogino *et al.*, 2021) <sup>[10]</sup>.

Usva *et al.* LCA on Finnish broiler chicken production divided their LCI process into three, chicken production, feed production and other life cycle stages. For chicken production, primary data was collected from 20 broiler chicken farms and a large dataset which consisted of meat producing companies in Finland. For feed production, feed mix and processing data was collected from three industrial feed companies. Feed operations data was obtained from three feed manufacturing companies while data on feed crops like wheat were acquired from ProAgria database (not public). Other non-domestic feed components were obtained from EcoInvent 3.0 database and literatures. The slaughter process data was collected from three slaughterhouses which included data on carcass, energy, refrigerants and animal transports. Energy data were obtained from Finnish Energy Association and EcoInvent 3.0 database (Usva *et al.*, 2023) <sup>[15]</sup>.

The LCA carried out by Martinelli *et al.* which used a comparative analysis between positive pressure (PP), dark house (DH) and organic (ORG) production systems collected data for PP and DH from the Federation of Farmers of Paraná (FEAP) database while data for ORG systems were collected directly from producers (Martinelli *et al.*, 2020) <sup>[7]</sup>. In the study done by Kalhor *et al.* on LCA in Iran, EcoInvent 2.0 database was applied for several inputs such as (production

of feed ingredients, packaging materials and cleaning agents, electricity, transportation, etc.), and data from production farms and slaughterhouse were compiled using questionnaires. The software used for LCI analysis was SimaPro V7.1 (Kalhor *et al.*, 2016) <sup>[4]</sup>. González-García *et al.* in their LCA study, collected data from through surveys, questionnaires, literature, the production company for feed, the slaughterhouse company, and EcoInvent database for feed ingredients, fuel and electricity data. The SimaPro 7.3.2 software was used to process the inventories (González-García *et al.*, 2014) <sup>[2]</sup>.

Life cycle inventory is a major part of the life cycle assessment process, and it is important that all inputs and outputs data are collected and analyzed to understand the effects of these processes on the environment. For the articles reviewed, secondary data was majorly obtained from the Eco Invent Database, other external databases (private) and through literatures while SimaPro software was used for analysis. Primary data were obtained through questionnaires and surveys from the farm owners, manufacturing companies, production companies, and suppliers.

### Impact Assessment

Life cycle impact assessment (LCIA) is a qualitative and quantitative assessment of the environmental impact of a product based on the resource, energy consumption data, and various emission data provided after the inventory analysis. Azmi *et al.* in their study considered the following impact categories - global warming, acidification, and eutrophication. The CML-IA (Centre of Environmental Science of Leiden University Impact Assessment) baseline method on the SimaPro software was used to for the impact calculations. Their research looked at five subsystems and feed production had the highest impact in all three categories while the consumer use subsystem had the lowest impact in all categories. For feed production, soybean meal production was the highest contributor to global warming while maize grain production was the highest contributor to acidification and eutrophication. Electricity was the most significant contributor in the slaughterhouse, supplier and consumer use subsystem for all categories (Azmi *et al.*, 2023) <sup>[1]</sup>.

Skunca *et al.* in their study calculated global warming potential, cumulative energy demand, ozone layer depletion, acidification potential and eutrophication potential. Their result showed that feed production had the highest contribution to global warming potential and was also the highest contributor at the chicken farm subsystem. According

to their report, farms with higher market share in the industry had higher impacts to the environments in terms of global warming potential, cumulative energy demand, ozone layer depletion and acidification potential compared to farms with lower market share while retailers with lower market share had higher impacts compared to those with higher market share. Energy use had the highest impact for slaughterhouse, meat processing, retail and household use for all categories (Skunca *et al.*, 2018) <sup>[14]</sup>.

In Ogino's study which compared conventional poultry production, with Lower protein diet methods, litter incineration and the use of both low protein diets and litter incineration, reported that feed production had the largest contribution to greenhouse gas emissions, which is consistent with results from other authors. The litter incineration system had a lower impact on the environment compared to conventional production systems and low protein diet systems – this was due to lower NH<sub>3</sub> emissions from the manure management process (Ogino *et al.*, 2021) <sup>[10]</sup>. Martinelli *et al.* in their study used the CML-IA 2 baseline 2000, version 4.2 for characterization of the impact categories which included acidification, eutrophication and global warming. The feed production subsystem had the largest contribution of CO<sub>2</sub> with corn and soybean production having the highest share followed by electric energy with the largest contribution coming from electric engines used in the feed factory (Martinelli *et al.*, 2020) <sup>[7]</sup>. Mostert's study that compared conventional production systems with other production systems (Dutch Retail Broiler (DRB) and Better Life one Star(BLS)) with the aim of increasing broiler welfare, in their results showed that BLS had lower GHG emissions compared to conventional and DRB production systems due to lower feed intake. Soybean product had the highest impact on greenhouse gas emissions (Mostert *et al.*, 2022) <sup>[9]</sup>.

Kalhor's study which was a comparative assessment of chicken meat production in summer versus in winter performed their impact categories according to CML 2 baseline 2000. The broiler production stage had a significant impact for all categories for both winter and summer due to the production and transportation of feed as well as emission in the farm. Acidification potential was mostly dominated by Ammonia evaporation from manure and SO<sub>2</sub> emissions from fossil fuels combustion while Eutrophication potential was dominated by NO<sub>3</sub> and PO<sub>4</sub> leaching into water due to chemical fertilizers used in soybean production. Their report showed that broiler production is the largest contributor to energy consumption with 56% followed by slaughterhouse and transportation with 31% and 13% respectively. More energy was required in winter for heating purposes leading to large amounts of fossil fuel combustion (Kalhor *et al.*, 2016) <sup>[4]</sup>.

González-García *et al.* in their study on broiler production systems in Portugal noted that chicken farm subsystem contributed the most to environmental impacts for all categories with feed production having the largest share. They also stated that soybeans production was the highest contributor for feed production since it is mostly used as a source of protein. Organic waste (manure and waste poultry beds) management were the highest contributors for acidification and eutrophication potential in the chicken farm subsystem. In the slaughterhouse subsystem, electricity had the highest contribution to all impact categories except for cumulative energy demand where packaging materials

production was higher than electricity. A study by Prudêncio da Silva *et al.* compared French and Brazilian chicken broiler production systems and revealed that feed production stage was the highest contributor for acidification in the Brazilian system while chicken production stage was the highest contributor to acidification in the French system. Besides from acidification, feed production was the highest contributor for all impact categories in the French production systems (Prudencio da Silva *et al.*, 2014) <sup>[11]</sup>.

Leinonen's study on broiler production systems in the UK stated that feed production, processing and transportation had the highest environmental impact compared to other components in the broiler production system. For primary energy use, farm oil and gas had the second highest impact after feed production followed by farm electricity use. Manure was the main contributor to acidification and eutrophication potential (Leinonen *et al.*, 2012) <sup>[6]</sup>. One of the major contributors to environmental impacts is feed production, which is due to soybean production – a main source of protein. Leinonen *et al.* conducted another study to see the effect of reduced protein diets on the overall production system. They compared soya-based broiler diets with reduced-protein diets (with added protease) and their results showed that there was a reduction in all impact categories when protease was used, with the biggest reduction in the global warming potential category which was as a result of decreased carbon emissions from land use charged related to soya production. In the broiler production chain, acidification potential and eutrophication potential had the biggest reductions in environmental impacts due to reduced feed protein content and nitrogen emissions from manure management (Leinonen & Williams, 2015) <sup>[5]</sup>. Impact assessment done by several authors for various production systems using different system boundaries have been reviewed in this section. Most authors used CML-IA (Centre of Environmental Science of Leiden University Impact Assessment) methodology to characterize the impact categories. Feed production was the highest contributor to most of the impact categories with soybean production having a high share as it is a major source of protein for poultry feed. The reason for this higher contribution is due to high land use change, use of mineral fertilizers in cultivation, processing of feed and feed ingredients in production plants and transportation of the feed to poultry farms. Acidification and eutrophication potential were largely due to emissions from litter compost in the farm and using litter as manure for crop production. A few authors suggested that using a low protein feed could help reduce the environmental impact of this subsystem (feed production) and this was proven with Leinonen *et al.* study the use of reduced-protein diets in place of soya-based broiler diets.

### Sensitivity and Scenario Analysis

Azmi *et al.* considered seven scenarios to see how they affects the various impacts categories. These scenarios include reduction of crude protein in feed, litter composting, installation of inverters on refrigeration compressors in the slaughterhouse, installation of inverters in supplier, increasing the efficiency of electrical energy by the consumer, and applying all the scenarios together. Litter composting had the highest reduction in impact for all the categories (global warming, acidification and eutrophication). Applying all the scenarios together also had a significant effect on the reduction of global warming,

eutrophication and acidification (Azmi *et al.*, 2023) <sup>[1]</sup>. Skunca *et al* reviewed possible improvement scenarios that could be explored but did not use them in his experiment. First direction was to use grain legumes instead of soybean, since grain legumes do not require mineral fertilizers application (Baumgartner *et al.*, 2008). Using chicken litter in a biodigester was suggested by Mainali as opposed to composting the litter which was used by Azmi, with the aim of using it to produce biogas for electricity (76% reduction) or for cooking (65% reduction) (Mainali *et al.* 2017). The other suggestions were to use energy efficient systems in the farms and recycling of household wastes (Skunca *et al.*, 2018) <sup>[14]</sup>.

Sensitivity analyses done by Mostert *et al* considered variation in feed intake, slaughter weight, emissions from feed production and emissions from Land Use Change (LUC) from soybean production. In their analysis, feed intake was increased and decreased by 5% while having the same slaughter weight and diet compositions while slaughter weight was increased and decreased by 5% while having the same feed intake and diet compositions. An 5% increase in feed intake led to a 4.5% increase in GHG emissions for all production systems and vice versa with a decrease in feed intake while a 5% increase in slaughter weight decreased emissions by 4.8% and a decrease led to an increase in emissions by 5.3% (Mostert *et al.*, 2022) <sup>[9]</sup>. Scenario analysis was conducted in the Portuguese study by González-García *et al.*, their study stated that the use of chicken manure as fertilizer (scenario A) helped to reduce environmental impacts in all categories but that using composting poultry litter (scenario B) had worse environmental effects and should not be considered. They report attributed this increase in environmental effects to emissions from the composting process and high energy required to compost the litter (González-García *et al.*, 2014) <sup>[2]</sup>. This is opposite to the findings by Azmi who stated that litter composting had the best reduction in environmental impacts.

Various scenarios and improvement techniques have been experimented and suggested to reduce the environmental impacts of broiler production in different countries. Some of the scenarios reviewed here include litter composting for manure applications, litter incineration for heat generation, litter for electricity generation or cooking purposes through a biodigester, substituting soybean with other protein feed options, using inverters for electricity, and adopting other energy efficient methods.

### Allocation method

Allocation is the distribution of input or output flows from the production process to the product system under study (ISO, 2006). It is important because it enables a precise assessment of the environmental effects of a system or product and may identify and address any potential environmental issues.

Azmi *et al* adopted mass allocation to allocate the environmental burden in the slaughterhouse subsystem. In carcass production, the main product was the chicken carcass but there were also other co-products in for of head, liver, intestine and gizzard, hence the environmental burden was assigned to the two outputs, 75.86% for the chicken carcass and 24.14% for the co-products (Azmi *et al.*, 2023) <sup>[1]</sup>. Skunca in their study of chicken meat chain in Serbia also used mass allocation principle (Skunca *et al.*, 2018) <sup>[14]</sup>. Ogino *et al* employed economic allocation in the production of soybeans

since soymeal (used for broiler feed) and soy oil were outputs from the cultivation and production process (Ogino *et al.*, 2021) <sup>[10]</sup>. Usva *et al* also applied economic allocation in feed processes (e.g. soybean and rape seed meal and oil production, oat peelings), carcass disposal, and the slaughter process (Usva *et al.*, 2023) <sup>[15]</sup>. Mostert *et al* in their study included the breeding stage, laying period and hatchery in their system boundary. They employed economic allocation at the laying period from multiple outputs (eggs delivered to hatchery, non-hatching eggs, meat) and at the hatchery stage (assuming unhatched eggs had no economic value, so all emissions were allocated to hatched eggs) (Mostert *et al.*, 2022) <sup>[9]</sup>. González-García *et al.* did not consider allocation in their study, this was because live chicken was the unique product in the chicken farm and chicken litter and waste did not provide any revenue to farmers. Infact, the disposal of the waste has to be paid for. For the slaughterhouse, the main product is the packaged chicken and other organic waste has no economic value in Portugal.

### Conclusion

The life cycle assessment (LCA) studies on broiler production systems have delivered critical insights into the environmental ramifications of this industry. By utilizing varying system boundaries—ranging from cradle to farm gate, cradle to slaughterhouse, to cradle to grave—and diverse functional units such as 1kg of live weight broiler chicken or 1kg of consumed chicken meat, these studies have effectively mapped the environmental impacts at different stages of the production process. The life cycle inventory analysis (LCI) highlighted that feed production, particularly soybean cultivation, stands as a major contributor to environmental burdens, alongside energy use, waste management, and transportation.

The impact assessment revealed that feed production consistently exerts the highest influence across several environmental categories, including global warming, acidification, eutrophication, and cumulative energy demand. This underscores the need for sustainable feed strategies, such as adopting low-protein diets and alternative production systems like organic or positive pressure systems, which have shown promise in mitigating these impacts.

Sensitivity and scenario analyses have further elucidated the significance of variables such as feed intake, slaughter weight, and emissions from feed and soybean production. Innovative scenarios, including litter composting, litter incineration, and energy-efficient systems, have been proposed as effective measures to curtail the environmental footprint of broiler production.

Moreover, the employment of allocation methods like mass allocation and economic allocation has facilitated a more precise distribution of environmental burdens across different production stages and outputs, thereby enhancing the accuracy of impact assessments and pinpointing areas needing attention.

Overall, these LCA studies have not only deepened our understanding of the environmental impacts associated with broiler production but also identified pivotal areas for improvement. The findings serve as a valuable foundation for informed decision-making and the advancement of more sustainable practices in the broiler industry. Continued research is essential to evaluate the long-term sustainability of alternative production systems and the efficacy of proposed improvement strategies, ultimately aiming to

reduce the environmental footprint of broiler production and promote a more sustainable future for the industry.

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