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A R T I C L E   I N F O

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A B S T R A C T

Poultry farming is often associated with negative environmental impacts, such as water quality degradation and greenhouse gas emissions. This study covers important gaps in the geographic scope of poultry farming using Life Cycle Assessment analysis. Data on animal feed, energy, packaging, and waste were collected from the poultry industry in Rondônia, Brazil. The life cycle inventory included all inflows and outflows of feed production, poultry housing, slaughter, processing, the retail market, and the functional unit of “1 kg chicken meat with 0.22 kg protein”. The ReCiPe Midpoint (H) method was used for seven categories of impact. The results showed that emissions of greenhouse gases (GHG, CO_2, N_2O and CH_4) during the feed production phase was dominant, totaling 2.0 kg CO_2-eq per kg of live weight produced. This stage was most relevant in six of seven categories of impacts assessed. During the poultry housing stage, terrestrial acidification was dominated by emissions of NH_3, P and N_2O from one-day-old chicks (hatching eggs, poultry house litter, and feed). The total environmental impact of producing broilers in Brazil amounted to 3.37 kg CO_2-eq per kg of meat at the consumer market gate. The LPG gas and biological waste from slaughterhouses was dominant in this phase. The retail stage revealed contributions above 43% in all impact categories due to high consumption of electricity (0.11 kWh (0.39 MJ) per kg of meat). Three scenarios were proposed and demonstrated, using biological residues as a source of nutrients for feed composition. The results showed that using poultry viscera meal led to better environmental outcomes for all impacted categories.

1. Introduction

Chicken is the most widely produced meat in the world (FAO, 2022), with meat production having tripled between 1990 and 2021, reaching 38.8 million Mg (FAO, 2022) with a per capita consumption of 14.8 kg year^{-1} in 2021 (OECD-FAO, 2022). For 2023, the USDA-FAS (2023) forecast global chicken production to be 2% higher, with Brazil finally surpassing China as the number one chicken meat-producing country in the world.

From an economic perspective, according to market forecasts, chicken meat is expected to reach US$ 429 billion by 2028 (Wood, 2023), leading global meat production over the next decade. Chicken’s

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position in the global meat marketplace is due in part to an increasing preference for white meat. In 2031, protein from poultry will comprise 47% of overall meat protein consumed (OECD-FAO, 2022).

However, the increase in production and consumption can lead to adverse environmental effects (United States Department of Agriculture - USDA, 2021). As underlined by Cheng et al. (2023), poultry production can be responsible for: (i) greenhouse gas emissions (GHG), with 0.79 billion Mg of CO_2 eq per yr (FAO, 2017); (ii) water depletion and eutrophication (Kist et al., 2009), air (Chung et al., 2021) and soil pollution (Yang et al., 2023); iii) potential environment burdens due to discharged solid waste such as feed, feathers, and chicken manure (Chung et al., 2021). Meeting global demand for chicken meat while maintaining environmental quality is a global challenge.

Life cycle assessment (LCA) is widely used to assess the potential environmental impacts of any human activity along its entire life cycle (ISO, 2006a). In the poultry market, LCA has been applied to assess environmental impacts at all stages of the production chain (Skunca et al., 2018) or in parts of its cycle (poultry housing and slaughtering stages; Cesari et al., 2017). Skunca et al. (2018) and Costantini et al. (2021) demonstrated that feed production, energy and water consumption, biological waste discharge and treatment, and gas emissions are the most common negative environmental indicators of chicken meat production. Lima et al. (2019) argued that animal feed is the main factor responsible for adverse environmental impacts of poultry due to uncontrolled land use for grain production, high fertilizer use, fossil fuels, and water demand. Conversely, Gernaey et al. (2018) and Martinelli et al. (2020) emphasize the most widely used strategies to mitigate environmental impacts are: (i) the addition of different protein sources to feed, (ii) changes in land use and biological waste, and; (iii) addition of enzymes and amino acids to animal feed. Recently, Santi et al. (2022) evaluated the replacement of beef meal with poultry waste meal in an industry in the northeast region of Brazil and found reductions of up to 50% in the categories used.

Life cycle assessments on poultry production in Brazil have grown in the last decade. Silva et al. (2014) evaluated different crop production and slaughter practices. Lima et al. (2019) conducted LCA in the Central-West region of Brazil and found that soymeal end corn gluten led to better environmental outcomes than the standard poultry diet. Martinelli et al. (2020) evaluated the eco-efficiency of different poultry production systems in southern Brazil and identified corn and soybean production as the main contributors to GHG emissions.

However, Brazil has continental dimensions meaning a high spatial heterogeneity of impacts due to differences in environmental conditions, agricultural production, locations, and practices (Poore and Nemecek, 2018). Notably: (i) regional variability strongly influences LCA results (Bulle et al., 2019); (ii) existing studies in this area in Brazil are primarily from central-southern regions, which are responsible for almost 46 percent of the total chicken population in Brazil (IBGE, 2023); (iii) most of the existing data, for instance, those about feeding processes, are mainly sourced from databases that do not represent the current situation.

Additionally, LCA on poultry production has never been conducted in the Brazilian Amazon region. Indeed, North regions have had among the most significant relative increases, with Rondônia leading the expansion in area and production (IBGE, 2023). Consequently, studies evaluating the environmental burden of chicken meat production in this area are urgently needed, and the use of LCA in the poultry sector has revealed critical gaps that require further research, especially in areas where chicken meat production is increasing (Costantini et al., 2021).

There is a consensus that feed production is the crucial environmental hotspot for environmental impacts of the chicken meat production chain, as summarized by Skunca et al. (2018) in LCA studies in this sector. The use of residues in animal feed have been studied as an appealing alternative to improve the environmental performance in the sector, since materials that would otherwise be discarded are returned to the production chain. Finally, although the use of biological residues as an alternative source of nutrients has been encouraged, it is still poorly documented (Costantini et al., 2021), and the use of amino acids in animal feed composition has not been widely supported by environmental studies (Mosnier et al., 2011).

To fill these gaps, an LCA analysis of poultry production was conducted Rondônia to: (1) understand and analyze if the addition of the amino acid Lysine hydrochloride (HCL, hereafter) to chicken feed reduces the use of ingredients in the diet; (2) determine if the addition and substitution of beef bone meal with poultry viscera meal in feed minimizes environmental impacts of broiler meat; (3) identify, analyze, and suggest improvements for critical environmental points of the feed, housing, slaughter and processing, and retail stages of poultry production.

2. Materials and methods

The ISO 14040 and 14,044 are considered the most important international standards in LCA studies for products and services (Klöpffer, 2012). The ISO standardized an LCA study as developed in four phases (ISO, 2006a, 2006b): (i) goal and scope definition; (ii) life cycle inventory analysis (LCI); (iii) life cycle impact assessment (LCIA); and, (iv) interpretation. The first phase includes: (a) unit functional, (b) function, (c) allocation, (d) product system, (e) system boundary, and (f) data quality requirements. The LCI phase includes all essential inputs flow and outputs that must be collected to fulfill the function and generate the inventory. The LCIA step quantifies the impact inventory data within each impact category utilized by classification and characterization (Koch et al., 2022).

Most of the performed LCA studies about poultry systems' environmental performance generally build in an attributional approach (Alves et al., 2019; Lima et al., 2019; Costantini et al., 2021). This study conducted an attributional LCA for broiler meat produced in Brazil, from production to marketing, aiming to analyze the environmental impact of broiler production considering different animal feeding strategies.

2.1. Product system

The Production system consists of a farm in Rondônia (Fig. 1) with intensive production. Temperatures in poultry sheds are maintained by LPG gas (liquefied petroleum gas), manual feeders, automatic drinkers, nebulizers, fans, thermometers for temperature control, and screens and curtains. Feed consists of concentrate and mineral salt. Additional feed details and the main characteristics of the poultry housing and finishing system are presented in Supplementary Material (Table 1 SM).

2.2. Inventory analysis

Primary data were obtained through on-site visits in a broiler farm between September 2018 and August 2019. The inputs-outputs used for modeling the product system are shown in the Supplementary Material (Table 2 SM). Other data were collected from ecoinvent® v3.6, Agrifootprint, LCA Food DK, Industry data, ULSCI and ELCD.

Slaughter and carcass processing stages occurred simultaneously and at interconnected locations. The cut-off criteria followed processes of studies in LCA: personal protective equipment, vaccines, labor, knives and dishes, infrastructure, and machines were not included (Johnson and Schwartz, 2002), as they result in insignificant impacts (Ross, 2014). Electricity calculations considered the consumption of equipment used in the farm chicken and processing plant. Water was calculated by technical methods related to the system's discharge data and function time.

Methane (CH_4), carbon dioxide (CO_2) and nitrous oxide (N_2O) emissions from waste management were estimated according to guidelines from the Intergovernmental Panel on Climate Change - IPCC (Intergovernmental Panel on Climate Change - IPCC, 2006a, 2006b). Ammonia (NH_3) emissions were calculated according to Amon et al.

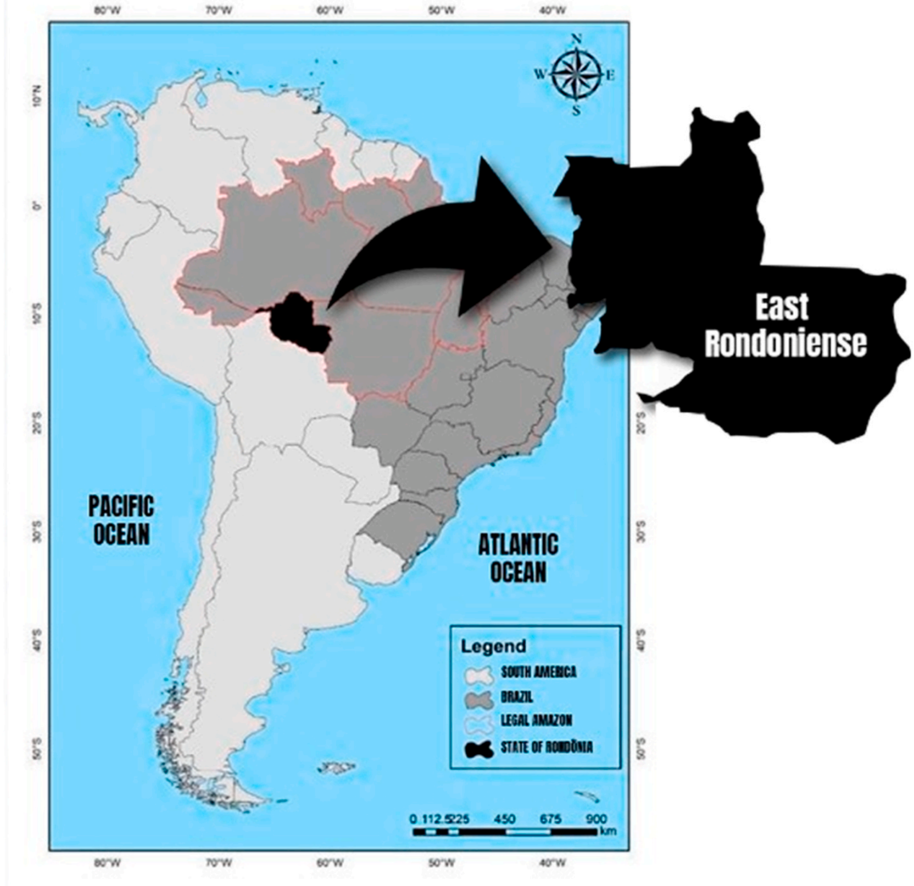

Fig. 1. State of Rondônia, region of the Brazilian Legal Amazon.

Table 1
Input and output flows considered in the scenario modeling.

Input *Raw material*	Unit	S1[a] (0.0101 kg)	S2[b] (0.26 kg)	S3[b] (0.23 kg)	S4[b] (0.29 kg)
Ammonia	kg	0.00156			
Ammonium Sulphate	kg	9.6E-04			
Sulfuric Acid	kg	0.00323			
Phosphoric Acid	kg	2.5E-04			
Salts	kg	5.0E-5			
Water	m^3	7.2E-4	3.3E-5	6.3E-4	7.7E-4
Caustic soda	kg	4.5E-5			
Nitric acid	kg	1.5E-5			
Others					
Electricity	kWh	0.0397	0.0002	3.6E-3	4.6E-3
Water	m^3	6.8E-4			
Effluent	m^3	4.04E-5			
Transport	tkm		1.2E-6	2.2E-5	2.9E-5

[a] Adapted from Oosterhuis (2005) and modified by Marinussen and Kool (2010).
[b] Costa et al. (2008).

(2016) and the nitrate (NO_3^-) and phosphorus (PO_4^{3-}) emission calculations were adapted from Halberg (2003).

Wastewater was estimated based on water consumption for every 100 L of water consumed, approximately 80 L of wastewater are generated, whereas the solid wastes considered the amount of material discarded by the staff (disposable gloves, plastic bag, film and other plastic waste). Allocation procedures were not necessary because the system has a single output (whole chicken) and unique sales value.

2.3. Impact assessment

The ReCiPe 2016 (H) method (Huijbregts et al., 2017), an update of the ReCiPe 2008 (Goedkoop et al., 2009) was used to estimate the potential environmental impacts based on input and output data of the inventory. Its use is recommended by Costantini et al. (2021) due to its reliability. The system framework and calculation of impacts were performed using SimaPro TM v. 9.2.0.1 Faculty. The faculty license is an academic version of the software with limited features. It is free for universities in non-OECD countries. Seven impact categories were considered: Climate Change (CC, kg CO_2-eq), Terrestrial Acidification (TA, kg SO_2-eq), Freshwater Eutrophication (FE, kg P-eq), Photochemical Oxidant Formation (POF, NMVOC), Agricultural Land Occupation (ALO, m^2.year^{-1}), Water Depletion (WD, m^3) and Fossil Depletion (FD, kg oil-eq), according to the recommendations for the Brazilian context from life cycle impact Assessment Research Network (RAICV, 2019).

2.4. Sensitivity scenarios

- Base scenario: Described in "Product System" (see item 2 of the methods). Used as reference to propose alternative or environmental improvement scenarios.
- Scenario S1: Addition of Lysine HCL (HCL, hereafter) amino acid to the feed. The experiment was conducted using 400 male broiler chickens from the Avian Farm Strain, with 5 treatments and 8 replications. This scenario considered treatments with HCL supplementation added to feeds at 1.04%, 1.10%, 1.16%, 1.22%, and 1.28% of the total lysine (National Research Council - NRC, 1994). Specific descriptions are in Borges et al. (2002).

- Scenarios S2, S3 and S4: addition of the Chicken (S2), ostrich (S3) and rhea (S4) viscera meal to replace beef meal (process from the Agri-Footprint database). The use of organic residues (not used for human consumption) from meat processing is an alternative raw material to produce animal feed with high nutrients content (Dozier et al., 2003). Scenario (S2) considered the chicken viscera (non-edible by-products) in the slaughterhouse (Supplementary Material Table 2). This process is a replacement of beef meal by poultry viscera meal at a proportion of 1.5% poultry viscera meal for every 0.012 kg of feed used at the growth stage. The simulation considered ostrich and rhea viscera in S3 and S4, respectively. The modeling did not consider the need to enrich chicken feed with any other nutritional ingredients to meet quality standards or nutritional composition. Further detailed descriptions were provided by Costa et al. (2008).

3. Results

3.1. Baseline scenario

The environmental impact of 1 kg of whole chicken meat was 3.37 kg CO_2-eq for climate change, 0.31 kg SO_2-eq for terrestrial acidification, 1.0E-03 kg P-eq for Freshwater eutrophication, 7.4E-03 NMVOC for photochemical oxidant formation, 6.15 m^2 years^{-1} for agricultural land occupation, 0.02 m^3 for water depletion and 0.43 kg oil-eq for fossil fuel depletion. Feed production was the process unit that contributed the most to the categories followed by poultry housing.

3.1.1. Environmental impacts of feed production

Emissions of CO_2 (72.2%), N_2O (26.5%) and CH_4 (1.3%) into the atmosphere were associated with fertilizer and diesel oil use in the agricultural phase of grain production. Ammonia emissions (88%) in the TA category and phosphorus (60%) and CH_4 (26%) in the FE category also were different from crop practices. For POF, NOx (80.5%) emissions were due to production of sodium chloride, while for WD, ALO and FD categories, water consumption prevailed to generate electrical energy, arable land occupation and the impacts due to use of diesel oil (Fig. 2).

Significant contributions of maize were due its presence and quantity in feed composition (Supplementary Material Table 1). Contributions also cover the presence and amount of maize in the three feed compositions, with the greatest participation being in the finishing and fattening phase (50%), followed by growth (43%) and pre-starter and starter (7%) phases.

Sorghum was another ingredient with a relevant contribution (23.7% in WD and 8.5%–4.5% for the other categories). Soybean contributed with 15.3% for FE and 14.2% for ALO, whereas the other categories had less than 8% contribution. Beef bones contributed to all impact categories: in CC (6.4%), TA (1.2%), FE (15.3%), POF (7.4%), ALO (12.1%), WD (16.1%) and FD (4.9%). Maize gluten contributed 16.4% to WD and from 0.7% to 5.6% to the other categories. The contribution of wheat bran ranged from 7.3% to 1%, and limestone contributed less than 1% to all impact categories (Fig. 2).

3.1.2. Environmental impacts of the poultry housing

One-day-old chicks contributed to all impact categories: CC (37%), TA (5%), FE (55%), 53% (POF), 99% (ALO), 59% (WD) and 56% (FD) (Fig. 3). The contributions to CC were due to CO_2 emissions (70.4%) associated with soybean production, while FE and POF were due to phosphorus (99%) and POF (62%) N_2O emissions, respectively, with the use of diesel oil. Finally, maize contributed 99% for ALO due to the occupation of arable land.

Poultry house litter was also relevant in poultry housing, with 52% (CC), 94% (TA), 38% (FE), and 8% (POF). The main contribution in TA was due to the NH_3 (99%) emissions associated with manure management (hatching eggs, poultry house litter, carcasses, and manure). The contributions of groundwater contaminants and soil phosphorus (48%), especially phosphate (46%), to FE were related to feeding and manure management (Fig. 3).

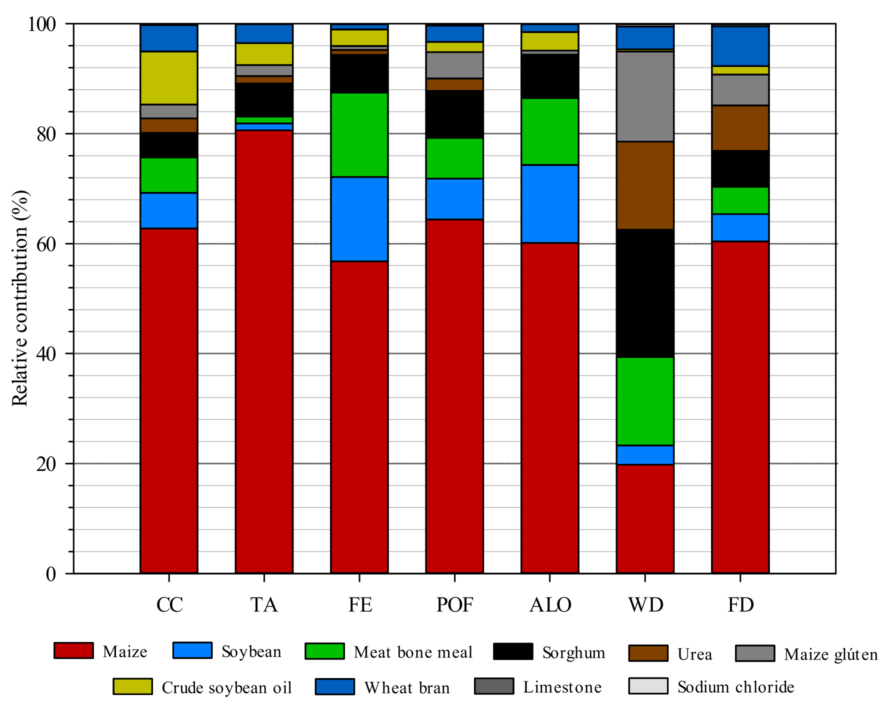

Fig. 2. Environmental impacts of feed production.
Legend: CC = climate change, TA = terrestrial acidification, FE = Freshwater eutrophication, POF = photochemical oxidant formation, ALO = agricultural land occupation, WD = water depletion, FD = fossil depletion.

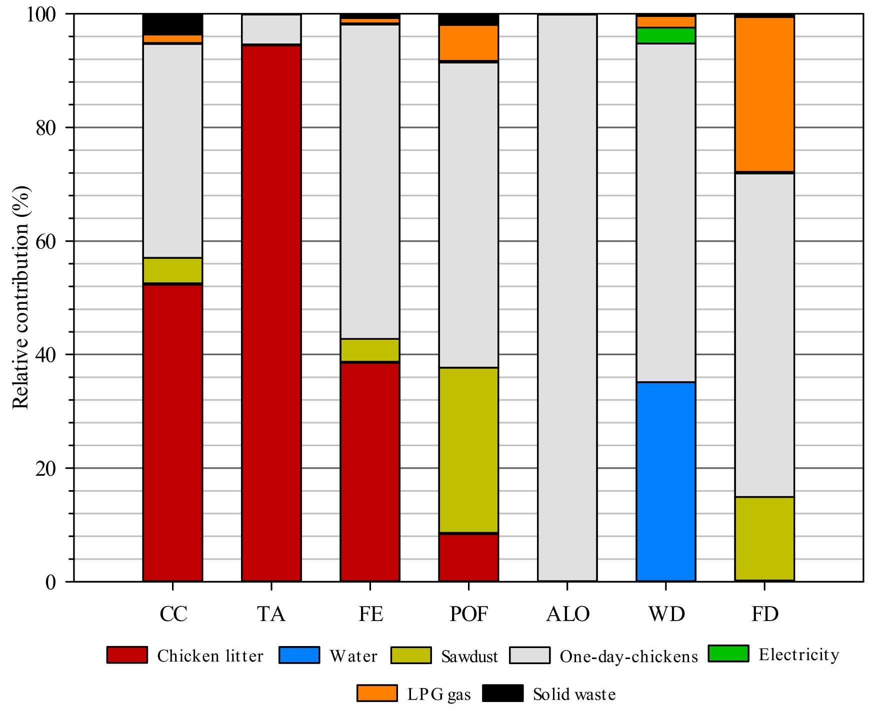

Fig. 3. Environmental impacts of poultry housing. Legend: as in Fig. 2.

The use of LPG gas to heat chicks was relevant to the categories FD (27%) and POF (6%), which were associated with the extraction of crude oil (94%) and N_2O (51%) emissions, respectively. Water used for hydration of chickens and hygiene of feeders and drinkers contributed 35% to WD. The wood sawdust was important for POF (29%) and FD (14%) flows due to N_2O (85%) emissions and fuel (53%), respectively.

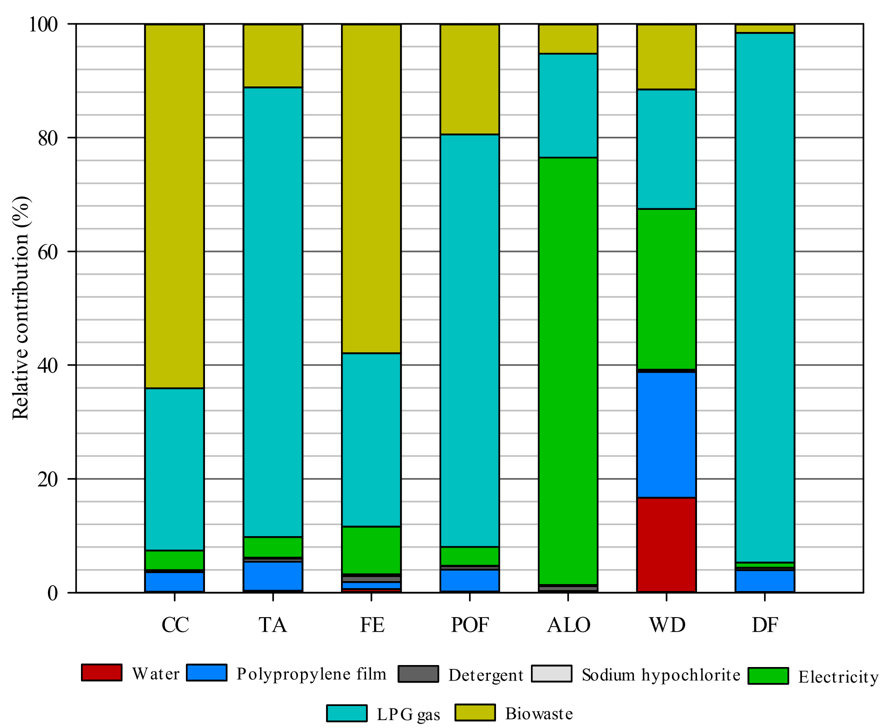

Fig. 4. Environmental impacts of slaughtering and processing. Legend: as in Fig. 2.

3.1.3. Environmental impacts of slaughter and processing room

The contributions of the processes used in this stage were dominated by LPG gas, biological wastes, and electricity; and moderately by packaging, water, detergent, and sodium hypochlorite. Contributions to ALO (99%) were associated with intensive occupation of forest areas as well as using dams to generate electricity (Fig. 4).

The biological wastes from the slaughterhouse (non-edible by-products) contributed to all impact categories (i.e., CC in 64%, 11% in TA, 58% in FE, 19% in POF, 5% in ALO, 12% in WD and 2% in DF) (Fig. 4). LPG gas was an important contributor to all categories (28% in CC, 79% in TA, 30% in FE, 72% in POF, 18% in ALO, 21% in WD and 93% in FD) (Fig. 4). CO_2 and N_2O emissions dominated contributions in CC, TA, and POF category; phosphate dominated contributions to FE; and fuel oil dominated contributions to FD.

3.1.4. Environmental impacts of retail

The contributions of this stage to the environmental impacts of meat production were dominated by electricity and packaging. Refrigerant gas, diesel, water, detergent, and wastewater did not make significant contributions (Fig. 5). Electricity contributed 67% of the impacts in the CC category, 47% in TA, 56% in FE, 45% in POF, 56% in ALO, 64% in WD and 44% in FD (Fig. 5).

Demand for chicken meat refrigeration in freezing chambers and refrigerators was crucial. Thus, this stage had high consumption of electricity, 0.11 kWh (0.39 MJ) (92%) per kg of meat, when compared to the poultry housing, slaughter, and processing stages.

The use of corrugated board boxes in transportation made relevant contributions to six of the seven categories: 22% in CC, 27% in TA, 40% in FE, 24% in POF, 43% in ALO and 29% in FD. These contributions were associated with CH_4, CO_2, NH_3, and P (phosphorus) emissions from raw materials and production activities of the cardboard box (Fig. 5).

The use of water for sanitizing contributed 34% to WD. Diesel used for electricity generation (in the absence of public supply) contributed 18% to POF and less than 9% to the other categories. Detergent contributed 4% to FD and less than 2% to the other categories. The refrigerant gas flow, LDPE, and wastewater contributed less than 1% (Fig. 5).

3.2. Strategies to mitigate the environmental impacts: sensitivity scenarios

3.2.1. Addition of lysine HCL to the feed

The contributions of S1 to the impacts was similar to those of the base scenario for all impact categories. There was a less than 1% increase in the impact categories with the addition of 1.5% HCL to the growth feed poultry (Fig. 6).

The main contributing flows in the scenarios (base scenario and S1) were CO_2 (73.5%), NH_3 (88%), phosphorus (95%), N_2O (81%), land occupation (98%), electricity (83%), and energy (88.2%), for the impact categories CC, TA, FE, POF, ALO, WD, and FD, respectively.

3.2.2. Substitution of beef bone meal by poultry viscera meal

Scenarios S2, S3, and S4 indicated that the substitution of beef bone meal with poultry viscera meal (broiler, ostrich and emu viscera meal) in feed production, resulted in reductions above 5% for the impact of categories CC and TA (5.3% and 5.1%, respectively), and 1.7% for FE, 1.9% for POF, 1.8% for ALO, 2% for WD and 2.75% for FD (Fig. 6). The contribution of broiler viscera meal (18.7%) had lower impacts compared to ostrich viscera meal (19.8%) and emu meal (20%) for WD (Fig. 6).

The main contributing flows in scenarios S2, S3, and S4 were CO_2 (CC, 19%), NH_3 (TA, 26%), P (FE, 30%), N_2O (POF, 21%), occupation of arable land (ALO, 29%) and coal (DF, 37%). The reduction of environmental impacts was more expressive when chicken feed for growth used in the baseline scenario was compared with feed for chicken growth of S2 (where beef bone meal replaced by broiler viscera meal). There was a reduction of 43.5% in CC, 43.8% in TA, 47.8% in FE, 47.6% in POF, 47.8% in ALO, 47.3% in WD and 46.7% in the DF, when the sensitive scenario S2 was modeled.

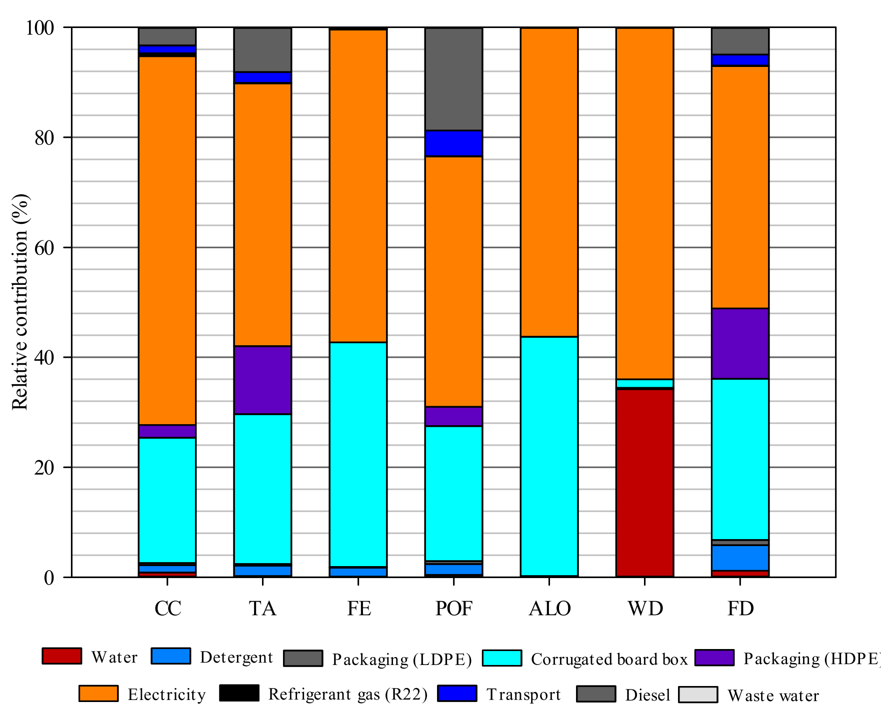

Fig. 5. Environmental impacts of retail. Legend: as in Fig. 2.

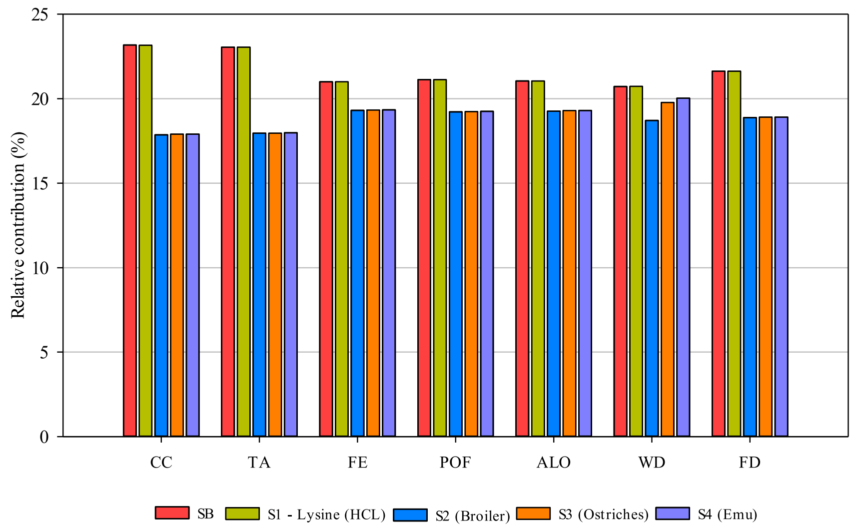

Fig. 6. Environmental improvement scenarios for broilers fed in the growth phase. Legend as in Fig. 2.

4. Discussion

The potential impact of 1 kg of whole chicken meat corresponded to 3.37 kg CO_2-eq for the CC category. These results were similar to those reported by Cesari et al. (2017), 3.0–3.25 kg CO_2-eq per kg of live chicken, and to the variation of 0.85 and 4.2 kg CO_2-eq found by Costantini et al. (2021) in a review of 45 studies on chicken meat production.

4.1. Environmental impacts of feed production

Animal feed, in this study, was identified as one of the main factors responsible for environmental impacts. Animal performance was related to feeding efficiency, weight gain, and feed conversion rate. Thus, make it clear that new emissions reduction strategies must focus mainly on the feed for chickens at the growth, finishing, or fattening stages.

Corn and soybean were the ingredients that presented an essential contribution to the impacts arising from feed. They made similar contributions to those found by Skunca et al. (2018), who applied life cycle assessment (LCA) to 20 farms in Serbia and found averages of 1.81–2.36 kg CO_2-eq. Other studies have reported that grain (corn, soybean, and wheat) and energy were dominant flows for the GWP (global warming potential), CED (accumulated energy demand), TA, and FE categories. Bengtsson and Seddon (2013) applied LCA and found that feed consisting of soybean meal and grain is the main hotspot in Australian chicken products, representing 79% of overall contributions.

These findings explain why Costantini et al. (2021) recommended using alternative sources of protein and feed that did not involve food competition, among other options. Using animal feed alternatives has been encouraged to minimize the environmental consequences of poultry meat production (Leinonen and Kyriazakis, 2016; Sala et al., 2017, 2020).

4.2. Environmental impacts of the poultry housing

The contributions were due to breeding one-day-old chicks (mainly). This explains why the inclusion of one-day-old chicks (for future fattening) in studies of LCA is highly recommended for the environmental assessment of poultry supply chains, according to the Livestock Environmental Assessment and Performance Partnership (LEAP, 2016).

In the chick starter feed, grain used (i.e., soybean and maize) underscore the need for environmental improvements. The analysis of the production efficiency of animal feed with maize and soybean as main ingredients, agricultural inputs, and dietary changes to low-impact foods may indicate better options (Clark and Tilman, 2017; Zucali et al., 2018).

Another important contribution to poultry housing environmental impacts was the chicken litter. The reduction of only 1% in the overall mortality rate in this study would improve the environmental performance of chicken meat, especially in the CC (1.2%) and ALO (1%). Several factors must be considered to reduce the broiler mortality rate to acceptable standards in the growth and finishing phase: climate, moisture, diseases management, hygiene, growth rate, design of house, feed & water, and other factors (Limbergen et al., 2020; Yerpes et al., 2020; Junghans et al., 2022).

Another option for improving the environmental performance in the phase is to enjoy the GHGs generated by poultry litter to produce biogas in digesters. Recovering methane is an exciting option that reduces the emission of harmful gas into the atmosphere and, in association, generates a cost-effective source of renewable energy, an alternative to the use of fossil fuels (Qureschi et al., 2022). However, it is necessary to assess the environmental efficiency of biogas production since hydroelectric power is Brazil's primary electricity production source and is considered clean and safe compared to other global electricity production (IEA, 2012; Ritchie and Roser, 2020).

Another option is broiler litter incineration and utilization of the generated heat for broiler-house heating, thus lowering GHG emissions and energy consumption, as noted by Ogino et al. (2021) when evaluating the environmental impacts of conventional broiler chicken production in Japan using the LCA; an outcome recently confirmed by Zisis et al. (2023) in their overview for Mediterranean areas.

The GHG emissions from this stage were not just from managing manure of poultry litter, as many studies have reported (Costantini et al., 2021; Fernández-Ríos et al., 2022; Rai et al., 2023). Emissions were also due to sawdust, solid waste, LPG gas, and electricity (to a lesser extent when compared to chicken litter and one-day-old chicks breeding emissions). Lima et al. (2019) performed an LCA from cradle to farm gate in Brazil and concluded that the contribution to GWP was due to the N_2O emissions from waste management.

4.3. Environmental impacts of slaughtering and processing room

The impact of this phase was due to various downstream processes (packages, electricity, LPG, and wastes). The dominance of impacts of energy flows and biological wastes in this unit was similar to that found by Skunca et al. (2018), who recommended the adoption of strategies for energy efficiency in slaughterhouses.

The decisive contribution of electricity and LPG gas to slaughterhouse emissions point to the importance of clean, renewable energy usage. Another critical point is that improvements in the carcass yield of the strains may lead to a substantial decrease in their environmental impacts (Silva et al., 2014; Tallentire et al., 2016).

Poultry production can offer several products and by-products in the phase; therefore, mitigation strategies for environmental stress in chicken meat production chain should focus on using biological sources of protein, which is still not a common topic in LCA studies (Costantini et al., 2021). Thus, the LCA can allow the investigation of different contributions generated by the slaughter process that influence decision-making and it assists in the choice of resources that minimize the possible environmental impacts (Tagne et al., 2022).

4.4. Environmental impacts of retail

In this study, the retail stage was primarily responsible for electricity consumption in the production of chicken meat. This is also identified in the literature. The retail stage had high energy demand and electricity consumption per kg of chicken meat in 82 stores in Serbia, ranging from 1.69 to 8.46 MJ kg^{-1} (Skunca et al., 2018).

Using energy-efficient refrigerators and freezers can contribute to reducing energy consumption at this stage. At the same time, studies to improve energy efficiency and alternatives to decentralize electricity generation with less impact can support decision-making for better environmental performance (Das and De, 2023).

As for packaging, companies should be encouraged to take measures aimed at alternative packaging solutions to improve the sustainability sector (Santi et al., 2022) since the packaging is indispensable in transport, storage, and conservation of chicken meat.

In general, as stated by Bengtsson and Seddon (2013) and Costantini et al. (2021), often sufficiently detailed information on the retail store packaging is missing in the cradle-to-retail or consumer LCA studies, being the present study a kick to the beginning of the studies in these phases.

Knowing the environmental impacts throughout the chicken meat production chain is essential because of the growing importance of Corporate Social Responsibility (CSR) includes changes that are increasingly turning to proactive and reliable management of the sectors (Hens et al., 2018).

Alternatives for environmental improvement can be implemented in chicken meat chains, as indicated in the literature. Skunca et al. (2018) discuss several options: grain legumes as a protein source in feed; treatment of chicken litter in a biogas digester; usage of energy-efficient systems through the entire chain; and more sustainable consumption in terms of waste recycling when it comes to retail.

5. Sensitivity scenario and recommendations

5.1. Addition of lysine HCL to the feed

Borges et al. (2002) found the addition of Lysine to the feed of broilers from 22 to 42 days affected the feed conversion and carcass weight gain. The simulation of environmental data in this study did not show any reduction in environmental impacts. In this case, the dietary lysine levels did not affect feed intake, and consequently, environmental performance was null. As reported by Lima et al. (2019), the regional aspects where the broilers are produced and the production system should be considered during the LCA, which may explain the difference in the results of this study.

For Mosnier et al. (2011), the addition of amino acids (tryptophan, valine, L-Lysine, L-threonine, and methionine) to the diet of broilers led to reductions in environmental impacts; the addition of Lysine reduced impacts of terrestrial eutrophication (less than 1%), terrestrial ecotoxicity (of 1%–2%), and cumulative energy demand (of 4%–5%) for pork and chicken feed productions. Incorporating amino acids to feed based on cereals and soybean meal, which are associated with deforestation, reduced climate changes (1%–2%), and soil acidification (less than 1%).

However, as stated by the cited authors, incorporating Lysine in feed and its contributions to environmental impacts should be carefully considered since the literature shows that crude protein-rich ingredients may inhibit the positive effects of the addition of Lysine. These results are due to the user inputs considered for the industrial production of Lysine, which includes different materials and energy: 1 kg of L-Lysine requires 1 kg of sugar, 0.5 kg of corn starch, 0.5 kg of wheat, 0.3 kg of ammonia, and 36 MJ of energy, supplied as electricity (50%) and natural gas (50%) to the plant.

5.2. Substitution of the beef bone meal by poultry viscera meal

Using biological residues from slaughterhouses for feed production is an exciting option that is rarely discussed in studies using LCA (Costantini et al., 2021). The results showed that using biological sources of nutrients increased environmental benefits for the production system and contributed to waste management.

The strategy for the recovery of biological residues from the poultry industry can contribute to the environment and improve the efficiency of resources, in addition to fostering the premise of a circular economy. The environmental burden of by-products from the poultry industry is a subject of scientific studies. However, it requires further studies using LCA focused on the potential impacts and life cycle cost (Kanani et al., 2020).

These findings provide the foundation for discussions about the recovery of biological residues as impact mitigation strategies and demonstrate that LCA methodology is essential for sharing production data from broilers (Bengtsson and Seddon, 2013).

It has been proven that the detailed description of the composition of the ration and phases of the birds' diet allowed researchers and stakeholders to find option cleaner production strategies for chicken meat. However, it is important to emphasize that each feeding strategy must be thought out and formulated according to the nutritional requirements of the chickens and the expected production level.

Furthermore, evaluating the nutritional function of the meat meal substitute is necessary. According to Smetana et al. (2015), alternative substitutes have different nutritional profiles and, therefore, different nutritional values. At the same time, different aspects of nutritional quality (protein and amino acid content, vitamins, fat and fatty acids, etc.) can vary in different proportions. Thus, it is necessary to develop a nutritional value estimate which would reflect the qualities of meat and substitutes for further studies. Further studies are needed to comprehensively assess the financial and environmental benefits of biological residues from poultry production and their feasibility for commercial application.

6. Conclusions

The hypothesis that adding amino acid (lysine HCL) to the feed of broilers would reduce environmental impacts was not confirmed. The simulation of data in this study showed no apparent reduction in environmental impacts, likely due to the use of inputs and materials rich in crude protein and energy to lysine production. Another factor may have been the dominant feed contributions (e.g., corn and soybeans), which can conceal the reduction of impacts. The substitution of the beef bone meal with poultry viscera meal in animal feed showed a decrease in all categories of analyzed impacts. The drop was more enhanced (above 43%) for the chicken growth phase feed, which is the best option. Chicken viscera meal production's environmental performance most closely resembled ostrich viscera meal and emu. Feed production was the dominant phase in six of seven impact categories due to CO_2, N_2O, and CH_4 indirect emissions from fertilizer and diesel oil used in grain production. Improvement strategies to reduce emissions within system boundaries should focus primarily on weight gain and feed efficiency broiler chicken. Carbon dioxide emissions from feed dominated the poultry housing phase, the one-day-old chicks, and NH_3 from poultry house litter. Alternative sources of animal feed and efficient use of renewable and non-renewable resources in poultry production are strongly recommended for reducing the overall environmental impact. Slaughter and processing were dominated by energy and biowaste flows and contributed in all impact categories. At the same time, electricity consumption was the determining factor in the retail phase with 0.11 kWh (0.39 MJ) (92%) per kg of meat. The biological waste from slaughter can be treated and applied to the soil, reducing dependence on fertilizers. Another practical use would be the production of by-products from the slaughter of poultry for animal feed. Using energy-efficient refrigerators and freezers and improving energy-efficiency alternatives to decentralize electricity generation with less impact can support the retail decision-making phase. This study represents an important novelty in considering the environmental effects related to the use of amino acids in poultry, a topic still unexplored by using LCA studies. Future research will focus on: *i*) input and output model flow in the industrial production of biowaste flour; and *ii*) the proposal of specific diets considering the nutritional requirements of chicken.

CRediT authorship contribution statement

Edmar Costa Alves: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Resources, roles, Writing – original draft. **Israel Henrique dos Santos Alves:** Data curation, Investigation, Software, Validation, Visualization. **Bruna Borges Soares:** Formal analysis, Investigation, Methodology. **Aurélio Ferreira Borges:** Conceptualization, Data curation, Validation. **Arshad Jalal:** Formal analysis, Investigation, Methodology. **Arun Dilipkumar Jani:** Data curation, Validation, roles, Writing – original draft, Writing – review & editing. **Cassio Hamilton Abreu-Junior:** Data curation, Supervision, roles, Writing – original draft. **Gian Franco Capra:** Data curation, Validation, Visualization, roles, Writing – original draft, Writing – review & editing. **Thiago Assis Rodrigues Nogueira:** Data curation, Formal analysis, Investigation, Validation, roles, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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