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Research article

Reducing the environmental impacts of Brazilian chicken meat production using different waste recovery strategies

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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

Chicken meat has achieved significant index rates worldwide, with Brazil leading production and exports. The agribusiness significance has led to strengthening attention to the environmental burdens produced by the poultry industry. This research considered reducing the environmental impacts in the life cycle of Brazilian chicken meat regarding strategies for recycling waste from the production process. An attributional cradle-to-gate life cycle assessment was performed, with the functional unit of 1 kg of slaughtered and unpacked chicken meat. The two suggested scenarios used: i) chicken bedding for biogas production and ii) chicken carcass waste as meat meals in feed production. Handling poultry litter for biogas production avoided methane and ammonia emissions, reducing over 50% of the environmental indicators of Climate Change, Terrestrial Acidification, and Freshwater Eutrophication. Reuse poultry waste to produce meat meals reduced from 12% to 55% in all impact categories, decreasing emissions from carcasses destined for decomposition in landfills and using less raw materials from bovine sources. Investigating the environmental performance of the chicken meat production chain encouraged the circularity of natural resources and waste recovery strategies in the system boundary, thus helping to accomplish Sustainable Development Goals 7, 9, 12, and 13 of the UN Agenda 2030

1. Introduction

The poultry sector is the fastest-growing livestock production, especially in developing countries. Estimates indicate that annual poultry production will exceed 37 billion by 2050, driven by market demand, population growth, income growth, and urbanization (Yitbarek, 2019; Yildiz, 2021). In 2022, Brazil (14.524 million tons) surpassed China (14.7300 million tons), taking second place in world poultry production, led by the United States (201.378005 million tons). Regarding exports, Brazil ranks first globally with around 35.6% or 4.822 million tonnes in 2022 (ABPA, 2023). Thus, it is a relevant economic activity with great potential to generate direct and indirect jobs throughout its production chain (Ferreira et al., 2018).

Besides the production and export indicators, chicken meat stands out regarding food safety, nutrition, and availability. Vitamin B, minerals, and low levels of saturated fat characterize the product. It is an essential source of proteins and is also the animal protein with the lowest relative cost compared to other livestock production (Windhorst, 2006; FAO – Food and Agriculture Organization, 2010; USDA – United States Department of Agriculture, 2021). However, the constant increase in demand for chicken production has raised concerns about the negative environmental impacts throughout its production chain. The greenhouse gas and dust emissions, odors, incorrect management of chicken bedding and dead animal carcasses, the soil and water contamination by

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disposal of chemicals elements or microorganisms are examples of contributors to potential negative environmental impacts from the chicken meat production chain (Oviedo-Rondón, 2008; Palhares and Kunz, 2011).

Using the Life Cycle Assessment (LCA) method makes possible a broad view of the potential environmental impacts associated with a product system and the possibility to propose contributions to improve its environmental performance. In addition, its use allows for sketching a more accurate picture of the proper balance between the advantages and disadvantages of product and process selection concerning environmental consequences (Willers and Rodrigues, 2014). In recent years, LCA has been frequently used to evaluate the environmental impacts of different systems, emphasizing research in livestock and animal products. Silva V. et al. (2014), Santos Junior et al. (2017), Willers et al. (2017), Soares et al. (2019), and Cabral et al. (2020) are some examples of works that used the LCA in assessing the impacts of the production of chicken meat, cheese, beef cattle, and buffalo and goat milk, respectively.

Studies applying LCA to identify environmental impacts in the chicken meat production chain in several countries are available in the literature. For example, Bengtsson and Seddon (2013) performed an LCA in an Australian production system, where feed production stood out as the most impactful stream in the chicken supply chain. The authors stated that farm management contributed to approximately one-third of the overall impact, mainly due to energy consumption and ammonia emissions. Other studies have evaluated chicken meat production systems in Iran (Kalhor et al., 2016), Italy (Cesari et al., 2017), Serbia (Skunca et al., 2018) and Mexico (López-Andrés et al., 2018), all of which have shown similar results. Overall, the environmental burdens of chicken meats were mainly due to rearing systems, specifically, feed production and energy use. In Brazil, a study by Martinelli et al. (2020) analyzed the eco-efficiency of chicken production and pointed to effluents from slaughterhouses and farm excreta to generate more significant savings and add value to the product system. More recently, Cooreman-Algoed et al. (2022), in Belgium, evaluated the environmental profile of chicken meat, whose results align with previous studies, highlighting that farming systems contribute most to impacts due to animal feed (chemical use and energy requirements) and emissions (decomposition of organic waste).

The literature emphasizes the importance of LCA studies in agroindustry and their use for improving production systems, given the relevance of the environmental impacts caused by this production chain. Using techniques and processes to minimize costs and add value to the waste generated is a promising research field with profitable economic gains. Studies addressing the treatment or reuse of waste in poultry farming have proven economically advantageous, such as using chicken bedding in digesters for biogas production for thermal energy (Barbosa et al., 2017; Dornelas et al., 2017). Other studies, such as Katajajuuri et al. (2008), Caires et al. (2010), and Xavier et al. (2012), to cite some, demonstrated the use of wastes for feed production. Besides, Silva E. et al. (2014) state that adding poultry residue to diets tends to follow the growth of poultry production for providing a better environmental and nutritional alternative to current conventional feed grains methods.

Despite its technical and economic feasibility, the development of studies with a LCA approach emphasizing waste reuse proposals to indicate the environmental feasibility and reliability of these applications is challenging.

It is necessary to provide more information on environmental impacts and the solutions to reduce the environmental burden in the poultry sector. This effort can help make product access to the markets or their permanence, fulfilling the continuous requests of stakeholders (including consumers, partners, and government) regarding the compliance of environmental performance indicators. The knowledge, identification, and improvement of the potential for environmental impacts in the chicken meat chains align with sustainable development principles, which seek a balance between the economic, social, and environmental dimensions. These principles are today well established as achieving the Sustainable Development Goals (SDGs) of the United Nations Agenda, specifically related mainly to SDGs 7, 9, 12, and 13 (United Nations, 2015).

In this sense, this study aimed to evaluate the environmental life cycle performance of chicken meat produced in Brazil and propose different strategic routes to recover waste from this production process.

2. Materials and methods

2.1. Area of study

A chicken processing industry in Bahia state was selected for primary data collection and definition of a geographical reference site (Latitude: 15°19′26.16″ S; Longitude: 41°18′01.52″ W; Elevation: 905 m). Bahia is an important player in national production, reaching a 2.40% share in 2022, ranking as the ninth largest producer and the top producer in the North and Northwest Brazilian regions (AviSite, 2023).

The industry of this study is responsible for much of the supply chain for the final product, including the processes of feed production, poultry farm, packing plant, and distribution of products to retailers. It can slaughter 13,000 birds/day, thus considered large-sized in the confinement of animals and medium-sized in the slaughter (Bahia, 2018). The key factors considered in selecting the industry were the level of technology used in the processes, reliability, assured access to information, and availability to participate of the research.

2.2. Product system

Initially, the industry purchases the inputs for feed production for chicken diets, namely corn, soybeans, soybean oil, beef meal, vitamins, and minerals.

The product system considered in this study (baseline scenario) and the corresponding unit processes are shown (Fig. 1), with their respective inputs and outputs. Shaded in grey are the improvements proposed in scenarios S1 and S2.

The contents of the ingredients vary with the lifetime of each animal group. Therefore, the consumption is quantified weekly by the difference between the amount of feed supplied and the leftover feed. The whole amount of each ingredient was calculated based on the nutritional requirements for a batch of animals throughout their life cycle.

Batches averaging 60,000 1-day-old chicks of the Cobb 500 breed vaccinated always arrive on Wednesdays. They are slaughtered at ages ranging from forty (40) to forty-five (45) days of life (Monday through Friday), according to the processing schedule.

The industry produces firewood (eucalyptus wood) to feed the heaters in the aviaries and supply the boilers. The water used throughout the system comes from four artesian wells on the same property as the company. The pumping system moves the water from the wells to storage tanks, which are distributed to different sectors of industry randomly, without proper control or standardization on which well should supply a given sector.

All birds for slaughter are from their own poultry house that uses an intensive breeding system, comprising seven streets with three sheds of 1260 m^2 each, resulting in an average density of 15.87 birds/m^2. Each street represents a production lot.

The industry only slaughters poultry from its aviary, installed on the same land as the industry, which uses an intensive breeding system. The location of the aviary complies with sanitary regulatory conditions and minimizes the activities of transporting birds to the slaughterhouse.

After sending the birds to the slaughter stage, occurs cleaning the empty sheds to receive a new batch of 1-day-old chick. Handling the chicken bedding from this process is a challenge to overcome. The average mortality rate of the animals is 6%, as recorded by the industry, which sends the dead animals to the municipal landfill. Birds that do not develop properly are donated.

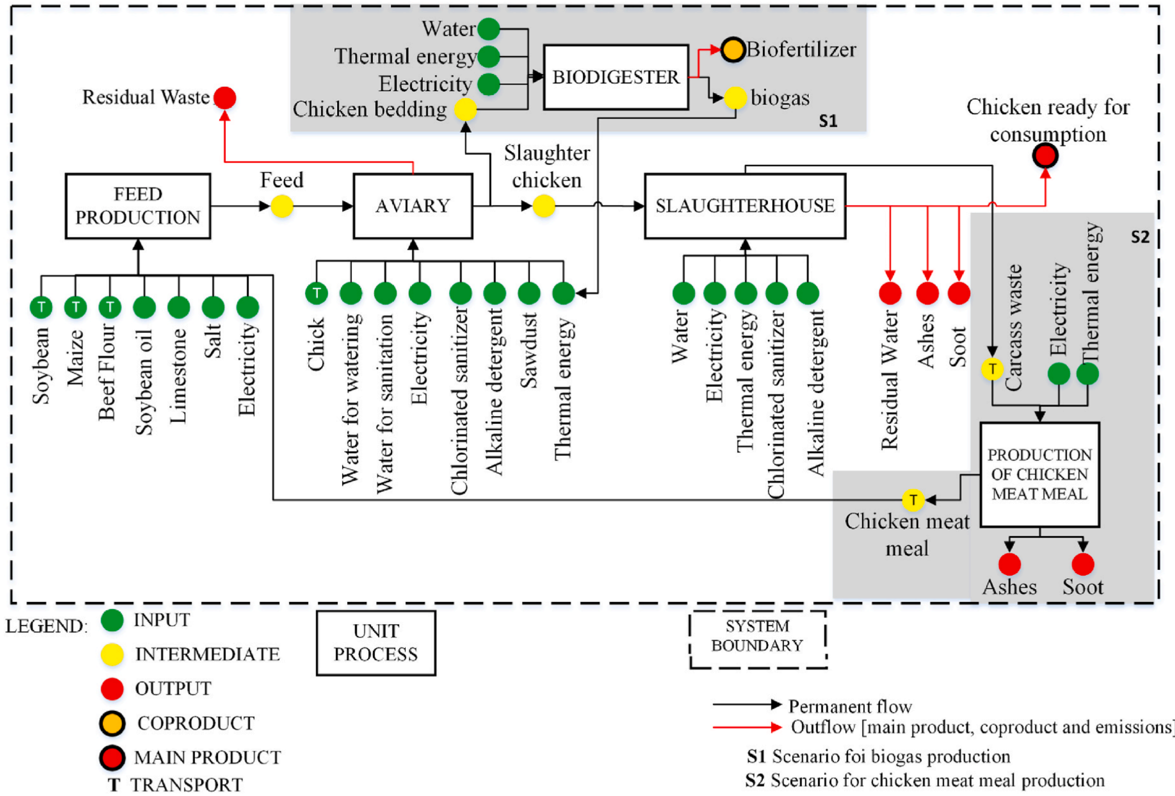

Fig. 1. Product System for 1 kg of chicken meat ready for packaging, considering the baseline scenario, S1, and S2.

The temperature control in the houses occurs by heating from burning wood, whose thermal power in each poultry house is up to 600,000 kcal/h. This procedure is necessary until the animal is three weeks old. Later, the adult birds require lower temperatures (up to 16 °C), for which four 1/5 HP fans provide ventilation to maintain in-house temperatures within the birds' comfort zone.

After the slaughtering of healthy chickens, the inedible offal, feathers, gland, organs, and other parts of the chicken not intended for human consumption (chicken carcass waste) are sent to the waste sector and then to the municipal landfill. The industry has a treatment pond where they dispose of their wastewater, including blood.

2.3. Proposed scenarios definition

Using life cycle thinking, it was possible evaluating the environmental impact of circularity within a system and make the best decisions accordingly. The scenarios suggested are known to be both technically and economically feasible, as identified in previous literature. However, further studies are needed to assess their environmental viability. Thus, two processes were selected: the use of chicken bedding in biodigester for biogas production as a source for heating the warehouses (S1); and the use of chicken slaughter waste in producing a chicken meal for animal feed (S2). From the life cycle perspective, these scenarios aim to improve processes and promote the development of systems that reduce waste throughout the production chain. This approach aligns with the principles of the circular economy.

2.3.1. Biogas production from chicken bedding (scenario S1)

The product system studied (baseline scenario) uses a wood oven for heating the poultry house. Ceratto (2016) states that heating expenses correspond to 11% of total costs for poultry farms, making it a prime area for operational improvements to reduce costs. This study suggests using chicken bedding for biogas production to heat poultry houses. The aim is to minimize energy expenses and address the problem of managing poultry waste.

The life cycle inventory obtained allowed for determining if chicken bedding could produce enough biogas to meet the heating needs of a poultry house, helping to assess the conditions and capacity of the biogas production. The heat demand is 1096 MJ, and the litter produced is 1.16 kg per kilogram of live chicken weight. The production of biogas is 0.1681 m^3 in 42 days, whose period corresponds to the time of a production batch in the aviary. A batch-type biodigester with a capacity of 6.04 MJ receives the chicken litter from the cleaning process of the sheds. The study used only the amount necessary to meet the heat demand of the aviary, considering the surplus burning.

2.3.2. Production of chicken meal from chicken waste (scenario S2)

The product system studied comprises feeding chickens with beef meals, which products include chicken parts that are not deemed suitable for human consumption and therefore discarded as waste (i.e., feathers, inedible offal, and blood).

Thus, scenario S2 modeling considered the beef meal process from the Agri-Footprint database, changing the input to chicken carcass waste instead of cattle meat byproducts. The rate of 14% of chicken meal from chicken waste for each kilogram of input was considered, according to Costa et al. (2008).

In this situation, it was feasible to substitute half of the beef meal with half of the chicken meal made from chicken waste to fulfill the need for animal meal in the food blend. However, no simulation was proposed with other scenarios, for example, substituting 100% of bovine meat meal, as changes in ingredients could impact animal nutrition once it was beyond the focus of the study.

The study considered sending the non-profitable parts of the poultry slaughter for processing in a beef meal industry far from 100 km to produce the two animal meals. The economic values of these products were outside the scope of this work.

2.4. Life cycle assessment

2.4.1. Goal and scope definition

This research aims to guarantee that the poultry industry obtains accurate and pertinent information for executing environmental evaluations of their industrial operations. Thus, this work intended to compare the traditional production system of poultry meat with scenarios considering waste recovery strategies from poultry houses and slaughterhouses, circulating them in the production chain, and establishing the following requirements.

- the function: to produce chicken meat for human consumption;
- the functional unit: 1 kg of slaughtered and cleaned chicken meat (CM) to be packed (i.e., not packed) and ready for consumption;
- the system boundary: cradle to the slaughterhouse gate, comprising the stages of feed manufacture, poultry handling, slaughtering, and cold storage.

2.4.2. Life cycle inventory analysis (LCI)

Data quality requirements of the LCI phase used primary data whenever possible and secondary data when necessary. Primary data were collected locally through monitoring production steps, interviews, and document analysis. The literature and inventory database were the sources of secondary data. Further, the pedigree matrix calculated the variances for each inventory item, according to Weidema et al. (2013).

The quantitative survey of elementary flows considered data collected at specific points, meetings with management staff, and analysis of industry documents concerning production and warehouse records.

As the product system studied results in more than one product with the same inputs and outputs of materials, energies, and emissions, it is necessary to establish an allocation method to distribute environmental impacts. Thus, the study evaluated both economic and mass allocation methods. The economic allocation method was selected based on its recurrent use in similar works (Bengtsson and Seddon, 2013; Silva V. et al., 2014; Cesari et al., 2017).

Furthermore, the economic allocation was considered due to its greater representativeness, as mass allocation may understate some environmental impacts.

Poultry litter's use as a representative waste product in mass allocation can overshadow the true environmental impact of other inputs and outputs. Most of the time, economic allocation is a more suitable method for reflecting the intent of the production system.

The economic values were collected in commercial establishments in the region since the industry granted only the retail selling price of the products. Therefore, the chicken cut valuation considers the economic value of each cut multiplied by its production volume and divided by the total production volume of all cuts. Subsequently, the economic allocation calculation and the shares were performed (Table 1).

The methods used to collect input, output, intermediate products, and byproducts data were as follows.

i) Energy: by analyzing the company's electricity bills.
ii) Water: as the industry did not have water control measurements in the shed sector, a water meter was installed for registration purposes for this study.
iii) Wood: the amount of wood used in the slaughterhouse boiler considered the difference between the volumes consumed before and after the heating period.
iv) The ratio of kg/m^3 and MJ/kg was performed based on the descriptions contained in the process of the eucalyptus wood item in the Ecoinvent 3 database. The calculus of the wood outputs (ash and soot) followed the study by Santos Junior et al. (2017), using 2.61% ash from the wood input, with the difference considered as soot (97.39%).
v) The difference in the carcass weight before and after the chilling process yielded a water absorption ratio of 8%.
vi) Waste, blood, and inedible viscera: a percentage of 15% of the animal's live weight ratio was estimated, according to Barbosa et al. (2001).

The estimation for biogas use considered the following calculations and parameters.

- Palhares (2004), where the biogas production per kg of chicken bedding with wood shavings is 0.01712 m^3;
- Santos (2001), established the production method with 15% inoculum, 75% water, and 10% chicken bedding;
- Catelan (2007), for the choice of gas heater equipment (Infrared gas heater);
- Funck and Fonseca (2008), for the gas system energy consumption (Equation (1)):

$$EC_{gas} = \frac{TGC \times LCV}{1,000,000} \quad (1)$$

where:

EC_{gas} = Energy consumption of the gas system (GJ);

TGC = Total gas consumption (m^3);

LCV = Lower Calorific Value, which is 35,900 kJ/m^3 for biogas, according to Funck and Fonseca (2008).

The excess biogas generated was disposed of by direct flaring.

The researcher validated the data obtained from documents and industry records, collecting further data for comparisons. This process guaranteed that the data reported by the industry was precise and aligned with the data collected by the research team. The feed production, poultry farm, and slaughterhouse inventories are presented (Table 2).

The software SimaProTM, version 8.0.5.13 was used for modeling the product system and calculating the potential environmental impacts (Pre consultants, 2015).

Table 1
Economic allocation factors.

Scenario allocation S0 and S2					
Product	Production (kg/year)	Mass Allocation Factor	Economic value (US$/kg)	Total economic value (US$)	Economic allocation factor
Chicken meat	6,240,480	44.30%	1.44	9,011,253.12	97.51%
Chicken bedding	7,847,107	55.70%	0.03	235,413.21	2.49%
Total	14,087,587	100%	–	9,475,624.22	100%
Allocation of scenario S1					
Product	Production (kg/year)	Mass Allocation Factor	Economic value (US$/kg)	Total economic value (US$)	Economic allocation factor
Chicken meat	6,240,480	9.56%	1.44	9,011,253.12	83.92%
Chicken bedding	59,010,244.64	90.44%	0.03	1,770,307.34	16.08%
Total	65,250,724.64	100%	–	11,010,518.35	100%

Source: the authors

Table 2
Inventory of 1 kg of chicken meat.

Producing 1 kg of feed production			
INPUT	S0	S1	S2
Soybean (kg)	0.290	0.290	0.290
Corn (kg)	0.600	0.600	0.600
Beef meal (kg)	0.05	0.05	0.02704
Chicken meal (kg)	–	–	0.02296
Soybean oil (kg)	0.05	0.05	0.05
Limestone (kg)	5.0×10^{-3}	5.0×10^{-3}	5.0×10^{-3}
Salt (kg)	5.0×10^{-3}	5.0×10^{-3}	5.0×10^{-3}
Electric power (kWh)	0.0235	0.0235	0.0235
TRANSPORT			
Soybean transport (kg.km)	0.0127	0.0127	0.0127
Transportation of corn (kg.km)	0.0263	0.0263	0.0263
Transport of meat-and-bone meal (kg.km)	3.951×10^{-3}	3.951×10^{-3}	3.951×10^{-3}
OUTPUT			
Feed (kg)	1	1	1
Aviary – 1 kg of live chicken for slaughter			
INPUT			
1-day-old chick (kg)	0.020	0.020	0.020
Feed (kg)	1.426	1.426	1.426
Water for hydration (L)	3.24	3.24	3.24
Sanitizing water (L)	14.76	14.76	14.76
Electric power (kWh)	0.0694	0.0694	0.0694
Wood (kg)	0.0756	–	0.0756
Biogas (m^3)	–	0.2105	–
Chlorinated sanitizer (kg)	3.81×10^{-4}	3.81×10^{-4}	3.81×10^{-4}
Alkaline detergent (kg)	9.502×10^{-4}	9.502×10^{-4}	9.502×10^{-4}
Sawdust (kg)	0.377	0.377	0.377
TRANSPORT			
1-day-old chick transport (kg.km)	2.898×10^{-3}	2.898×10^{-3}	2.898×10^{-3}
OUTPUT			
Chicken for slaughter (kg)	1	1	1
Wastewater (L)	14.761	14.761	14.761
Ash (kg)	2.381×10^{-3}	2.381×10^{-3}	2.381×10^{-3}
Soot (kg)	3.589×10^{-4}	3.589×10^{-4}	3.589×10^{-4}
Chicken bedding (kg)	1.16	1.16	1.16
Ammonia[b] (kg)	1.04×10^{-2}	–	1.04×10^{-2}
Methane[b] (kg)	7.8×10^{-3}	–	7.8×10^{-3}
Nitrous oxide[b] (kg)	4.0×10^{-4}	–	4.0×10^{-4}
1 kg of chicken meat production			
INPUT			
Chicken for slaughter (kg)	1.084	1.084	1.084
Water (L)	0.413	0.413	0.413
Electric power (kWh)	0.21	0.21	0.21
Thermal energy (Wood) MJ (kg)	1.61×10^{-2}	1.61×10^{-2}	1.61×10^{-2}
Chlorinated sanitizer (kg)	9.65×10^{-4}	9.65×10^{-4}	9.65×10^{-4}
Alkaline detergent (kg)	2.07×10^{-4}	2.07×10^{-4}	2.07×10^{-4}
OUTPUT			
Chicken meat (kg)	1	1	1
Wastewater (L)	0.3342	0.3342	0.3342
Carcass residues (kg)	0.164	0.164	0.164
Soot (kg)	4.8×10^{-5}	4.8×10^{-5}	4.8×10^{-5}
Grey (kg)	3.22×10^{-4}	3.22×10^{-4}	3.22×10^{-4}
Biogas production[c]			
INPUT			
Chicken bedding (kg)	–	0.164	–
Water (L)	–	1.23	–
Manure (kg)	–	0.246	–
OUTPUT			
Biogas (m^3)	–	0.1681	–
Biofertilizer (kg)	–	1.64	–
Production of chicken meal from chicken waste[c]			
INPUT			
Carcass residues (kg)	–	–	0.164
Electric power (Wh)	–	–	a
Thermal energy (MJ)	–	–	a

Table 2 (*continued*)

Producing 1 kg of feed production			
OUTPUT			
Chicken waste meal (kg)	–	–	0.02296
Soot (kg)	–	–	a
Grey (kg)	–	–	a

[a] Values used were from the Agri-Footprint database for the beef meal process.
[b] IPCC, 2006 (Supplementary Material).
[c] Inventory of the proposed scenarios.
Source: the authors

2.4.3. Life cycle impact assessment (LCIA)

The impact categories selected were climate change (CC, in CO_2 eq), ozone depletion (OD, in CFC-11 eq), terrestrial acidification (TA, SO_2 eq), freshwater eutrophication (FE, in P eq), photochemical oxidant formation (POF, in NMVOC), particulate matter formation (PMF, in PM10 eq), water depletion (WD, in m^3) and fossil depletion (FD, in oil eq). These categories were chosen based on relevance and frequency in previous works addressing the environmental impacts of chicken meat, with boundaries and methodology aligned with the objective proposed in this research (González-Garcia et al., 2014; Silva V. et al., 2014; Kalhor et al., 2016; Cesari et al., 2017; Skunca et al., 2018).

The methodology chosen for of impact assessment was the ReCiPe 2008, Midpoint (H) v. 1.12, one of the most used and accepted in several LCA studies, including agro-industrial systems (Goedkoop et al. 2008).

2.4.4. Assumptions and limitations of the LCA study

According to ISO 14040 (ISO, 2006a) and ISO 14044 (ISO, 2006b), this study does not comprise a comprehensive assessment of all environmental issues of the chicken meat product system. Besides, it states the following assumptions and limitations.

i) The functional unit considered all chicken cuts and the elementary processes to obtain them.
ii) Chicken meat (CM) refers to slaughtered and raw chicken, which includes all chicken cuts produced, excluding packaging. The study did not consider the packaging because its use depends on the different ways of disposing of the product for selling: polystyrene trays wrapped in polyvinyl chloride plastic film containing 1 kg of product or polyethylene bags with a volume of 1 kg and 3 kg of product.
iii) The transport of soybean oil, vitamins and minerals, firewood, intermediate products, and waste was disregarded once measuring or obtaining accurate information on the number of trips was impossible. Thus, considering the short distance and frequency of trips, these were disregarded compared to other transport.
iv) The industry under study uses less than its full installed physical capacity and operates 8 h/day, five days/week. Therefore, extrapolating the production data to plants that operate with different capacities or utilization may result in relevant changes in the use of resources.

3. Results and discussion

3.1. Impact assessment of the baseline scenario (S0)

The chicken meat (CM) presented the highest impact values in the baseline scenario in all categories used (Table 3).

This result can explain that CM corresponds to the most significant impacts by the chosen allocation method (economic) and the impacts of the slaughterhouse fully. On the other hand, the highest share of chicken bedding (CB) was in TA and POF, mainly caused by emissions from chicken litter.

When evaluating the unit process of the CM, the feed production has

Table 3
Potential environmental impacts of 1 kg of chicken meat and chicken bedding.

Impact categories	Unit	Total	Chicken meat	Chicken bedding
CC	kg CO_2eq	4.56	4.46	0.10
OD	kg CFC-11eq	8.23E-08	8.17E-08	6.30E-10
TA	kg SO_2eq	0.20	0.20	4.95E-03
FE	kg P eq	2.96E-04	0.00029	6.79E-06
POF	kg NMVOC	0.34	0.34	8.31E-03
PMF	kg PM10eq	0.10	0.10	1.87E-03
WD	m^3	0.05	0.04	9.56E-04
FD	kg oil eq	0.28	0.28	4.28E-03

CC: climate change, OD: ozone depletion, TA: terrestrial acidification, FE: freshwater eutrophication, POF: photochemical oxidant formation, PMF: particulate matter formation, WD: water depletion, FD: fossil depletion.
Source: the authors

the most significant contribution in five categories (CC, TA, FE, POF, FD). These results confirm the studies by Bengtsson and Seddon (2013), González-Garcia et al. (2014), Silva V. et al. (2014), and Martinelli et al. (2020), which show that chicken feed has a relevant contribution to the impacts. The impact contribution of each unit process is shown (Fig. 2).

Feed production was the most impactful step. Soybean was responsible for 46.20% of the impacts in the CC category, 19.03% in TA, and 28.30% in FE. Maize contributed 19.69% in CC, 47.51% in FE, and 29.98% in FD. The results by Cesari et al. (2017), Silva V. et al. (2014), and Bengtsson and Seddon (2013) corroborate those found.

The aviary contributed the most in the WD category because of the water required for the hydration of the birds, which directly increases with the number of animals in place. While hydration is directly related to the number of animals, the cleaning occurs regardless of the number of animals in the aviary. Thus, the greater the number of animals, the lower the impact per kilogram of water use partitioning.

The OD and PMF categories were more influenced by the slaughterhouse stage, with thermal energy as the main contributor in these categories, with 63.08% and 72.35%, respectively. Thermal energy for the slaughterhouse also contributed in the categories CC (8.65%), POF (17.19%), and FD (26.81%). All these impacts resulted from the eucalyptus used for burning in the boiler.

As the objective of this study does not consider proposing changes in feed formulation concentrations, it disregards the feed production input for better visualization of impacts at the product system boundaries. Additionally, the thermal energy for the slaughterhouse, 1-day-old chick, feed complements, salt, and limestone were removed for better identification of the other flows and for not having viable substitutes within the aim of the study (Fig. 3).

Analyzing the maintained inputs, the contributions of chicken bedding to the impacts in CC, TA, POF, and PMF stood out. For example, in the CC category, emissions of gases such as carbon dioxide (CO_2), carbon monoxide (CO), ammonia (NH_3), and methane (CH_4) are the main contributors coming from the handling of poultry manure, obtaining a total of 0.01085 kg of CO_2 equivalent.

The TA category obtained significant participation in chicken bedding (50.35%) and beef meal/beef flour (21.81%). Both have the ammonia emitted from poultry manure and cattle urine as elementary flow. For POF, the causes are the emissions from the chicken bedding. Finally, in the category PMF, the main contribution was the dust emitted by the chicken bedding due to the dry feces and the sawdust production. The thermal energy for the poultry house showed representativeness in the categories CC (3.24%), OD (6.03%), and mainly in FE (11.25%), POF (10.46%), and PMF (10.21%). These originate from wood-burning and eucalyptus cultivation.

As in the study by Bengtsson and Seddon (2013), beef meal has a relevant contribution in CC (6.75%), TA (21.81%), FE (7.21%), and PMF (7.84%), with beef cattle pasture cultivation as the most significant flow.

The results open the possibility of evaluating the environmental impacts of various alternatives, such as replacing corn and/or soybeans in the feed. However, this scenario would require assessing the nutritional change in the animals' performance, which is beyond the scope of this work. Thus, for this study, two scenarios were proposed: the use of digesters to produce biogas and biofertilizer from chicken bedding; and the use of chicken waste as an input for the production of animal meat meal (chicken meal). Such scenarios, described below, do not affect the development and performance of chickens.

3.2. Comparison between firewood and biogas for thermal energy generation in poultry houses (S0 – S1)

Using chicken bedding in a biodigester for biogas production has a lower impact on the environment than the traditional method of not utilizing chicken bedding for thermal energy production in poultry houses (Fig. 4).

The most relevant reductions were in CC (54.78%), TA (56.74%),

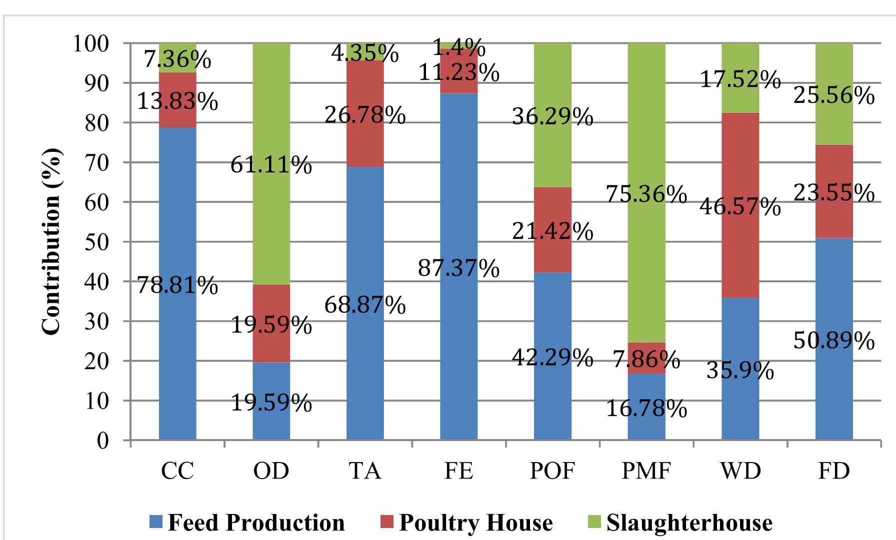

Fig. 2. Contribution of the unit process for 1 kg of chicken meat. CC: climate change, OD: ozone depletion, TA: terrestrial acidification, FE: freshwater eutrophication, POF: photochemical oxidant formation, PMF: particulate matter formation, WD: water depletion, FD: fossil depletion.

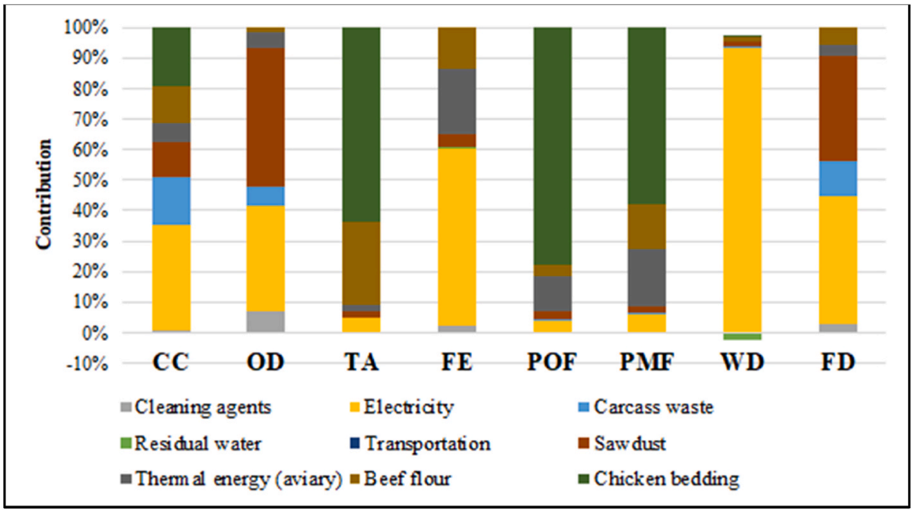

Fig. 3. Input contribution analysis of the product system, with exclusions. CC: climate change, OD: ozone depletion, TA: terrestrial acidification, FE: freshwater eutrophication, POF: photochemical oxidant formation, PMF: particulate matter formation, WD: water depletion, FD: fossil depletion.

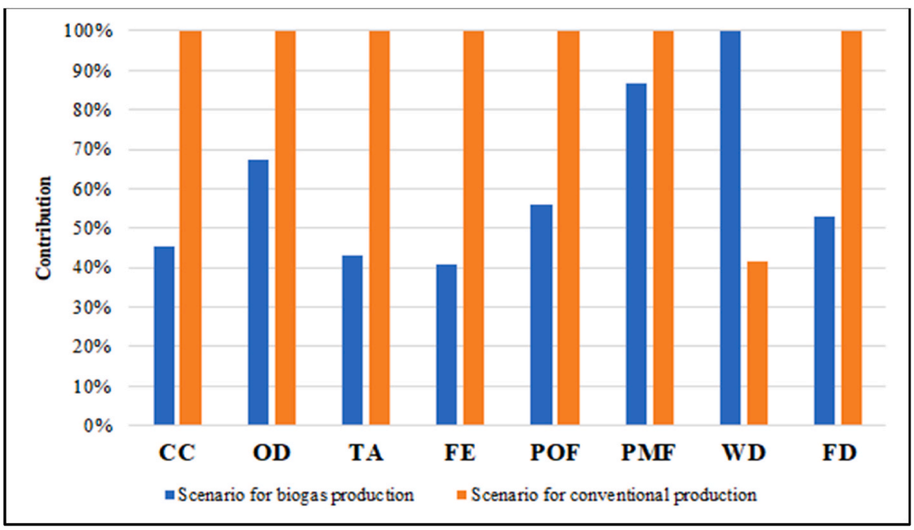

Fig. 4. Comparing the use of the conventional system (S0) with biogas as fuel for heating the poultry house (S1). CC: climate change, OD: ozone depletion, TA: terrestrial acidification, FE: freshwater eutrophication, POF: photochemical oxidant formation, PMF: particulate matter formation, WD: water depletion, FD: fossil depletion.

and FE (58.98%). In the CC category, chicken bedding used in the biodigester reduced methane emissions by generating heat in the poultry house. The less use of firewood also contributed positively to the lower impact in CC. Because of its less efficiency than biogas, burning firewood emitted higher rates of CO_2, and the cultivation of eucalyptus (firewood used) presents large shares in nitrous oxide emissions (N_2O) due to fertilizers.

The reductions in OD (32.53%) also occurred to the previously mentioned reductions. The reduction in TA was due to the non-disposal of chicken bedding in soil, reducing the impacts caused by ammonia release and its fermentation. There was a similar reduction in FE because using the chicken bedding in the biodigester reduced the impacts on water bodies.

The WD category was the only one that increased its contribution to the proposed scenario (58.56%) due to the high water demand in the biodigester.

An important factor in reducing environmental impacts for this proposal is the increased biofertilizer production from chicken bedding, using the same amount of inputs (except water). Instead of sending the chicken bedding as fertilizer, as commonly occurs, it is used as an input in the biodigester for heating production. Notably, biodigestion produces a biofertilizer suitable for farming due to its fertilizer properties.

This practice improves the system's overall production volume, producing more revenue and volume for allocating impacts. Thus, more kilograms are produced with the same volume of elementary flows, leading to lower amounts of related impacts per kilogram of product. Only water consumption and the impacts for WD increased at the product system boundary, and the contributions in the other categories decreased, thus being a trade-off for decision-making.

A comparison of the impact contribution for 1096 MJ generated, required for 1 kg of chicken production in the Aviary unit process, shows the difference in environmental impacts of using firewood and biogas for thermal energy production (Table 4).

Evaluating the categories studied, in WD, the biogas heater generated the most significant impact (325 times greater) due to the water used in the biodigester, as previously discussed. In FE, the contribution was 20% greater, with the volume of biofertilizer generated as a co-product being the main responsible.

Table 4
Comparing the environmental impacts to produce 1096 MJ of thermal energy from Eucalyptus firewood and Biogas.

Impact Category	Unit	Eucalyptus firewood	Biogas
CC	kg CO_2 eq	0.25	0.05
OD	kg CFC-11 eq	3.54E-08	6.18E-10
TA	kg SO_2 eq	1.56E-03	3.76E-04
FE	kg P eq	5.48E-06	6.67E-06
POF	kg NMVOC	3.17E-03	1.05E-04
PMF	kg PM10 eq	0.02	7.32E-05
WD	m^3	5.75E-04	0.18
FD	kg oil eq	0.067	4.24E-03

CC: climate change, OD: ozone depletion, TA: terrestrial acidification, FE: freshwater eutrophication, POF: photochemical oxidant formation, PMF: particulate matter formation, WD: water depletion, FD: fossil depletion.
Source: the authors

In the other categories, thermal energy in the aviary was less impactful with biogas fuel. The leading cause is no wood production and burning (eucalyptus), responsible for at least 84% of the impact contribution in all categories. In CC, it represented 17.97% of the impacts caused by firewood, which shows positive results of its application.

Eucalyptus cultivation is responsible for the total difference in the categories of OD (57.3 times greater), TA (4.1 times greater), and FD (15.8 times greater).

3.3. Comparison between beef and chicken meals (S0 – S2)

This stage evaluated the use of chicken carcass waste to produce chicken meat meals and its use as an input in feed.

The chicken meal partially replaced the beef meal, considering using this waste generated by the industry. Xavier et al. (2012) state that the efficiency of transforming meat waste into a chicken meal is 14% for chicken. Thus, all chicken waste from the industry replaced 46% of the standard feed input, comprising a mix.

From a technical point of view, Silva E. et al., (2014) evaluated the applicability of poultry viscera meals in broilers' diets by studying some variables, such as feed consumption, weight gain, carcass yield, chicken cuts yield, and abdominal fat. The authors state that adding poultry residues to diets tends to accompany the growth of poultry production by providing a better nutritional alternative to current conventional methods of grain for feed. The results showed that the inclusion of residue improved the performance of the birds and maximized the carcass in the noble cuts. The authors did the nutritional assessment of the animals fed the diet.

Initially, evaluating the difference in impact contribution in the slaughterhouse unit process, the chicken fed with the mix, despite avoiding the disposal of chicken carcass waste in landfills, resulted in small but irrelevant (<3%) reductions in environmental impacts in the selected categories. Thus, the impact assessment considered the contributions of the whole product system (Fig. 5).

The results show a trend towards better environmental performance for using poultry meat meals produced with the carcass waste of the industry itself. The reduction in the impact categories can be explained by the non-disposal of waste in landfills, the lower use of beef meal in the feed, besides the minimization of industrial waste, as Skunca et al. (2018) stated. These actions avoid carcass decomposition problems, which, combined with the reduction in the use of cattle meal, directly influence the reduction of environmental impacts in all evaluated categories, CC (23.11%), OD (14.91%), TA (27.13%), FE (19.51%), PMF (6.5%), WD (25.31%), FD (20.71%).

3.4. Comparison between the traditional system (S0) and the system with the two proposed scenarios (S1 and S2)

Comparing baseline scenario (S0) with simultaneously the two scenarios proposed in this study occurred reductions in seven of eight impact categories (Fig. 6), except for the WD category, with an increase (57.40%) due to the water consumption for the biodigester, as already discussed.

The results indicated impact reduction in the categories CC (53.51%), OD (33%), TA (50.72%), FE (55.99%), POF (43.95%), PMF (12.42%), and FD (46.49%). The reduction in environmental impacts was driven by the smaller share of bovine meal in the feed formulation, the proper disposal of poultry carcass waste, and the non-use of chicken bedding for fertilization, particularly in the CC category. The decrease in greenhouse gases was primarily due to lower CH_4 emissions from ruminant digestion of cattle and chicken bedding, as well as the decomposition of chicken carcasses. However, the most significant contributor to the reduction of impacts was increased by fertilizer production using biodigestion.

According to Dieterle et al. (2018), the quantitative results of the LCA can support innovations within the qualitative framework of a circular economy perspective, allowing waste valorization in the same

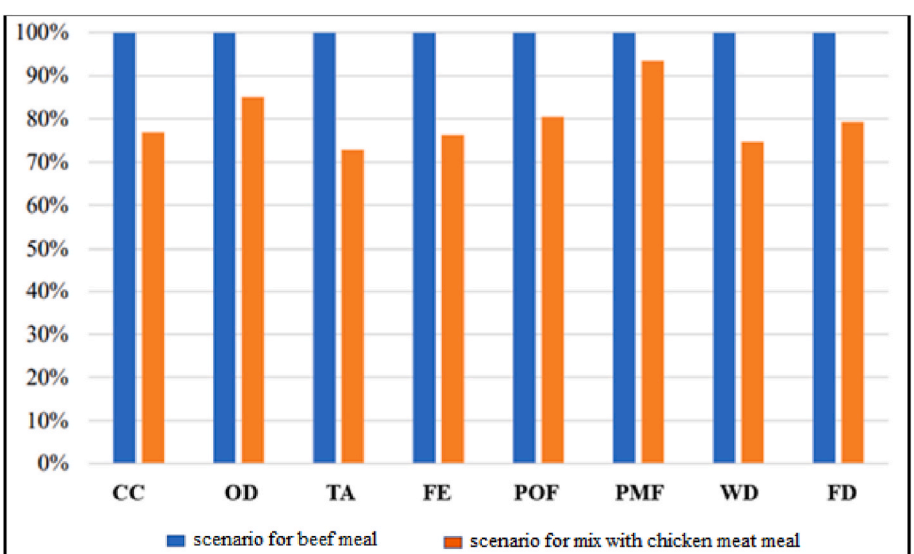

Fig. 5. Comparing the use of beef meal (S0) with the mix with chicken meat meal (S2). CC: climate change, OD: ozone depletion, TA: terrestrial acidification, FE: freshwater eutrophication, POF: photochemical oxidant formation, PMF: particulate matter formation, WD: water depletion, FD: fossil depletion.

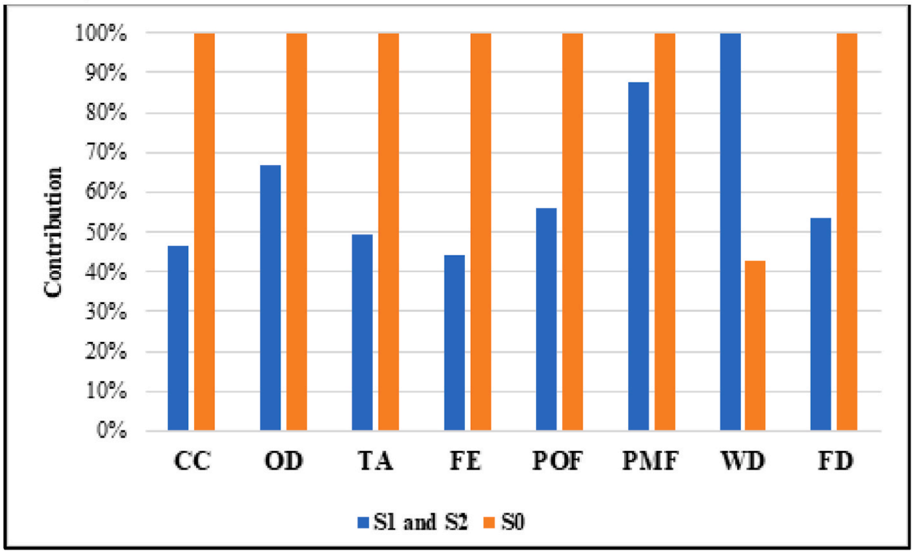

Fig. 6. Comparison between the traditional system (S0) and the system with the two proposed scenarios (S1 and S2). CC: climate change, OD: ozone depletion, TA: terrestrial acidification, FE: freshwater eutrophication, POF: photochemical oxidant formation, PMF: particulate matter formation, WD: water depletion, FD: fossil depletion.

or different cycles. Furthermore, the effectiveness of waste management practices can be better measured if circular economy principles are examined in association with life cycle thinking (Sharma et al., 2022), as explored by the scenarios under study.

This comprehensive analysis of the environmental impact of the proposed scenarios can significantly aid in making informed decisions, promoting a business-oriented approach, and adequately conducting and interpreting LCA studies.

The focus, therefore, is not only on minimal material usage and zero waste in a production system but also on circularity throughout the entire chain from an LCA perspective. Furthermore, this approach addresses the challenges of high-quality recirculation routes and prevents negative trade-offs during the product lifecycle, as noted by Dieterle et al. (2018).

3.5. Evaluation with mass allocation

Once changes in the allocation can affect the results and there is no consensus on the better method for multifunctional systems, it is advisable to verify the consequences of different allocation methods on the impacts. Thus, a mass allocation analysis was also performed (Fig. 7).

It was possible to identify a considerable shift of chicken bedding impacts contribution compared to the economic allocation previously discussed (item 3.1). This discrepancy results from the large volume of chicken bedding obtained as a byproduct.

ISO 14040 (ISO, 2006a) recommends avoiding allocation and using system expansion. However, some product systems are multifunctional, and thus, the system expansion may not be appropriate for those.

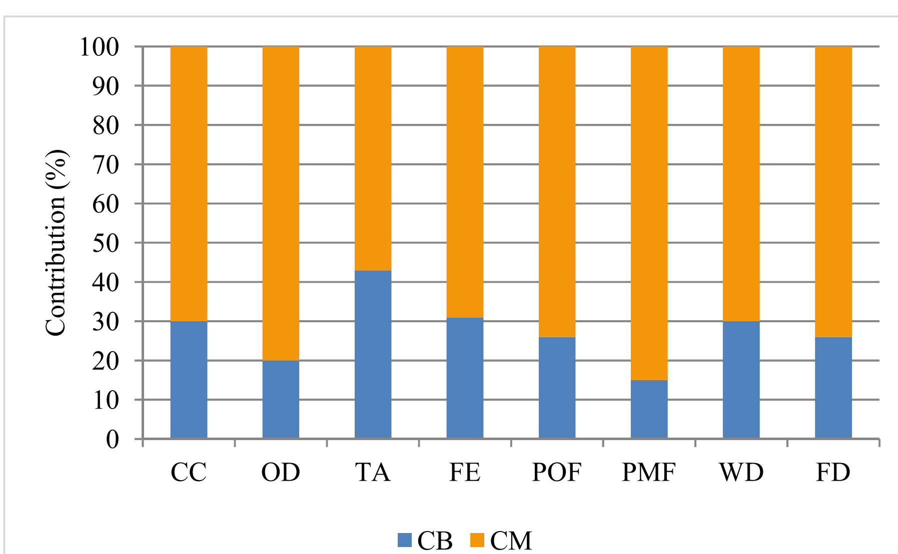

Fig. 7. Impact Assessment of Chicken Meat (CM) and Chicken Bedding (CB) by mass allocation. CC: climate change, OD: ozone depletion, TA: terrestrial acidification, FE: freshwater eutrophication, POF: photochemical oxidant formation, PMF: particulate matter formation, WD: water depletion, FD: fossil depletion.

4. Conclusions

The study aims to enhance environmental management in the poultry industry and applies to a broader audience and different contexts. The demand and installed capacity of the production system may vary by study but do not affect the appropriate use of results.

Partial replacement of feed meal with chicken feed showed viability in reducing environmental impacts associated with using corn and soybean in feed production. The use of biogas for thermal energy generation and production of biofertilizers reduced most environmental impacts, except for water consumption, and is viable in regions with abundant water.

These strategies contribute to the Sustainable Development Goals related to affordable and clean energy (SDG 7), industry, innovation, and infrastructure (SDG 9), responsible consumption and production (SDG 12), and climate action (SDG 13). The poultry industry's data can contribute to chicken meat and the inventory database, enhancing global life cycle inventories, with benefit the scientific and industrial for future impact assessment studies and developing Environmental Product Declarations for poultry products.

It is advisable to conduct additional research, specifically on modifications to animal feed methods, to enhance environmental sustainability. Additionally, addressing or mitigating environmental concerns can improve the industry's reputation and increase the value of its goods. Finally, it can be achieved through effective communication and marketing to society, including consumers and stakeholders.

Authors contributions

Ramon Araújo dos Santos: Investigation, Data collection, Formal analysis, Writing original draft preparation. **Jéssyka Silva da Costa:** Modeling and analysis of the product system, Work review, Planning, analysis and discussion of results. **Henrique Leonardo Maranduba:** Formal analysis, Validation. **José Adolfo de Almeida Neto:** Supervision, Writing- Reviewing and Editing. **Luciano Brito Rodrigues:** Conceptualization, Supervision, Funding acquisition, Project management, Writing- Reviewing and Editing.

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

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2023.118021.

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