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Energy, Environmental and Economic Analysis of Broiler Production Systems with and Without Photovoltaic Systems

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Abstract

The study analyzed energy, environmental impact and costs in intensive broiler production systems in the southeast of the state of Minas Gerais, Brazil, comparing scenarios with and without photovoltaic systems. Four configurations were evaluated, considering different types of ventilation (positive and negative pressure) and photovoltaic generation. The Life Cycle Assessment (LCA), with a functional unit of 1 kg live weight and a cradle-to-gate approach, indicated that photovoltaic systems reduce between 2.58 t and 4.96 t of CO_2-eq annually, in addition to offering better energy efficiency. Economically, sheds with positive pressure ventilation have the lowest cost-benefit ratios, while the feeding subsystem was the one that contributed the most to global warming, among the environmental impact categories evaluated in the LCA. Photovoltaic systems demonstrated the potential to reduce electricity costs between 19.4% and 26.5% per year. However, coffee husks, used as chicken litter, represented 36.5% of production costs, highlighting the need for more economical alternatives. It was concluded that photovoltaic systems are a viable solution to reduce environmental impacts and increase profitability, reinforcing the importance of strategies to optimize the use of resources in poultry farming.

Keywords: distributed generation; economic costs; energy; greenhouse gas emissions; life cycle assessment

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1. Introduction

Among the paths that are necessary for sustainable development in agriculture is the quantification and comparison of the energy, economic and environmental aspects of the products and processes carried out in the agricultural sector. In Brazil, broiler chicken production is a prominent activity in national agriculture, and studies in this area contribute to the development of the sector. Consolidated data from 2022 shows that in Brazil, poultry farming is responsible for producing around 14.5 million metric tons of chicken, with the country being the 2nd largest producer and largest exporter of chicken meat in the world. Traditionally, the southern region of Brazil is the main producer, with around 64.42% of national production. The state of Minas Gerais is the sixth largest producer in the country, with 7.24% of national production. The Zona da Mata mesoregion, in Minas Gerais, contributes around 8.0% of the state's broiler chicken production [1,32].

Intensive broiler production systems, compared to other similar production systems, are generally identified as more environmentally efficient [30]. Still, given the growth of the sector, there has been greater concern about poultry farming and its impact on the environment and human health [26,29].

Studies have sought to understand the potential vulnerabilities and future impacts of climate change on global agricultural production systems, as well as broiler production systems. Quantifying environmental load parameters in Life Cycle Assessment (LCA) makes it possible to determine how much greenhouse gas emissions affect the environment, for example [20,40].

Life cycle assessment is one of the most comprehensive and robust methodologies used to evaluate the environmental impacts of products and services. LCA identifies critical points in the production chain, while also offering the opportunity to evaluate different production scenarios, which contributes to decision-making on reducing associated impacts and improving the efficiency of these production systems [10,45]. During the last decades, studies evaluating the energy intensity and LCA of various products from the agri-food industry have been carried out [5,22,34].

Regarding the adoption of LCA in poultry farming, one example is the work carried out by Pishgar-Komleh et al. [36], who quantified total greenhouse gas emissions, energy use efficiency in production and cost-benefit ratios in different broiler housing systems in a region of Iran. In turn, Lima et al. [25] evaluated the global warming potential and other environmental impacts of conventional broiler systems in the southern region of the state of Mato Grosso do Sul, Brazil. Such studies in new regions, both for Brazil and other countries, are extremely important for the development of technologies, to identify the life cycle profiles of production systems in the regions and also to identify methods that can reduce environmental impacts associated with production processes.

Martinelli et al. [26] used LCA to evaluate the environmental impacts and eco-efficiency of conventional, Dark House and organic broiler chicken production systems on farms in the southern region of Brazil. Rocchi et al. [40] compared conventional, free-range and combined free-range production systems with an olive grove in Italy.

Energy is one of the most important inputs for economic growth, human development and is widely needed in the production of agricultural systems. Energy analysis is one of the most useful methods for assessing the sustainability potential of an agricultural practice. Through it, we help promote competitiveness along with cost reduction, which results in the minimization of environmental pollution related to energy, for example [36].

Li et al. [24] presented in their study that non-renewable energy in poultry production systems can represent up to 50% of energy use and contribute to 20.0% to 35.0% of life cycle impacts. The authors proposed the adoption of photovoltaic systems in intensive poultry production sheds, as an alternative to reducing the use of energy directly from the electricity grid, and consequently reducing the use of energy in the production system [24].

Although greenhouse gas emissions are lower in poultry farming compared to ruminant production systems, there is a contribution to polluting gases [45]. Regarding the study on the contribution to the global warming potential of waste produced in broiler production systems, Martinelli et al. [26] state that gases and waste released during the raising of broiler chickens contribute to the greenhouse effect, such as methane and nitrous oxide from manure management and ammonia from the decomposition of excrement. A joint analysis between energy use, quantification of environmental impacts and economic costs allows a comparison of the energy efficiency of a production system [36].

There is a lack of research mapping the environmental impacts, energy consumption, and economic costs of broiler production systems in Brazil [12]. Brazil is a large country with distinct regions, and studying new regions contributes to understanding the extent and extent of environmental impacts, as well as helping to develop new measures to reduce greenhouse gas emissions, economic costs, and energy use, with the aim of achieving more sustainable production processes.

The objective of this study was to evaluate energy consumption, the main environmental impacts using the LCA approach, and the economic costs of intensive broiler production systems with and without photovoltaic systems in the Zona da Mata region of Minas Gerais. The study sought, through environmental, energy and economic assessments, to identify which scenarios in production systems are most sustainable for the environment and economically most profitable for rural producers.

2. Materials and Methods

2.1. Characterization of the object of study

Intensive broiler production systems present in municipalities in the Zona da Mata mesoregion, located in the southeast of the state of Minas Gerais, Brazil, were analyzed (Figure 1). The data were collected in broiler production systems located in 12 of the 23 municipalities where the slaughterhouse operated.

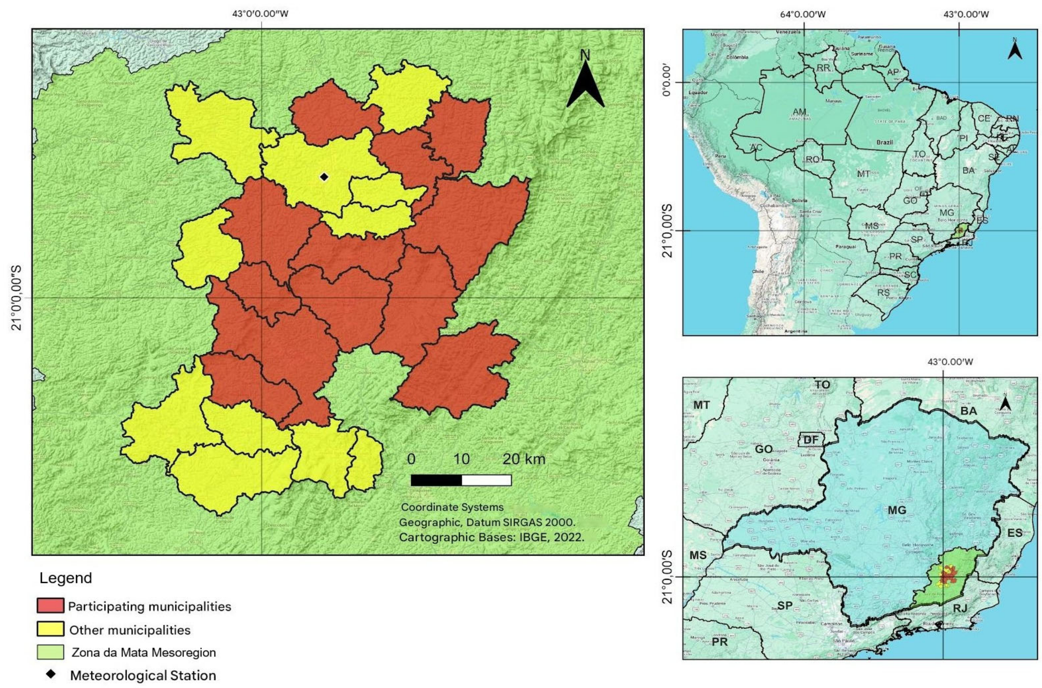

Figure 1. Geographic location of the municipalities where the integrating company operates. Source: Own elaboration with QGIS software.

The farming systems adopted in the region include Conventional, Blue House, and Dark House. The Conventional system uses positive-pressure ventilation, where air is drawn into the house by fans, creating a pressure higher than that of the external environment. The Blue House and Dark House systems, on the other hand, feature negative-pressure ventilation, in which air is drawn out of the house through exhaust fans, promoting more uniform air circulation and internal environmental control. The Blue House system has side walls that can be covered with blue curtains and uses a moderate number of fans, while the Dark House has walls covered with black curtains, a greater number of fans, and high airflow, favoring the maintenance of controlled environmental conditions, especially in regions with sharp climate variations. These characteristics directly impact production performance, bird thermal comfort, and environmental ventilation and humidity management.

In addition to the two production systems, the way in which the chicken farm used electrical energy in the captive energy market in the Regulated Contracting Environment was considered. It was found that there were broiler chicken sheds without photovoltaic systems (SFV) or with photovoltaic systems (CFV), that is, with consumer units that had or did not have distributed generation, in accordance with Federal Law 14,300/2022 [8].

Initially, it was necessary to prepare an inventory of data relating to the use of water, energy, raw materials and associated economic costs in order to understand the inputs and outputs of broiler production systems.

In this way, the data for preparing the farm inventory were obtained from poultry farmers through the application of questionnaires, interviews carried out in the field and technical production reports. The information was obtained from July to June (12 months), covering six production cycles of the year. The database obtained from the technical production reports consisted of production indices of 150 batches of broiler breeders.

Thus, four possible scenarios were defined for broiler production systems in the mesoregion, considering the type of production system and the profile of the electricity consumption unit. These scenarios were classified as PP-SFV (Positive Pressure without photovoltaic systems), PP-CFV (Positive Pressure with photovoltaic systems), PN-SFV (Negative Pressure without photovoltaic systems), and PN-CFV (Negative Pressure with photovoltaic systems). Positive-pressure systems include conventional sheds that use fans to introduce air, while negative-pressure systems include sheds such as Blue House and Dark House, which use exhaust fans for air extraction, generally associated with more efficient control of the internal environment. The integration or not of photovoltaic systems represents a significant differentiator in local energy generation, impacting the costs and sustainability of the systems. The evaluation of these four scenarios allowed us to identify the differences and particularities regarding environmental impacts, energy use, and economic costs from the perspective of rural producers.

Data on the climatic conditions that characterize the study region were obtained from the Langley Research Center (LaRC) Prediction of Worldwide Energy Resource (POWER) Project of the National Aeronautics and Space Administration (NASA) for the year 2020.

In relation to the climatic conditions of the region (Table 1), it appears that the maximum temperatures in almost all months are between 28.0 °C and 39.4 °C, approximately, except in the months of May and June which recorded the lowest values maximum temperatures ranging from 28.0 °C to 29.5 °C (winter period). Minimum temperatures show greater variations in relation to the variations recorded in maximum temperatures for the period. The months with the lowest temperatures were concentrated between the months of May and August (8.4 °C to 12.3 °C) and with an average monthly rainfall of approximately 22.13 mm. Along with the periods with the lowest temperatures recorded, there was a lower incidence of rainfall and only in the months of October to February did the highest concentrations of rainfall occur, reaching up to 260.3 mm in the month of January. As for relative air humidity, average values between 63.3% and 87.0% were recorded for the entire period evaluated.

Table 1. Average data on maximum temperature, minimum temperature, relative humidity and precipitation in the study region in 2020. Source: POWER (2024).

Month	Maximum Temperature (°C)	Minimum Temperature (°C)	Relative humidity (%)	Precipitation (mm)
January	32.3	17.4	85.4	260.3
February	30.8	17.4	87.0	219.6
March	29.9	14.7	86.5	140.7
April	29.8	13.8	85.6	48.3
May	28.0	8.4	83.4	47.3
June	29.5	11.3	79.0	6.7
July	30.8	12.3	75.0	14.5
August	33.8	9.4	71.8	20.0
September	37.9	14.5	63.3	38.3
October	39.4	15.0	71.1	113.0
November	33.1	12.7	79.5	139.7
December	33.7	17.9	81.0	163.4

2.2. *Assessment of Environmental Impacts Using the LCA Approach*

The first approach of this study refers to the assessment of the environmental impacts of broiler chicken production using the LCA methodology, which was carried out in accordance with ISO standards 14.040:2009 and 14.044:2009 [18,19]. The results were recorded according to the functional unit of "1 kg live weight", as well as the inputs and outputs recorded in the life cycle inventory (LCI).

The poultry farming process encompasses several subsystems, such as the hatchery (day-old chick production), feed production, broiler production, and broiler processing (slaughterhouse). In this work, only the feed production and broiler production subsystems were discussed, as can be seen in Figure 2.

2.2.1. Defining Objective and Scope

The purpose of defining the scope of the LCA is to present the elements present in the poultry supply chain. The LCA in this work is considered attributional, as it is characterized by the allocation of co-products and the use of average LCI data in view of a system considered static. Figure 2 shows the respective inputs and outputs of the system under study.

The inventory time limit was established by the broiler chicken rearing period, characterized by a production cycle that goes from housing the animals in the shed, at one day old, until pre-slaughter, with an average of 46 days of life (from *cradle to gate*). During this period, production resources were evaluated until the final product was obtained, the chicken ready for slaughter, considering a cradle-to-gate system boundary. The functional unit considered in this work with the ICV was "1 kg of live weight" [25]. Due to the impossibility of fully citing all the inputs involved in the process based on the information gathered from broiler chicken producers, and considering the objective of the research, there were limitations in some variables and other systems along with the definition of all inventory reviews, such as medications, breeders, incubation of chicks from one day old and construction of production infrastructure on farms. Overall, these data would have a small contribution to the results, in addition to being external processes in relation to the two subsystems evaluated (feed production and broiler production).

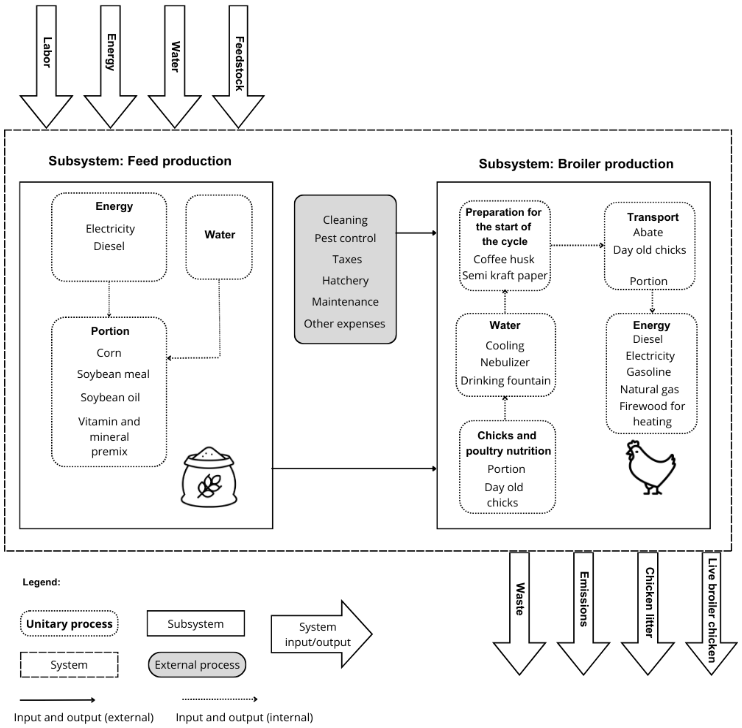

Figure 2. Limits and flow diagram of the study system. Source: Own elaboration.

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2.2.2. Life Cycle Inventory Analysis (LCI)

The data preprocessing stage was conducted based on the definition of the elementary input and output flows relative to the functional unit established for the system. Initially, the systematic collection of primary data was carried out in the field, respecting the previously defined boundaries of the system under evaluation. The data obtained were then organized, validated, and used to prepare the life cycle inventory, according to the procedures described in ISO 14040.

For each scenario evaluated, the input and output values were referenced to the functional unit and normalized according to the annual average observed on a representative agricultural property, ensuring comparability across the different contexts analyzed. Table 2 presents the unitary data for each entry in the ICV of each of the study scenarios in order to evaluate the environmental impact of 1 kg live weight produced.

Table 2. Life Cycle Inventory data per kg live weight chicken, for each of the study scenarios. Source: Own elaboration.

Inputs	**Unit**	**Study Scenarios**			
		PP-SFV	**PP-CFV**	**PN-SFV**	**PN-CFV**
Subsystem: Feed production					
Use of water and energy					
Electric energy - distributor (*)	kWh	0.05729		0.03595	
Diesel	kg	0.00027		0.00017	
Water use	L	0.25461		0.15976	
Feed ingredients (basic average composition between phases)					
Corn	kg	0.98397		0.91570	
Soybean meal	kg	0.03135		0.02917	
Dicalcium phosphate	kg	0.60745		0.56530	
Soy oil	kg	0.07785		0.07245	
Limestone	kg	0.02107		0.01961	
Choline Chloride (70%)	kg	0.00853		0.00794	
L-Lysine HCL	kg	0.00244		0.00227	
Premix vitamins	kg	0.00348		0.00324	
DL-methionine	kg	0.00087		0.00081	
Sodium chloride	kg	0.00192		0.00178	
Premix minerals	kg	0.00139		0.00130	
Avilamycin	kg	0.00017		0.00016	
Monensin	kg	0.00104		0.00097	
Subsystem: Chicken Production					
Area, chicks and bird nutrition					
Day-old chicks	kg	0.01402		0.01351	
Shed area	m^2	0.00470		0.00381	
Chicken feed	kg	1.74155		1.62070	
Energy (Electricity, Biomass and Fuels)					
Electric energy - distributor([a])	kWh	0.05719	0.00176	0.07066	0.00110

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Diesel	kg	0.00093	0.00174
Gasoline	kg	0.00039	0.00024
Natural gas	kg	0.00023	0.00029
Firewood for heating (*Eucalyptus urograndis*)	kg	0.00035	0.00033
Water			
Water - Cooling	L	0.00000	1.09166
Water - Nebulizer	L	1.11782	1.09166
Water - Drinking Fountain	L	1.49043	3.63885
Road transport by trucks			
Transport - Feed	t/km	5.82 E-07	3.79 E-07
Transport – Day-old chicks	t/km	2.80 E-09	2.70 E-09
Transport - Chicken for slaughter	t/km	4.53 E-07	3.09 E-07
Batch start preparation			
Coffee husk - chicken litter	kg	0.13948	0.11935
Semi kraft paper - day old chicks	kg	0.00053	0.00033

Legend: PP-SFV: Positive pressure without photovoltaic systems; PP-CFV: Positive pressure with photovoltaic systems; PN-SFV: Negative pressure without photovoltaic systems; PN-CFV: Negative pressure with photovoltaic systems; (*) Single entry with different values between all four scenarios evaluated in the study, due to the type of profile of the electricity consuming unit.

The main characteristics and respective technical coefficients that represent the production systems under study are described in Table 3. It was verified that mainly the Cobb® and Ross® strains of both sexes are adopted in the broiler breeding process. The nutritional diets taken as reference in the study were adopted in relation to the birds' breeding phases (Pre-initial: 1 to 8 days; Initial: 9 to 16 days; Growth: 17 to 24 days; Fattening: 25 to 33 days; Slaughter : from 34 days) and the ingredients used in the composition of the feed, according to the recommendations of Rostagno et al. [41].

Table 3. Technical coefficients of the evaluated production systems. Source: Own elaboration.

Coefficient	Unit	Production system	
		Pressure Positive	Pressure Negative
Shed area	m²	1.605	2.074
Lots per year	Number of batches/year	6	6
Average age of slaughter	days	46	46
Average interval between batches	days	14	14
Chickens produced per batch	heads/lot	17.867	27.808
Chickens produced per year	heads/year	107.203	166.848
Density	heads/m²	11.13	13.41
Average final weight	kg/head	3.187	3.108

Feed consumption	kg/head	5.550	5.289
Average amount paid	USD/head	0.2010	0.2241
Mortality	%/batch	5.97	4.76
Food conversion	kg feed/kg chicken	1.76	1.69

The financial costs obtained during data collection were quantified according to the current Brazilian currency and converted to US dollars for all analyses. A conversion factor was used, in which 1.00 Brazilian real (BRL) was equivalent to approximately 0.21 US dollars (USD). Table 4 presents the average daily weight gain by sex in broiler production systems, also calculated based on the average values obtained from technical production reports.

Table 4. Average daily weight gain by sex in broiler production systems. Source: Own elaboration.

Unit	Production system			
	Positive Pressure		Negative Pressure	
grams/ head	Males	Females	Males	Females
	72.06	63.43	72.05	64.36

The functional unit for electricity consumption in the PP-SFV and PN-SFV scenarios, both characterized by broiler production systems without photovoltaic systems, was determined based on the average annual total consumption recorded on a reference farm. In these scenarios, it was considered that all energy demand is met exclusively by electricity supplied by the local electricity distributor's network, which characterizes the system's complete dependence on an external source of electricity.

In the PP-CFV and PN-CFV scenarios, which represent production systems with grid-connected photovoltaic systems, it was verified, together with the warehouses visited during data collection, that the consumer units served by these warehouses presented a minimum demand from the local electricity distribution grid. This demand corresponds to the availability cost charged for a two-phase, low-voltage grid with a minimum of 50 kWh, classified as B2 (rural) tariff. In other words, despite photovoltaic generation, these units still maintain an active connection to the grid, which is used to meet this minimum demand when necessary, directly reflecting the lifecycle inventory data.

2.2.3. Life Cycle Impact Assessment (LCIA)

The LCIA consisted of calculating the environmental impact based on the ICV unitary processes. Using the SimaPro® program version PhD 9.2.0.2, the available Ecoinvent® database version 3.8 and the CML-IA method Version 3.02/World 2000 (global scope of application), impact categories were quantified and analysis of data uncertainty was performed.

In this analysis, the midpoint impact assessment level was considered, which refers to impact categories throughout the chemical, physical and biological process systems (environmental mechanism), before the final point of the category. The midpoint characterization does not refer to the damage that can be caused to the environment and human health [27].

Based on the work of Pelletier [34], Leinonen et al. [23], Martinelli et al. [26] and Beal et al. [6] and in the CML-IA methodology described by Sleeswijk et al. [44] and Guinee et al. [15], the environmental impact categories of acidification (kg SO_2-eq), eutrophication (kg PO_4-eq) and global warming potential (kg CO_2-eq) were chosen, which represent the pollutant emissions most analyzed in the studies found in literature on the application of LCA in broiler production systems.

Mostert et al. [28] highlight the initial relevance of focusing on reducing greenhouse gas (GHG) emissions in broiler production, recognizing that, although other environmental impact categories are also important, establishing simultaneous targets for multiple indicators can pose a significant challenge. Thus, prioritizing GHG emissions emerges as a fundamental step to guide mitigation efforts and policies in this production chain, while the integrated approach to other impact categories can be the subject of future investigations.

The works published by Usva et al. [48], Alves et al. [2], Cheng et al. [9], Lima et al. [25] and Martinelli et al. [26] present relevant results and discussions about the impact categories that were also analyzed in this work. These studies address impacts such as global warming potential, acidification, eutrophication, and energy resource use, which are critical for evaluating broiler production systems. In particular, these authors highlighted the importance of feed management and waste management as key factors that significantly influence the environmental footprint of these systems. Integrating these impact categories into the life cycle inventory contributes to a comprehensive analysis of environmental effects and enables the development of more effective strategies to mitigate impacts on the broiler production chain.

2.2.4. Life Cycle Interpretation

The interpretation of the life cycle was based on the results obtained from the LCA, so that the calculated potential environmental impacts were converted into recommendations and conclusions about the performance of the evaluated scenarios, according to the scope and objective of the LCA study [18,19].

2.2.5. Uncertainty Analysis

The variations present in the data can be described by a distribution, expressed by a range or standard deviation. Statistical methods such as Monte Carlo techniques can be useful for calculating data uncertainty in LCA results [37,38]. The various data inputs may contain some degree of uncertainty and, when aggregated, have the potential to impact the results obtained in the LCA. Therefore, when comparing the impacts generated by different processes or products, it is crucial to check whether the disparities between them are statistically significant [35,37].

In this study, a Monte Carlo analysis was performed using the CML-IA Version 3.02/World 2000 method, assuming a uniform distribution with a 95% confidence interval and evaluating the parameters through 5,000 independent simulations. In addition to the uncertainties inherent in the tertiary data from the Ecoinvent database, the quality and variability of the primary data obtained directly through interviews with rural producers was assessed, incorporating their specificities and uncertainties into the model [4]. The Monte Carlo simulation thus allowed considering the variability of the experimental data, both maximum and minimum, for each scenario evaluated, enabling a more robust probabilistic analysis of the environmental performance in broiler production.

2.3. Assessment of Economic Costs and Energy Use

Based on the work of Pishgar-Komleh et al. [36], detailed analyses were conducted regarding energy and economic use in broiler production. This study evaluated direct and indirect energy inputs, such as fuel, electricity, and feed, as well as associated costs, considering different production systems. Furthermore, energy efficiency indices and economic indicators were calculated to better understand the relationship between energy consumption and the economic viability of production. The results and methodologies presented by Pishgar-Komleh et al. [36] served as a basis for guiding the energy and economic assessment in this study, helping to identify opportunities for optimization and reduction of environmental impacts.

2.3.1. Energy Usage Analysis

The energy values for each of the inputs were quantified by the respective energy coefficient (MJ/unit) multiplied by the quantity used in the production of broiler chickens for the period of one year in each of the study scenarios. The sum of the calculations of the energy values of the inputs resulted in the input energy. In a similar way, the output energy value was obtained, which corresponded to the number of kilograms of live chicken produced over a period of one year multiplied by the respective energy coefficient.

The energy indices used to analyze energy use were the indicators of energy efficiency (EE), energy productivity (PE) and net energy (EL), according to equations 1 to 3.

The Energy Efficiency Index (Equation 1) can be interpreted, if the value found is equal to one, the output energy is equal to the input energy. Likewise, it appears that if greater than one, the higher the value achieved in the index, the greater the EE of the production system will be, that is, more energy was obtained at the output due to the inputs that were needed at the input of the system [11,16,36].

$$EE = \frac{Output\ power\ (MJ)}{Input\ power\ (MJ)} \quad (1)$$

Energy Productivity (Equation 2) measures the amount of production of a given product depending on the total input energy that was required in the process. In this work, the total available input energy represents the amount of energy required to satisfy broiler production [11,16,36].

$$PE = \frac{Broiler\ production\ (kg)}{Input\ power\ (MJ)} \quad (2)$$

As for Net Energy (Equation 3), if EL > 0, it indicates that energy was gained, that is, the production system was capable of producing more energy than was spent on production. Otherwise, if EL < 0, it indicates that the output energy was lower than the necessary demand from the production system [11,16,36].

$$EL = Output\ power (MJ) - Input\ power\ (MJ) \quad (3)$$

2.3.2. Energy Usage Analysis

The studies by Andrade et al. [3] were adopted as a reference for the economic analysis carried out in this work, complemented by the contributions of Ibrahim et al. [17], Qaid et al. [39], and by the methodologies proposed by the National Rural Learning Service (SENAR) [42] for cost management in agriculture. In this analysis, the economic viability of the production systems was assessed considering the financial resources needed to cover all stages of the poultry activity throughout an annual production cycle. The economic analysis consists of identifying and quantifying the costs involved, such as inputs, labor, and operating expenses, as well as the possible financial returns, thus allowing to assess whether the production is financially sustainable for the producer.

Initially, we sought to understand the associated variable costs, also known as effective operating cost (COE), which is the result of the sum of all direct expenses of the production process. The COE includes maintenance expenses, energy, labor, improvements, taxes, for example.

Next, we have the total operating cost (COT) which consisted of the sum of the COE, family labor costs and depreciation of agricultural equipment (Equation 4) depending on the useful life, such as silos, electric generator, chainsaw, microtractor, photovoltaic plant, chimney, ovens, for example.

$$COT\ (USD) = COE + Family\ labor + Depreciation \quad (4)$$

Thus, the formation of the total cost (TC) was made by the sum of the COT and the opportunity cost (Equation 5), which consist of interest on the capital tied up in the broiler farm, if one had chosen to invest this money in some type of financial application or investment. This is important to include in the cost composition, as it helps the producer's financial decision-making, as he will be able to verify whether the investments made in his warehouse are being more profitable than a financial investment of the same resource. In this analysis, for comparison purposes, a profitability of investment in savings was considered at an interest rate of 6.0% per year [42].

$$CT\ (USD) = COT + Opportunity\ cost \quad (5)$$

Profit (Equation 7) is the difference between gross income (RB) and CT, and positive values are expected to maintain the enterprise, in the same way as in the gross margin (MB) and net margin (ML) indices. The MB is an indicator that presents the difference between the RB and the COE (Equation 8), which if positive, it is considered that the financial viability of the production system is viable.

$$RB = [Chickens\ produced\ per\ year\ (heads/year) * Average\ amount\ paid\ (USD/head)] + [Poultry\ litter\ produced\ per\ year\ (t/year) * Average\ amount\ paid\ (USD/t)] \quad (6)$$

$$Profit\ (USD) = RB - CT \quad (7)$$

$$MB\ (USD) = RB - COE \quad (8)$$

ML (Equation 9) is another indicator that is calculated based on the difference between gross income and COT. If ML > 0, it is considered that the system is economically viable in the medium term, however profit must be observed for long-term analyzes [3].

$$ML\ (USD) = RB - COT \quad (9)$$

The last index is the cost-benefit ratio (RCB), calculated by the ratio between RB and CT (Equation 10). The higher the RCB value, the greater the profitability of the production system [3,17,39].

$$RCB = \frac{RB}{CT} \quad (10)$$

3. Results and Discussion

3.1. Assessment of Environmental Impacts

The results for the environmental impact categories are shown in Table 5 and Figure 3, for each of the scenarios evaluated. The production system with positive pressure and without photovoltaic systems was the one that presented the highest results among the impact categories. However, within each production system, with or without photovoltaic systems, a difference in results was observed between each of the impact categories evaluated.

In this work, the Global Warming Potential (GWP) ranged from 2.52 kg CO_2-eq to 2.92 kg CO_2-eq for the scenarios evaluated. These values are close to those found by Cheng et al. [9] of 2.98 kg CO_2-eq (China), Lima et al. [25] of 2.70 kg CO_2-eq (Mid-West, Brazil) and Usva et al. [48] of 2.40 kg CO_2-eq (Finland). Alves et al. [2], in turn, pointed out that the impact of climate change was 3.37 kg CO_2-eq (North, Brazil), greater than that quantified in this work and in the other works mentioned.

Table 5. Results of environmental impact categories based on Life Cycle Assessment. Source: Own elaboration.

Impact Category	Unit	Study Scenarios			
		PP-SFV	PP-CFV	PN-SFV	PN-CFV
Acidification Potential (AP)	kg SO_2-eq	1.78 E-02	1.77 E-02	1.54 E-02	1.53 E-02
Eutrophication Potential (EP)	kg PO_4-eq	2.29 E-02	2.29 E-02	1.98 E-02	1.98 E-02
Global Warming Potential (GWP)	kg CO_2-eq	2.921	2.913	2.530	2.520

Legend: PP-SFV: Positive pressure without photovoltaic systems; PP-CFV: Positive pressure with photovoltaic systems; PN-SFV: Negative pressure without photovoltaic systems; PN-CFV: Negative pressure with photovoltaic systems.

It is important to highlight that these authors considered, in addition to the feeding and chicken rearing subsystems, the poultry slaughter process. This implies the use of a different functional unit than those adopted in this study. While this work presents the results in terms of kg CO_2-eq per kilogram of live chicken produced, the referenced authors adopted a functional unit that encompasses all stages up to slaughter, which should be considered when comparing quantitative values across studies. In the present work, the feed production subsystem was the largest responsible, with around 91.0%, for GHG emissions, which was also recorded similarly in the previously mentioned works.

Lima et al. [25] identified in their literature review that the global warming potential varies significantly, between 1.39 and 6.83 kg CO_2-eq. This variation can be attributed to several factors, such as fossil fuel consumption, chicken feed production, age at slaughter, feed conversion, and the technological level adopted in the poultry sheds. These factors directly influence environmental outcomes, which explains the range observed in the impact estimates. Thus, although specific factors can lead to significant variations, they follow a consistent logic that reflects the technical and operational conditions of the production systems analyzed.

Regarding the GWP values obtained in this study, it was observed in Figure 3 that the highest values are recorded in the PP-SFV and PN-SFV scenarios. For systems that had photovoltaic systems when raising broiler chickens, an approximate reduction of 8 grams in GHG emissions was observed for the positive pressure (PP) system and 10 grams for the negative pressure (PN) system, when compared to SFV systems. It should be noted that despite initially representing a small value among the scenarios evaluated, this is a value that is in reference to the functional unit of work, that is, 1 kg live weight.

A PP system produces an average of 340,067 kg of live chicken per year, while a PN system produces a value of around 516,458 kg. In the evaluation of each scenario, the PP-SFV emits approximately 993.23 t CO_2-eq annually and the PP-CFV, 990.65 t CO_2-eq, that is, an estimated reduction of 2.58 t CO_2-eq per year for a broiler house with photovoltaic plant. During the study period, the integrating company had 239 active sheds for raising PP broiler chickens, which represented approximately 63.0% of the production systems in the study region. If photovoltaic systems were adopted in all of these warehouses together with the Electric Energy Compensation System, an approximate reduction of 616.6 t CO_2-eq per year in GHG emissions could be achieved.

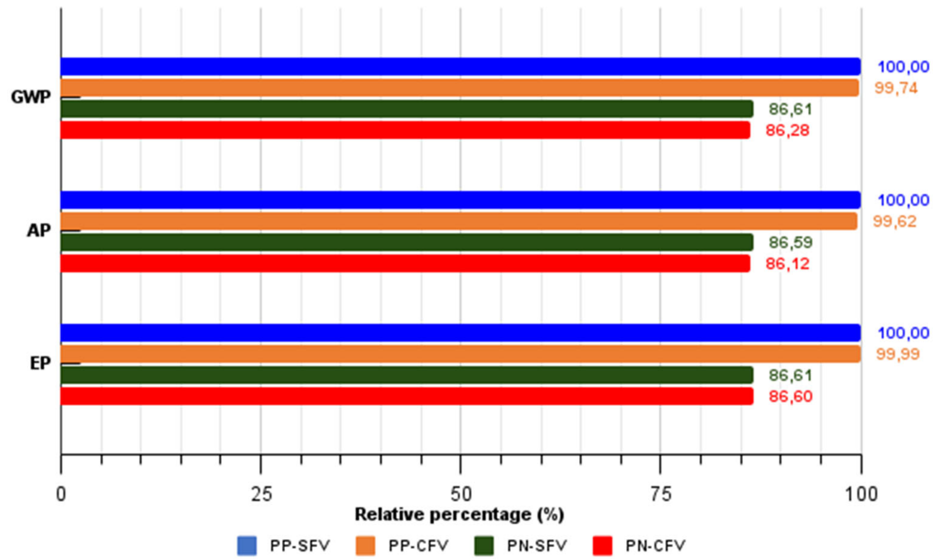

Figure 3. Relative percentage values of environmental impacts calculated based on the Life Cycle Assessment. Legend: PP-SFV: Positive pressure without photovoltaic systems; PP-CFV: Positive pressure with photovoltaic

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systems; PN-SFV: Negative pressure without photovoltaic systems; PN-CFV: Negative pressure with photovoltaic systems. Source: Own elaboration.

In the PN system, the PN-SFV scenario presented annual emissions of approximately 1,306.4 tons of CO_2-eq, while the PN-CFV scenario recorded 1,301.4 tons of CO_2-eq. The difference between these two plans is related to the presence of photovoltaic systems in the PN-SFV, which reduce electricity consumption from the conventional grid. This reduction resulted in an estimated reduction of 4.96 tons of CO_2-eq per farm equipped with photovoltaic systems. Considering that, during the same period, the integrated company had 138 active PN-type breeding sheds, the widespread adoption of these systems could generate a total reduction of approximately 684.5 tons of CO_2-eq per year. Thus, the first scenario refers to the average reduction per production unit, while the second projects the aggregate impact if the entire operation were converted to the photovoltaic system. Thus, a justification can be verified for seeking alternatives for new poultry farmers to use photovoltaic systems on their farms.

In Table 5 it is possible to verify that the broiler chicken production system with a higher level of technology (PN-CFV) is capable of reducing annually around 0.40 kg CO_2-eq per 1 kg live weight, compared to the system with a lower level of technology (PP-SFV). The reduction in greenhouse gas (GHG) emissions observed in intensive broiler production systems with higher technological levels, especially those incorporating photovoltaic systems, can significantly contribute to the formulation of public policies aimed at decarbonizing and decentralizing the electricity sector [13]. In the context of the energy transition, this contribution is related to how electricity is generated and consumed in these production systems, as local generation through renewable sources such as solar energy reduces dependence on the conventional grid and mitigates the carbon footprint of broiler production. Thus, the adoption of clean technologies in poultry houses not only reduces operating costs but also aligns production with energy and climate sustainability goals.

Another point to be mentioned is that the reduction of GWP is associated with the targets defined in Sustainable Development Goals 7 and 13, which can be assessed as the inclusion of more sustainable practices in the broiler chicken production chain, being essential for facing contemporary environmental challenges and promoting effective integration with the UN Sustainable Development Goals [31].

The Eutrophication Potential (EP) ranged from 1.98 E-02 to 2.29 E-02 kg PO_4-eq and the Acidification Potential (AP) from 1.53 E-02 to 1.78 E-02 kg SO_2-eq in the four scenarios (Table 5). It was observed that PN systems produce the lowest values, while PP systems presented the highest levels of eutrophication and acidification potential. The difference in values within the same production system was verified, which only considered whether or not it had photovoltaic systems. After the calculation, it can be seen that the differences are insignificant in terms of impacts, that is, they present a similar profile for each production system, regardless of whether with or without photovoltaic systems.

Regarding AP, the results found in the literature were: Cheng et al. [9] of 0.53 E-2 kg SO_2-eq, Lima et al. [25] of 4.00 E-2 kg SO_2-eq, Martinelli et al. [26] of 1.80 E-2 kg SO_2-eq (Southern Brazil) and Alves et al. [2] of 31.00 E-2 kg SO_2-eq. Only the result of Martinelli et al. [26] was close to that obtained in this work, as can be seen in Table 5. It is believed that one reason for the differences in the values recorded in the literature for the AP is due to the way in which the impact was allocated between the evaluated subsystems in LCA. Acidification occurs mainly due to human actions that negatively impact the environment, such as the combustion of fossil fuels. In the case of Alves et al. [2] the AP value (31.00 E-02 kg SO_2-eq) was much higher, as the poultry slaughter subsystem was considered, which stood out for its large use of natural gas and the biological waste produced.

Regarding the EP assessment, the values found were: Cheng et al. [9] recorded 0.091 E-2 kg PO_4-eq, Lima et al. [25], 2.60 E-2 kg PO_4-eq, Martinelli et al. [26] 3.50 E-2 kg PO4-eq and Alves et al. [2] reported 0.10 E-2 kg PO_4-eq. Only the results of Lima et. al [25] and Martinelli et al. [26] are closer to what was obtained in this work. One justification for this difference in results is that the work of

Cheng et al. [9] and Alves et al. [2] analyzed systems with lower broiler production, when compared to the systems studied by the other authors. Non-intensive chicken production systems tend to contribute less to the eutrophication of water resources when compared to intensive systems. This is because typical intensive production processes, such as the management of large volumes of waste and the intensive use of fertilizers and water, release larger quantities of nutrients such as nitrogen and phosphorus, the main agents of eutrophication. The analysis is performed considering a functional unit of kilograms of live chicken produced, which allows us to compare the relative contributions of these systems to the nutrient load that can cause eutrophication in water bodies. Therefore, the smaller scale and lower intensity of non-intensive production is reflected in a proportional reduction in eutrophication potential.

In relation to all impact categories evaluated, the results achieved in this work are compatible with the values obtained by other studies available in the literature. Although a range of estimated GWP values are indicated in the literature, for example, the values change due to the technology model of the production system, climatic conditions, use of energy from non-renewable sources and the ingredients in the feed formulation, mainly.

The importance of sustainability in poultry production was highlighted in the environmental impact assessment. The inclusion of photovoltaic systems in agriculture, through distributed generation, not only reduces environmental impacts but also contributes to strengthening the energy transition. This is because these systems promote the decarbonization and decentralization of the electricity sector, ensuring greater independence in electricity generation and consumption compared to traditional production methods.

3.2. Energy Usage Assessment

Table 6 presents the average energy values calculated as a function of input and output for each of the chicken production systems in the study region. The average input energy for a production system over a one-year period in the PP-SFV, PP-CFV, PN-SFV and PN-CFV scenarios were 7.03 GJ, 6.82 GJ, 10.34 GJ, and 9.91 GJ, respectively. Regarding the output energy (live chicken and chicken litter), the values were 6.65 GJ for the PP systems and 9.67 GJ for the PN systems.

Table 6. Energy inputs and output for the scenarios studied. Source: Own elaboration.

			Energy values per scenario (MJ.Year $^{-1}$)			
	Unit	Energy coefficient (MJ/Unit)	**PP-SFV**	**PP-CFV**	**PN-SFV**	**PN-CFV**
A. Inputs						
Subsystem: Feed production						
Energy usage						
Electricity	kWh	11.21[a]	2.190 E+08	2.190 E+08	2.190 E+08	2.190 E+08
Diesel	L	47.80[a]	4.370 E+06	4.370 E+06	4.370 E+06	4.370 E+06
Feed ingredients (basic composition)						
Corn	kg	7.24[a]	2.430 E+09	2.430 E+09	3.610 E+09	3.610 E+09
Soybean meal	kg	10.94[a]	1.170 E+08	1.170 E+08	1.740 E+08	1.740 E+08
Dicalcium phosphate	kg	10.00[a]	2.080 E+09	2.080 E+09	3.080 E+09	3.080 E+09
Soy oil	kg	38.60[b]	1.030 E+09	1.030 E+09	1.520 E+09	1.520 E+09
Limestone	m^3	1.59[a]	1.580 E+04	1.580 E+04	2.350 E+04	2.350 E+04
Choline Chloride (70%)	m^3	1.59[a]	6.410 E+03	6.410 E+03	9.510 E+03	9.510 E+03
L-Lysine HCL	m^3	1.59[a]	1.830 E+03	1.830 E+03	2.720 E+03	2.720 E+03
Premix vitamins	m^3	1.59[a]	2.620 E+03	2.620 E+03	3.880 E+03	3.880 E+03
DL-methionine	m^3	1.59[a]	6.550 E+02	6.550 E+02	9.710 E+02	9.710 E+02
Sodium chloride	m^3	1.59[a]	1.440 E+03	1.440 E+03	2.140 E+03	2.140 E+03

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Premix minerals	m^3	1.59[a]	1.050 E+03	1.050 E+03	1.550 E+03	1.550 E+03
Avilaminica	m^3	1.59[a]	1.310 E+02	1.310 E+02	1.940 E+02	1.940 E+02
Mononsina	m^3	1.59[a]	7.850 E+02	7.850 E+02	1.160 E+03	1.160 E+03
Subsystem : *Chicken Production*						
Chicks and bird nutrition						
Day old chicks	kg	10.33[a]	4.950 E+07	4.950 E+07	7.600 E+07	7.600 E+07
Energy (Electricity, Biomass and Fuels)						
Electric energy - distributor (*)	kWh	11.21[a]	2.190 E+08	6.730 E+06	4.310 E+08	6.730 E+06
Diesel	L	47.80[a]	1.520 E+07	1.520 E+07	4.530 E+07	4.530 E+07
Gasoline	L	28.99[c]	3.850 E+06	3.850 E+06	3.850 E+06	3.850 E+06
Natural gas	m^3	49.50[a]	4.950 E+06	4.950 E+06	9.900 E+06	9.900 E+06
Firewood for heating (*Eucalyptus urograndis*)	kg	20.25[d]	2.430 E+06	2.430 E+06	3.650 E+06	3.650 E+06
Preparation for the beginning of the cycle						
Coffee husk - bed	kg	17.55[e]	8.360 E+08	8.360 E+08	1.140 E+09	1.140 E+09
Semi Kraft Paper - One Day Chicks	kg	37.70[f]	6.790 E+06	6.790 E+06	6.790 E+06	6.790 E+06
Economic and social data						
Labor	H	1.96[a]	1.130 E+07	1.130 E+07	1.130 E+07	1.130 E+07
Total energy input (MJ.Year $^{-1}$)			7.029 E+09	6.817 E+09	1.034 E+10	9.911 E+09
B. Outputs						
Live chicken	kg	10.96[a]	3.730 E+09		5.660 E+09	
Chicken litter	kg	13.37[g]	2.810 E+09		4.010 E+09	
Total energy output (MJ.Year $^{-1}$)			6.540 E+09		9.670 E+09	

Legend: PP-SFV: Positive pressure without photovoltaic systems; PP-CFV: Positive pressure with photovoltaic systems; PN-SFV: Negative pressure without photovoltaic systems; PN-CFV: Negative pressure with photovoltaic systems. (*) Single entry with different values between all four scenarios evaluated in the study, due to the type of profile of the electricity consuming unit. References: [a]Pishgar-Komleh et al. [36]; [b]Zheng et al. [49]; [c]Sordi et al. [46]; [d]Silva [43]; [e]Freitas [14]; [f]Teodoro [47]; [g]Pasolini et al. [33].

Figure 4 shows the average values of the energy input components along with the four scenarios evaluated. Food was the one that made the biggest contribution to total input energy consumption, corresponding to 82.3%, followed by coffee husks (11.7%), electricity (4.5%), day-old chicks (0.7%) and others (fuel inputs, firewood for heating, semi-kraft paper and human labor, with 0.8%).

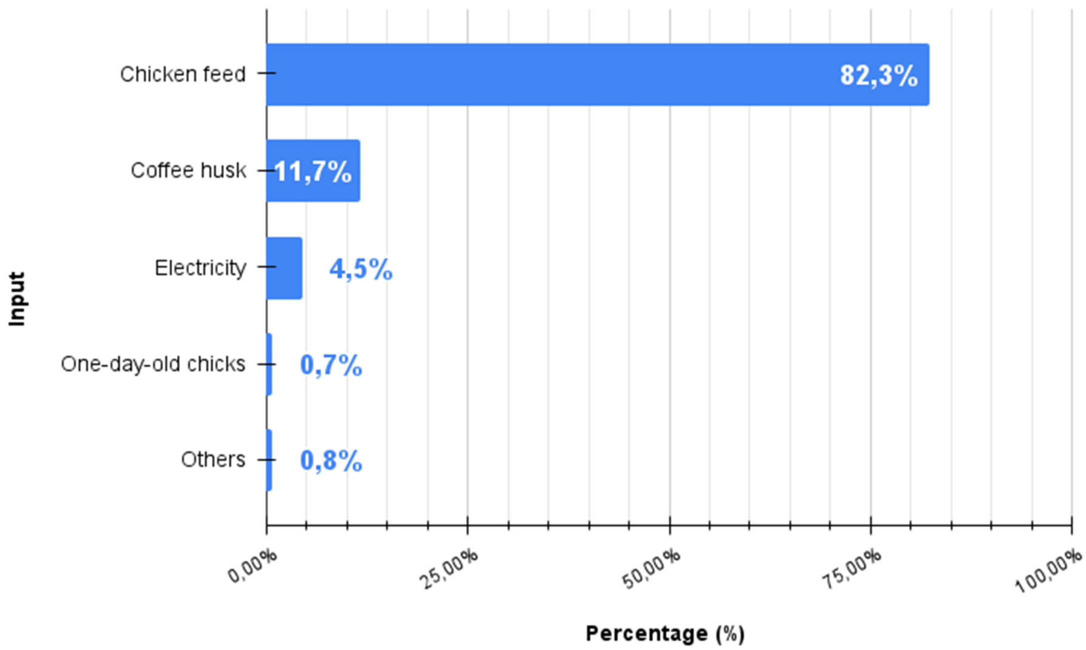

Figure 4. Participation of the average input energy of inputs in the production of broilers. Source: Own elaboration.

The results of Heidari et al. [16], 8.6%, and Pishgar-Komleh et al. [36], 3.0% were similar to what was obtained here (4.5%), in relation to the use of electrical energy. However, fuel inputs (59.2% to 71.0%) and feed (25.0% to 31.8%) presented the highest composition in the studies mentioned in the previous paragraph, contrary to what was observed here (Figure 4). The consumption of the set of fuels (diesel oil, gasoline and natural gas) was included in the item "others", as it represented only 0.52% of energy inputs. While in the mentioned works fuels are responsible for the highest energy values, The feed in this study is the item that contributes around 82.0% of the total energy demand in the production of broiler chickens. Just as in the assessment of environmental impacts, which found that the feed is the main contributor to GHG emissions, the feed also contributes. was the component with the highest share of energy use.

The energy indices Energy Efficiency (EE), Energy Productivity (PE) and Net Energy (EL) for the production of broiler chickens in the Zona da Mata of Minas Gerais are presented in Table 7. The energy efficiency index showed that PP systems have a lower energy use efficiency when compared to PN systems and that if the production system is a consumer-generator together with the Electric Energy Compensation System [8], there is an increase in the efficiency of the use of energy resources that can reach around 4.5%.

Table 7. Energy indices of evaluated broiler production systems. Source: Own elaboration.

Index	Unit	Study Scenarios			
		PP-SFV	PP-CFV	PN-SFV	PN-CFV
Energy Efficiency (EE)	-	0.930	0.966	0.944	0.988
Energy Productivity (PE)	kg.(MJ)$^{-1}$	4.84 E-05	4.99 E-05	5.00 E-05	5.21 E-05
Net Energy (EL)	MJ	-4.89 E+08	-2.77 E+08	-6.65 E+08	-2.41 E+08

Legend: PP-SFV: Positive pressure without photovoltaic systems; PP-CFV: Positive pressure with photovoltaic systems; PN-SFV: Negative pressure without photovoltaic systems; PN-CFV: Negative pressure with photovoltaic systems.

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The energy productivity index reflects the efficiency with which energy is used to generate production. The results presented in Table 7 indicate that the system with more advanced technology, represented by the PN-CFV scenario, has an energy productivity 7.2% higher than the system with less technology, the PP-SFV. This difference is driven by factors such as better practices in energy consumption management, mainly due to the use of photovoltaic systems in conjunction with electricity consumption, which together result in lower energy consumption per unit of product.

Regarding the evaluation of the net energy index, it can be seen in Table 7 that in all scenarios the output energy was lower than the input energy. The PN-SFV scenario presented the highest value of energy losses among the production systems, while the PN-CFV scenario represents a system with lower losses, despite still recording an energy production lower than the energy required for the broiler chicken production. The differences in net energy values observed in the four scenarios evaluated were largely due to electricity consumption supplied by photovoltaic systems installed in poultry sheds. The adoption of these systems significantly reduced dependence on conventional grid energy, reducing the use of non-renewable sources and, consequently, total electricity consumption. This reduction is possible because the energy generated locally through solar radiation is used directly to power essential production equipment, such as ventilation, heating, lighting, and automated systems, improving the systems' energy efficiency. Thus, the integration of photovoltaic energy into production systems contributes to an effective reduction in energy consumption and promotes the environmental sustainability of poultry production.

Among systems with photovoltaic systems, it was observed in Table 6 that PP-CFV has an energy loss 13.0% greater than PN-CFV. For systems without photovoltaic systems integrated in production, the PN-SFV system has an energy loss 26.5% greater than the PP-SFV.

Since the highest energy consumption is related to feed production and the use of coffee husks, it is necessary to evaluate alternatives for the use of feed ingredients and poultry litter with lower energy coefficients. This is because, even with the adoption of photovoltaic systems, the scenarios evaluated were unable to present systems with higher output energy than input energy. Therefore, to further increase the energy efficiency of systems, it is essential to seek alternative and more sustainable sources for feed formulation and poultry waste management.

It is considered necessary to adopt feed formulated with more sustainably produced agricultural ingredients, such as those from organic crops, which reduce carbon emissions and the use of fossil fuels. Furthermore, it is suggested to seek alternative raw materials for poultry litter, such as agricultural byproducts or recycled organic waste, which can reduce the energy demand in the production and management processes. These measures aim to reduce total input energy consumption and, consequently, increase the energy efficiency (EE) and energy productivity (EP) of poultry production systems [2,10].

3.3. Economic Assessment

Table 8 presents the entire allocation of associated production costs for each of the scenarios evaluated. From this cost allocation it was possible to evaluate which inputs lead to the highest expenses in broiler production systems.

Table 8. Composition of the annual costs of the evaluated systems. Source: Own elaboration.

	Study Scenarios			
	PP-SFV	**PP-CFV**	**PN-SFV**	**PN-CFV**
A. Producer cost (USD.Year $^{-1}$)				
Energy (Electricity, Biomass and Fuels)				
Electric energy - distributor (*)	3,779.76	116.07	7,443.26	116.07
Diesel	415.06		1,189.83	
Gasoline	198.21		198.21	
Natural gas	124.19		248.39	
Firewood for heating	1,987.10		2,980.66	

(*Eucalyptus urograndis*)				
Preparation for the beginning of the cycle				
Coffee husk - bed	6,147.60		8,383.10	
Semi Kraft Paper - One Day Chicks	365.13		365.13	
Economic and social data				
Labor	12,605.69		12,605.69	
Taxes				
Charging for the Use of Water Resources	199.79		199.79	
Environmental Licensing	201.45		201.45	
Harvesting and selling firewood	36.49		36.49	
Chainsaw registration	25.02		25.02	
Other expenses				
Food - Pick up service	447.1		894.2	
Telephone and Internet	99.36		670.65	
Maintenance of equipment, machines and facilities	4,502.03		4,452.35	
Fire extinguishers	16.56		16.56	
Pest control and cleaning products	129.42		167.43	
Total producer cost (USD.Year $^{-1}$)	31,279.97	27,616.28	40,078.20	32,751.01
B. Recipes				
Live chicken	21,548.66		37,398.89	
Chicken litter	17,387.16		24,838.80	
***Total revenue* (USD.Year $^{-1}$)**	38,935.82		62,237.69	

Legend: PP-SFV: Positive pressure without photovoltaic systems; PP-CFV: Positive pressure with photovoltaic systems; PN-SFV: Negative pressure without photovoltaic systems; PN-CFV: Negative pressure with photovoltaic systems. (*) Single entry with different values between all four scenarios evaluated in the study, due to the type of profile of the electricity consuming unit.

After obtaining the initial results of the economic analysis, it was decided to disregard payment for paid labor in the cost calculation, as the vast majority of poultry farmers in the study region work with family labor. However, it is important to clarify that, if these payments were considered, labor costs would represent between 31.5% and 45.6% of annual production costs in the plans evaluated. This decision was made to reflect the local reality, where family labor, although not formally paid, represents an important productive and economic resource. However, this disregard implies a significant underestimation of total costs, which should be taken into account when interpreting the economic results presented.

The study found that adopting family labor in poultry farming contributes to reducing total production costs, a fact also observed by Beal et al. [6], who identified paid labor as one of the largest costs in conventional broiler production systems. This reduction occurs because family labor, often unpaid formally, reduces direct expenses with wages and labor charges, increasing the economic viability of rural properties [7]. Furthermore, the use of family labor plays an important social role, as it enables families to remain in rural areas, promoting local development and the preservation of farming communities.

This dynamic is related to the sustainability of the broiler production chain not only from an economic perspective, but also from a social and environmental perspective, aligning with the Sustainable Development Goals (SDGs), especially SDG 2, which aims to eliminate hunger, promote food security, and promote sustainable agriculture. Research shows that production systems that

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encourage family work tend to have greater resilience and less socio-environmental impact, reinforcing the role of this model for sustainable rural development [31].

The results in the PP-SFV scenario indicated that 32.9% of the costs are related to the acquisition of coffee husks, followed by the maintenance of equipment, machines and facilities (24.1%), electricity (20.2%), firewood for heating (10.6%), food in collection services (2.4%), diesel oil (2.2%), semi-kraft paper (2.0%) and others (5.5 %) represented by taxes, gasoline, natural gas, pest control and cleaning products and telephone.

In the positive pressure broiler production scenario with photovoltaic systems, PP-CFV, the costs of purchasing coffee husks were 41% of total costs, followed by maintenance of equipment, machines and facilities (30.0%), firewood for heating (13.2%), food in collection services (3.0%), diesel oil (2.8%), semi-kraft paper (2.4%), electricity (0.8%) and others (6.9%). The results showed a significant reduction in electricity consumption by the electricity distributor, a reduction of 19.4% per year.

For negative pressure production systems, the PN-SFV scenario showed that 30.5% of the costs are related to the purchase of coffee husks, electricity (20.2%), maintenance of equipment, machines and facilities (16.2%), firewood for heating (10.8%), diesel (4.3%), food in collection service (3.3%), telephone and internet (2.4%), semi-kraft paper (1.3%) and others (4.0%) represented by taxes, gasoline, natural gas, pest control and cleaning products.

For the last scenario evaluated, PN-CFV, expenditure on purchasing coffee husks represented 41.6% of production costs, followed by maintenance of equipment, machines and facilities (22.1%), firewood for heating (14.8%), diesel oil (5.9%), food collection service (4.4%), telephone and internet (3.3%), semi-kraft paper (1.8%), electricity (0.6%) and others (5.4%). The results also point to a significant difference in electricity consumption with the electricity distributor, a reduction of 26.5% annually. Table 9 presents a summary of production costs and the economic indices evaluated in the study.

Table 9. Annual indices and costs of evaluated broiler production systems. Source: Own elaboration.

	Unit	Study Scenarios			
		PP-SFV	**PP-CFV**	**PN-SFV**	**PN-CFV**
Gross Income	USD. year^{-1}	38,935.82	38,935.82	62,237.69	62,237.69
Variable costs					
COE		30,733.51	27,069.82	34,397.01	27,069.82
Fixed Costs					
COT		33,543.41	31,349.34	37,206.91	31,349.34
Opportunity cost		2,190.16	2,190.16	2,190.16	2,190.16
Total Cost		35,733.57	33,539.50	39,397.07	33,539.50
Profit		3,202.25	5,396.32	22,840.62	28,698.19
Gross Margin		8,202.31	11,866.00	27,840.68	35,167.87
Net Margin		5,392.41	7,586.48	25,030.78	30,888.35
Cost-Benefit Ratio	-	1.09	1.16	1.58	1.86

Legend: COE: Effective operating cost; COT: Total operating cost; PP-SFV: Positive pressure without photovoltaic systems; PP-CFV: Positive pressure with photovoltaic systems; PN-SFV: Negative pressure without photovoltaic systems; PN-CFV: Negative pressure with photovoltaic systems.

For all scenarios evaluated, as shown in Table 9, the production systems demonstrated cost-effective strategies, yielding positive profits. However, the system with the most advanced technology, the PN-CFV scenario, demonstrated a profit 88.8% higher than the PP-SFV system. This

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difference is primarily due to the greater operational efficiency provided by automation and the use of energy generated by photovoltaic systems, which significantly reduces electricity costs—one of the largest expenses in poultry production. Furthermore, photovoltaic systems allow for greater energy independence and reduced variable costs, increasing producers' profit margins. Meanwhile, the total cost profile of the PP-CFV and PN-CFV systems is similar, but systems incorporating photovoltaic technology guarantee a profit 81.2% higher than systems without this resource, highlighting the positive impact of using these renewable sources on production economics.

In relation to the MB and ML indices, it was verified that the values calculated and recorded in Table 9 are positive and thus it is concluded that the broiler production systems are economically stable and remunerative [3]. It is noteworthy that profits increase when broiler production systems have photovoltaic systems that inject electrical energy credits into the consumer unit of the production system, while RCB decreases according to the reduction in the level of technology. Furthermore, PP production systems have the lowest RCB values. According to SENAR [42], it is crucial to evaluate the relationship between gross income and total costs, since production systems with values equal to or less than one can cause losses to rural producers, in addition to making the production process unfeasible.

3.4. Uncertainty Analysis

The results of the Uncertainty Analysis obtained from the simulation with the Monte Carlo tool, together with SimaPro®, are presented in Table 10.

Table 10. Average and coefficients of variation for the impact categories assessed in the uncertainty analysis. Source: Own elaboration.

Study scenario	Impact Category	Acidification Potential (AP)	Eutrophication Potential (EP)	Global Warming Potential (GWP)
	Unit	kg SO_2-eq	kg PO_4-eq	kg CO_2-eq
PP-SFV	Average	1.84 E-02	2.30 E-02	2.921
	CV(%)	164.11	39.34	11.76
PP-CFV	Average	1.79 E-02	2.30 E-02	2.913
	CV (%)	172.04	39.67	11.99
PN-SFV	Average	1.58 E-02	1.99 E-02	2.530
	CV (%)	166.93	39.07	11.70
PN-CFV	Average	1.61 E-02	1.99 E-02	2,520
	CV (%)	162.45	39.19	11.81

Legend: PP-SFV: Positive pressure without photovoltaic systems; PP-CFV: Positive pressure with photovoltaic systems; PN-SFV: Negative pressure without photovoltaic systems; PN-CFV: Negative pressure with photovoltaic systems.

The work of Pereira et al. [35] was used as a reference for the uncertainty analysis of the production systems studied. The results for the GWP impact category showed less variation in the results presented, with fewer associated uncertainties.

Regarding the acidification (AP) and eutrophication (EP) categories, the values presented in Table 10 indicate moderate to high coefficients of variation (CV). This variability can be explained by the nature of the primary data attributed to the feed production subsystem inputs, which exhibit greater fluctuations due to flows involving primarily corn and soybeans, ingredients that comprise the majority of chicken feed formulations. These raw materials are subject to significant variations in origin, costs, agricultural practices, and transportation processes, generating significant uncertainty in inventory data. Studies such as that by Leinonen et al. [23] have also observed this high uncertainty

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in similar analyses, highlighting that variability in basic raw material data directly impacts the coefficients of variation in the related environmental categories.

4. Conclusions

This study evaluated broiler production systems using the Life Cycle Assessment methodology, analyzing environmental impacts, energy use, and economic costs for rural producers. Based on the results obtained, it was concluded that:

- Production systems with photovoltaic systems have the potential to reduce between 2.58 t CO_2-eq (positive pressure systems) and 4.96 t CO_2-eq (negative pressure systems) annually, while also presenting better energy efficiency indices.
- No significant differences were observed between positive and negative pressure systems, with or without photovoltaic systems, in terms of the environmental impact categories assessed, given that the Brazilian electricity grid has a high share of renewable sources.
- All scenarios analyzed demonstrated economic viability, with negative pressure systems standing out as presenting the best cost-benefit ratio.
- Feed production represented a significant portion of global warming potential (approximately 82%) and total energy demand, indicating the need for specific strategies for this phase.
- The highest costs were related to the use of coffee husks for chicken bedding (36.5%), facility maintenance (23.1%), and the use of firewood for heating chicks (12.4%).
- The incorporation of photovoltaic systems allows for a reduction in electricity costs between 19.4% and 26.5% per year, promoting not only savings but also greater energy sustainability [50].
- The most sustainable system, both environmentally and economically, was the negative pressure system with photovoltaic systems, while the least sustainable was the positive pressure system without photovoltaic generation.

Given the significant reduction in emissions and costs provided by photovoltaic systems, it is recommended that public policies encourage the adoption of this technology in poultry production through subsidies, facilitated credit lines, and technical training programs. Furthermore, special attention to feed production, the main driver of environmental impact and energy consumption, justifies investments in research into more sustainable and efficient feed formulations [52].

Rural producers can benefit from the adoption of photovoltaic systems and technologies that increase energy and operational efficiency, promoting environmental and economic improvements. Integrating companies and government agencies should support processes that facilitate technological modernization.

This study was based on data specific to a region of Brazil and may not fully capture the country's variations in climatic conditions, agricultural practices, and economic structures. Furthermore, the economic analysis did not consider formal remuneration for family labor, which may impact cost assessments.

Future research should explore the optimization of feed formulation to reduce environmental impact, a detailed analysis of the adoption of different renewable sources, and an assessment of the long-term economic effects of technological modernization. Studies involving other regions and complementary production systems are also important to broaden the applicability of the results [51].

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