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Sustainability comparison of commercial Brazilian organic and conventional broiler production systems under a $5SE_NSU$ model perspective

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ABSTRACT

This study aimed to evaluate the sustainability of a commercial organic broiler production system based on the concept of strong sustainability. Thus, the FIVE SEctors of SUstainability model ($5SE_NSU$) under a perspective of Goal Programming philosophy were used and the results were compared to a commercial convencional broiler production system. For the data collection, two case studis were carried out in a representative commercial organic broiler production system (*UPrO*) and commercial conventional broiler production system (*UPc*) in the state of São Paulo from October/2020 to June/2021. The environmental and social dimensions were considered as providers of resources for the system and receivers of products and negative externalities. Environmental criteria were performed using the Emergy Synthesis, while economic criteria were performed using calculation models based on Economic theory. Furthermore, social criteria were performed using data collected on a farm. In the end, the broiler production system sustainability was compared using a general sustainability index by means of the Goal Programming philosophy. The results show a trade-off between animal welfare and economic and environmental costs. The lower stocking density in *UPrO* raised the animal welfare by providing more area/animal, but increased the resource consumption, GHG emission and the production cost. However, when social results were considered, *UPrO* showed more pathways to achieve a more sustainable commercial broiler production, as shown by the general sustainability index (43.2 and 49.4 for *UPrO* and *UPc*, respectively).

1. Introduction

In recent years, organic farming and consumption practices have sparked great interest in the population, as these support the health of people and the environment (Chekima et al., 2019). Interest in organic chicken meat has also shown growth in the same period (Eurostat, 2021; NASS, 2021). There are many reasons for the growth of organic chicken production and, because of this, animal welfare corcens in the broiler production has become an area of debate in industrialized societies (Dransfield et al., 2005; Kim et al., 2018; Verspecht et al., 2011). Successive consumer pressure on the animal industry for products that are offered by respecting animal welfare has raised discussions on the topic (Schipmann-Schwarze and Hamm, 2020). Among the concerns, the high stocking densities used in conventional poultry production systems have been heavily criticized for bringing a negative aspect to poultry welfare (Vanhonacker and Verbeke, 2009). This led to debates regarding the benefits of lower stocking density in commercial broiler systems and its prosperity. Moreover, "environmental benefits" and "a more environmental-friendly system" were cited as organic choice motivation for both poultry producer and chicken consumers (Schipmann-Schwarze and Hamm, 2020; Sparks et al., 2008).

Traditionally, the conventional broiler production system is characterized by the high-technological investments in buildings and equipment, and broilers with high genetic performance and fast growing (slaughtered in ~42 days) housed in small areas (~32 kg of meat/m^2) and fed with corn and soybean-based diets. The organic broiler production system presents several kinds with different features. However, the Brazilian commercial organic broiler system that seems increasing in recent years are those that present the same features of the conventional systems but with lower stocking density, access to paddock areas, and fed with organic corn and soybean-based diets. In Brazil, all guidelines

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List of acronyms

$5SE_NSU$	FIVE SEctors of SUstainability model
UPrO	Representative commercial organic broiler production system
UPc	Commercial conventional broiler production system
GHG	Greenhouse gas
GP_m	Goal Programming
Y	Emergy
ES	Emergy Synthesis
I	Natural resources
R	Renewable resources
N	Non-renewable resources
F	Economic resources
F_N	Non-renewable fraction of economic resources
ELR	Environmental Load Ratio
EER	Emergy Exchange Ratio
EMR	Emergy/money ratio
ESI	Emergy Sustainability Index

about the production of chickens in an organic system are contained in Normative Instruction 46, of October 6, 2011, in the provisions of Law No. 10831, of December 23, 2003 (commonly defined as the "Organic Law"), and in Decree 6323 of December 27, 2007 (Brasil, 2003, 2011, 2014). Through these legislations, lower stocking density and accessibility of animals to grazing paddocks are defined.

However, if on the one hand, the lower stocking density confers high animal welfare, better zootechnical performance (Estevez, 2007) and a more environmental-friendly system than the conventional one, in an empirical perspective from producers and consumers (Schipmann-Schwarze and Hamm, 2020; Sparks et al., 2008), on the other hand, reducing the number of broilers brings consequences not only as a lower productivity per area (Estevez, 2007; Verspecht et al., 2011), but also concerning increased production costs, since it led to higher input costs (i.e., labor) (SCAHAW, 2000). Thus, one-dimensional evaluations may choose the best system erroneously or superficially when they consider socioeconomic or environmental aspects separately. That said, it becomes essential to use methodologies that make it possible to assess sustainability in broiler production in a holistic perspective.

There are several studies in the scientific literature that use multidimensional tool to assess the sustainability in commercial poultry sector. Among them, Rocchi et al. (2019) compared different kinds of free-range poultry production systems to a conventional indoor poultry production system using a multicriteria tool combining environmental sustainability, economic feasibility and animal welfare. The authors observed better results for free-range animals orchard-based, combining environmental and economic benefits. Méda et al. (2021) evaluated the French conventional and free-range poultry production sectors using a multicriteria tool based on economic, social, and environmental dimensions. The authors observed which free-range performed well in the all three dimension. Also, the conventional standard production showed lacked competitiveness and heavily relied on imported soybean meal.

On the other hand, there are few studies which compared organic and conventional broiler production systems in a holistic way (Bokkers and Boer, 2009; Castellini et al., 2012; Rocchi et al., 2019). Recently, Rocchi et al. (2021) compared different organic poultry production systems to convencional production system using a multicriteria tool based on human, environmental and animal welfare dimensions. The authors observed which organic systems showed better human and animal welfare performance whereas conventional system showed better environmental performance.

In most of these studies, ecosystem services and "free" resources provided by the environment are not inserted in the calculation models (Liu et al., 2018). The absence of environmental free inputs accounting could limit the understanding of the best production system. In this sense, the Emergy Synthesis (*ES*) is a methodology that considers the work of nature as a provider of resources, enabling an evaluation of environmental costs together with the economic costs involved in the production activity, alongside the supply of goods and services of society (Almeida et al., 2013; Giannetti et al., 2013a, 2013b). *ES* studies the windows that integrate society with nature, understanding that the generation of monetary wealth occurs from the interaction with natural resources (Brown and Ulgiati, 2004; Odum, 1996).

Several studies in the scientific literature aim to assess the sustainability of poultry production systems from the *ES* (Castellini et al., 2006; Nacimento et al., 2022; Zhang et al., 2013). However, to the best of our knowledge, studies that evaluate the sustainability of poultry production systems from the economic and ecological dimensions jointly, based on *ES* and cost theory, are scarce (Castellini et al., 2012; Cheng et al., 2017). This study was partly based on the study of Castellini et al. (2012). The novelties of this study were: (i) evaluation of the sustainability in a general perspective, integrating the environment and social dimension as providers of resources and receivers of emissions and products as well as economic dimension, and using the Goal Programming philosophy; and (ii) evaluation of the sustainability from representative commercial broiler production systems. For the authors, since the commercial broiler production systems do not present large differences among world regions, the model and their contributions could be extended not only to Brazil, but also to other world regions. Thus, this study aimed to evaluate the sustainability of a commercial organic broiler production system in a holistic point-of-view, using the FIVE SEctors of SUstainability ($5SE_NSU$) model from the perspective of Goal Programming philosophy and then comparing to a commercial convencional broiler production system.

2. Material and methods

The sustainability assessment is an important concern at several levels in the hierarchy of agricultural systems (Lowrance et al., 1986; Lynam and Herdt, 1989). However, it is particularly relevant at farm level (Hansen and Jones, 1996). Modeling behavioral and technical relationships at farm level is used by agricultural production economists to evaluate the optimal means to allocate scarce resources to achieve desired goals. These modeling efforts are increasingly being used to assess larger policy issues integrating agricultural production systems and sustainability (Weersink et al., 2002). With regards to sustainability, the first concept proposed by the Brundtland report (1987) allowed different interpretations and propositions of conceptual sustainability models. According to the relationship among the main capital forms (environmental, social, and economic), it is possible to obtain "weak", "intermediate", and "strong" sustainability models. In particular, the strong sustainability model implies that different capitals cannot be substituted because they provide different and unique contributions (Giannetti et al., 2020).

Finally, the farming systems are dynamic, stochastic, and purposeful systems. By delimiting the framework at the farm level, it becomes easier to assess stronger sustainability by identifying failure criteria, making assumptions about the future behavior of the system inputs, and hypothesizing constraints (Hansen and Jones, 1996). Thus, in this study, farm level was adopted as the framework because it is the most important unit of decision analysis for economic and technological decision-making. In addition, the use proposition of the $5SE_NSU$ model allows for a better comprehension of the sustainability in farming systems because it integrates environmental, social, and economic capital in a holistic point-of-view.

The study was carried out at the Laboratory of Socioeconomic and Animal Science of the School of Veterinary and Animal Science of the University of São Paulo, Pirassununga, Brazil, from October 2020 to June 2021. It was approved under protocol number 1303010221 by the

Committee of Ethics in the Use of Animals, School of Veterinary and Animal Science, University of São Paulo (CEUA-FMVZ/USP).

2.1. Selection of the commercial organic (*UPrO*) and conventional (*UPc*) broiler production unities

The spatial boundaries were established as the area used to broiler production. For *UPrO* $= building \cup paddock$; and for *UPc* $= building$. The time window was one year. The methodology was divided into two stages: (i) definition of the representative production unit (*UPrO*) for broiler produced in an organic system; (ii) indication of a *UPrO* for a case study that was consistent with the characteristics determined in the first step. The theorical definition of *UPrO* was obtained from the technical staff of the agroindustry using a semistructured questionnaire. After the *UPrO* theoretical definition, a representative organic broiler production unit was selected. A case study of the organic broiler production unit was conduced in order to get to know the technological package (feeders, drinkers, air conditioning system), as well as the management intrinsic to production.

From the *UPrO* definition, a conventional broiler production unit (*UPc*), similar to *UPrO* in the technological package, as well as the management intrinsic to production, were selected.

Subsequently, questionnaires were remotely applied to the producers in order to raise quantitative data concerning the production, as well as information about zootechnical performance indicators. In this step, all the data collections were remotely performed for both *UPrO* and *UPc*.

2.2. Broiler production unities location

The *UPrO* selected for the study is located in Pirassununga, São Paulo, Brazil (Lat −21.9980468 S, long - 47.4280861, W; https://www.gps-coordinates.net/). The *UPc* was located in São José do Rio Preto mesoregion, São Paulo, Brazil (Lat −20.7836955S, long −49.8149752, W; https://www.gps-coordinates.net/) (Fig. 1).

Both *UPrO* and *UPc* presented automated feeding and drinkers, heating from a wood-fired oven, and cooling using a combination of ventilation (positive pressure) and nebulization. Aspects related to primary data inventory, as well as stocking and zootechnical features for *UPrO* e *UPc*, are described on Table 1.

2.3. Economic cost assessment model development

Economic cost model was developed according to the Economic

Table 1
Inputs, stocking, and zootechnical features for commercial organic and conventional broiler production systems.

Inputs	Unit	Broiler systems	
		UPrO	*UPc*
One-day chicks	*un*	12,700	25,000
Nutrition	- - - - -	- - - - - -	- - - - - -
Corn	*kg*	31,968	73,887
Soybean meal	*kg*	17,087	34,909
Energetics	- - - - -	- - - - - -	- - - - - -
Electricity	*kwh*	2,198	3,000
Gas	*L*	11.5	30.0
Diesel	*L*	22.5	40.0
Firewood	m^3	15.4	30
Bedding (wood shaving)	*t*	18	15
Stocking features			
Total area	m^2	8,459	2,250
Covered surface	m^2	1,409	2,250
Paddock	m^2	7,050	-
Stocking density (covered surface)	$birds/m^2$	9.01	11.11
Stocking density (paddock)	$birds/m^2$	1.80	-
Zootechnical performance			
Flocks per year	*n*	5.5	5.8
Final weight	*kg/bird*	2.45	2.55
Slaughter age	*days*	43	46
Total feed consumption	*kg/bird*	4.43	4.61
Feed conversion	*kg : kg*	1.80	1.84
Mortality	%	3.00	1.38

Adapted from Nacimento et al., (2022).
For economic indicators calculation: for the residual rate (%) and useful life (years) of facilities and equipment, data suggested by CONAB (2010) were used. For the building, a residual rate of 20% and a useful life of 40 years were defined for the brickwork building. For the rotavator, a residual rate of 5% and a useful life of 12 years were defined. For the other equipment (i.e. feeding, watering, and air conditioning systems), the values for residual rate and useful life were defined from the median of a database with information on 340 agricultural implements listed by CONAB (2010), which is set at 5% and 12, respectively. The use of the median is justified for this purpose since the values present a high discrepancy between them, and the median may represent the reality more faithfully for this set of data;
Considering certifications for "antibiotic free", "animal welfare" and "organic production". Average values per audit of R$3,000.00/day were considered, with audits twice a year (personal report. Certified Humane Brasil, 2021);
The annual interest rate was 4.15% and the inflation rate was 2.22% for June/2021;
The bedding has been reused 4 times, according to personal reports.

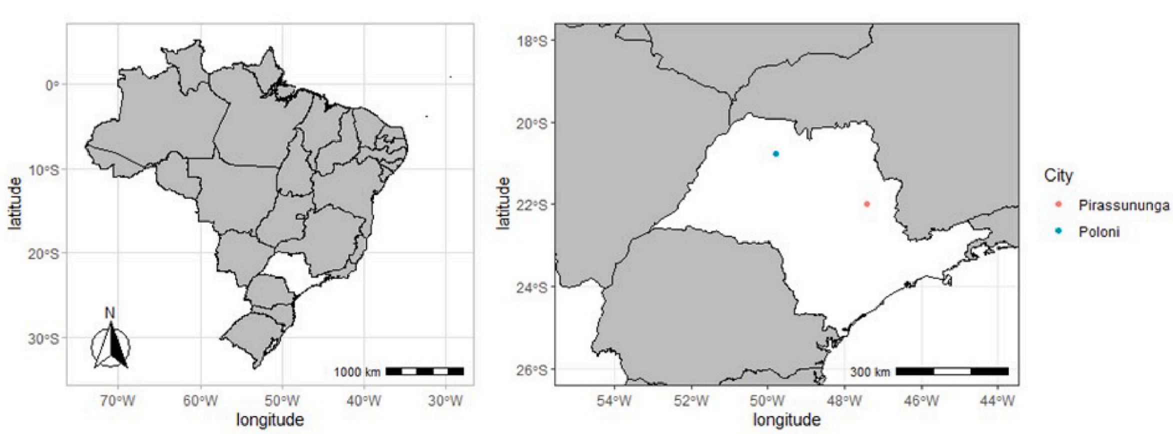

Fig. 1. Geographical location of Pirassununga and Poloni, São Paulo, Brazil. The *UPrO* was located in Pirassununga (pink point) and *UPc* was located in Poloni (green point)
Note: *UPrO* is the representative production unit for broiler raised in an organic system, and *UPc* is the broiler production unit raised in a conventional system.
Source: For map: EstatGeo: https://bityli.com/VdZGu); ggplot2 package (RStudio®) was used to the map construction.

theory, considering the total cost as the result of the sommatory of the variable cost and the fixed cost (*Total cost* $=$ *variable cost* $+$ *fixed cost*). The calculation memory is provided in the Supplementary Material 1.

The cost inputs were established as variable as long as they are changed with the inclusion of broiler flocks. The cost inputs were established as fixed as long as they are not changed as a consequence of the inclusion of broiler flocks. The flock was established as the product resulting from the studied production systems at the end of the production period (~45 days). The prices to one-day-chicks, nutrition, eletric power, fuels, bedding, wood, transport, sanity analysis, technical assistance and catching services were obtained from producers, technical staff of the agroindustry, and spot prices. The prices were obtained for June/2021.

The variable cost was considered the sommatory of the one-day-chicks, nutrition, sanity, energetics (fuels, eletric power, and heating), bedding, transport, and miscellaneous. The fixed cost was considered the sommatory of maintenance and depreciation of machinery and buildings, registered man power, technical assistance, tax, insurance, certifications, opportunity cost, and fixed capital.

The nominal price praticed by the organic broiler in R$/kg of live weight was estimated from the market price for processed organic broiler. For this, 20.4% of the maket price for processed organic broiler was deducted since this value was related to slaughterhouse, management, and market costs (Figueiredo et al., 2007). The carcass yield was estimated in 70%, in accordance with Nacimento et al. (2021), for broilers with ~2.5 kg of live weight without intestines, feathers, head, neck, and feet. For conventional broiler, the nominal price praticed was R$5.50/kg of live weight, according to quotation for july/2021.

2.4. Model development in emergy synthesis (SE)

In livestock systems, they consider the energies provided by environmental local resources ($I = R + N$) economic resources (F), resulting in a particular quantity of product (Odum, 1996). The advantages of *SE* use are: (i) aggregated evaluation of environment-human systems (Bastianoni and Marchettini, 1996); (ii) approach in energy values for each input in any production system (Zhang et al., 2013); (iii) short-term and long-term sustainability assessment and comparing systems in different locations (Castellini et al., 2006); (iv) economic inventory-based assessment, enabling the decision making, considering ecological and socioeconomic aspects. The *ES* model used to perform the emergy indicators for this study is available in Nacimento et al. (2022) and Supplementary Material 2.

2.5. The FIVE SEctor SUstainability model adoption

The FIVE SEctors SUStainability model ($5SE_NSU$) is a tool that assists in the holistic assessment of the sustainability of a given system (Giannetti et al., 2019). It is a model aligned to the input-state-output concept (environment-society-economy) that follows the idea of the model proposed by Pulselli et al. (2015), which postulated sustainability as an aspect that interrelates compartments of human activities in a physical, social, and economic context (see Fig. 2). The model considers five sectors: (*S*1) the environmental sector as a provider and (*S*2) receiver of externalities; (*S*3) the production unit sector as a producer of goods and services; and (*S*4) the social sector as a provider of labor and inputs and as a consumer of goods and services (*S*5).

The conception of this model is based on six axioms, three of which (i, ii, and iii) were proposed by Goodland (1995) and Goodland and Daly (1996). These three axioms are related to natural resource limits considering exploitation rates and consumption in order to guarantee the current development patterns. Three other axioms were suggested by Giannetti et al. (2019):

(i) no resource should be used at higher rates than its generation rate;

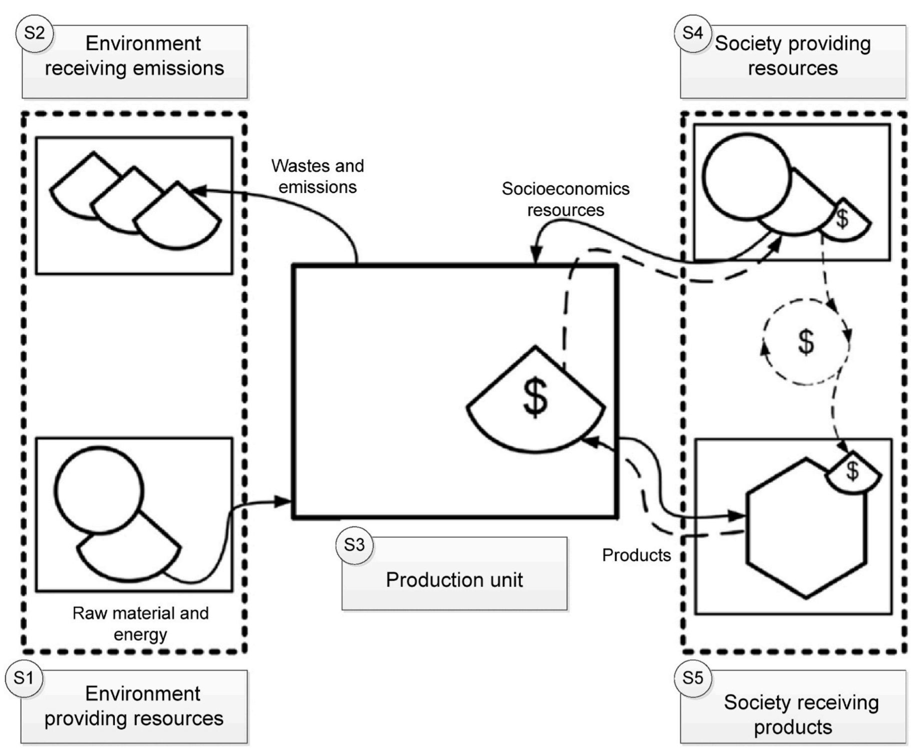

Fig. 2. FIVE SEctor SUstainability model ($5SE_NSU$). The used simbology is according to emergy theory (Odum, 1996). Circular symbols represent energy sources; "tank" symbols represent stocks; hexagonal symbol represents a society as consumers; continuous lines and arrows represent energy and material flows; and dashed lines and arrows represent money flows. "S" is sector.
Source: adapted from Giannetti et al. (2019).

(ii) no contaminant should be produced at higher rates than their natural recycling process, neutralization, and absorption by the natural environment;
(iii) non-renewable resources should never be used faster than the necessary time to replace them with a renewable resource;
(iv) there must be a balance between the environment as a supplier of resources and as a receiver of waste and pollutants, which could be achieved by cleaner production practices, environmental care, and conservation;
(v) the production of goods must be limited to the restrictions imposed by the sustainable exploitation of natural resources and by responsible consumption of the society;
(vi) for humans as social beings, their relationship with the economic system, by providing labor and receiving manufactured products, must be balanced.

The five sectors were: Sector 1 (*S*1) the environmental cost of broiler production; Sector 2 (*S*2) the environmental load of broiler production; Sector 3 (*S*3) the economic cost for the producer; Sector 4 (*S*4) the local society as labor and farm inputs provider; and Sector 5 (*S*5) the advantages of the production systems to the consumers. From the emergy perspective, the money only circulates on the right side of the diagram which shows human activities. On the left side are shown only energy and material flows (Giannetti et al., 2019).

The advantages of using the $5SE_NSU$ model are: (i) its multidimensional capacity; (ii) provision of a multidivisional aspect, allowing environmental, social, and productive aspects to be taken into consideration; (iii) it is a multicriteria approach that can be understood as an important tool that assists in decision making for more sustainable systems since it combines different indicators with various weights and measures; and (iv) the use of multimeric indicators, integrating metric units of energy (J or kcal), volume (L), mass (g, kg or t), monetary (R$, US$) besides labor force (Giannetti et al., 2019). Also, from the $5SE_NSU$ model, it is possible to use indicators coming from different performance evaluation models, such as economic indicators and indicators in emergy.

2.6. Application of Goal Programming in the $5SE_NSU$ model

Goal Programming (GP_m), is a continuous mathematical methodological tool for handling multiple and conflicting problems that are translated into Multi-Criteria Decision Analysis (MCDA) situations. In this sense, the calculation of the $5SE_NSU$ algebra is based on the philosophy of GP_m as a tool for MDCA in order to obtain an Overall System Sustainability Indicator (Giannetti et al., 2009; Simon, 1955), to express the results according to the proximity between the relative values of the indicators and their targets. Modifications were made in order to adapt it for a $5SE_NSU$ model analysis. Considering a decision problem where G_i is the existing objective. For the use of the methodology of the application of GP_m in the $5SE_NSU$ model, the study of Giannetti et al. (2019) and García et al. (2021) were used. The Goal Programming philosophy's application to the $5SE_NSU$ model is described in Supplementary Material 3.

2.7. Definition of indicators

The definition of indicators for the broiler production systems and their allocation as environmental, social, and economic indicators followed the five sector model suggested in the $5SE_NSU$ model. The sustainability indicators were obtained from economic cost calculation models based on the Economic Theory and in the *ES*. In addition, farm collected information used for the development of the calculation models were also inserted as indicators. The indicators were: non-renewable resource and the non-renewable fraction of external input (*N*%; K_{11}); emergy (sej/kg of live weight.yr; K_{12}); GHG emissions by the production system (kg CO_2 eq/kg of live weight; K_{21}); Environmental Load Ratio (*ELR*; sej/sej; K_{22}); Emergy Exchange Ratio, referring to the exchange of real wealth from the money paid by the producer and the inputs provided by the economy (sej/sej; K_{31}); total cost of the producer (R$/kg of live weight; K_{32}); labor directly involved in the production of chicken (employees/1000 t of live weight.yr; K_{41}); the exchange ratio in real wealth between the producer and the agro-industry from the labor emergy and the emergy of money paid for labor employed in production (sej/sej; K_{42}); *em* price or fair price for kg of live chicken in each production system, considering the environmental contributions (R$/kg peso vivo; K_{51}); and the Emergy Sustainability Index (sej/sej; K_{52}). The values for each indicator related to each sector are presented in the Table 2, which also includes the units of each indicator and their desired direction (minimize or maximize) and their objectives. The objectives for each indicator were inserted as the best values found for each indicator, according to the scientific literature.

In order to homogenize the indicators, each sector presented the values of the indicators in a functional unit (kg of live weight) or in a dimensionless one (sej/sej or %), in a period of one year. Two indicators per sector were selected, totaling ten indicators represented by the letter *K* followed by the sector number and the sector indicator number. Among the selected indicators, some have maximization or minimization as desirable direction. The justifications, as well as the calculations for obtaining the proposed indicators are described below:

K_{11} is the used non-renewable resources in relation to total emergy (*N*%). The minimization of this indicator is justified because, according to the emergy theory, systems that have lower inputs of non-renewable resources, consequently have higher inputs of renewable resources which, in turn, tend to be more sustainable (Brown and Ulgiati, 1997). where *N* is the emergy from local non-renewable resources (sej); F_N is the non-renewable fraction of resources imported from the economy (sej); *Y* is the total emergy required for the production of the broiler chicken (sej).

K_{12} is the total emergy (sej/kg of live weight) used for production. The minimization of this indicator is justified because the lower the emergy used for the production of a given product or service, the lower its environmental cost.

$$Y = R + N + F_N + F_R$$

where *R* is the emergy from local renewable resources (sej); F_R is the renewable fraction of resources imported from the economy (sej).

K_{21} is the Emission of GHG in CO_2 eq/yr per kg of live weight. Obtained from the sum of emissions of N_2O, CH_4 and CO_2 in CO_2 eq/yr. In this study, we considered the emissions from the bedding, firewood and fossil fuels as energy, as well as CO_2 from animal respiration. The minimization of this indicator is justified because the lower the GHG emissions, the lower the environmental impact caused by the system. The calculations for the emissions of N_2O, CH_4 and CO_2 are described in the Supplementary Material 2 (IPCC, 2006).

K_{22} is the environmental load ratio (*ELR*). The *ELR* is a measure of disturbance to environmental dynamics generated by development driven by resources external to the system. The reduction of this indicator is justified since production systems that exhibit $ELR \leq 2$ indicate relatively low environmental impacts (Brown and Ulgiati, 2004; Tiezzi and Marchettini, 1999).

$$ELR = (N + F_N)/(R + F_R)$$

K_{31} is the Emergy Exchange Ratio in producer-related (EER_2). This indicator is obtained from the emergy coming from the inputs under contractual responsibility of the producer and the emergy of the money paid by the producer to the input suppliers (sej/sej). From this indicator, it is possible to observe which of the partners has an advantage in the exchange in emergy (Brown and Ulgiati, 2004). It is suggested to seek the maximization of the indicator, since the higher the quotient obtained, the greater the emergy obtained from the inputs with less expenditure of emergy of money.

Table 2
Description of indicators and their targets for broiler production systems.
$N\% = (N + F_N)/Y$

Sectors	Indicators	Unit	Desirable direction	Production systems		Objectives**	References
				UPrO	*UPc*		
Sector 1	K_{11}: Value of local non-renewable resource sources (*N*) and the fraction of non-renewable resources imported from nature (F_N) used in the production per kg of chicken meat in a year. K_{12}: Emergy (*Y*) is the energy previously used for the generation of a given process or product. In the study, we considered Y used per kg of broiler live weight in one year.	% sej/kg of live weight	*Min* *Min*	50.3 1.12E+13	86.1 3.49E+12	19.0 3.41E+12	Cheng et al. (2017) Cheng et al. (2017)
Sector 2	K_{21}: Value referring to gas emissions (GHG) in CO_2 eq/yr per kg live body weight produced. CO_2 production was estimated at the farm level (GHG) for nitrous oxide (N_2O), methane (CH_4) and carbon dioxide (CO_2) using models proposed by IPCC (2006). CO_2 emissions from chickens were estimated from models proposed by Strom (1978) and CIGR (1984). All estimated values of gas production were converted to kg CO_2 equivalent per year. K_{22}: The Environmental Load Ratio (*ELR*) is defined as the ratio of emergy between the inputs from the economic system and the local renewable resources.	kg CO_2 eq/kg of live weight sej/sej	*Min* *Min*	0.534 1.012	0.625 6.211	0.154 $ELR \leq 2$	Lima et al. (2019) Brown and Ulgiati (2004)
Sector 3	K_{31}: Emergy Exchange Ratio for the producer (EER_2). Suggested based on the *EER* indicator, the proposed indicator suggests measuring the greatest beneficiary in the exchange between the emergy coming from the resources bought by the producer and the emergy coming from the money received by the producer in the provision of services to the agro-industry. Measured from real wealth, this indicator seeks to express how the producer, as a member of the productive system, contributes to society from the purchase ($\$ \times EMR$) of products from society as a provider of resources (*Y*). K_{32}: Total cost is the sum of fixed and variable costs, measured from Economic Theory.	sej/sej R$/kg of live weight	*Max* *Min*	0.964 0.624	1.143 0.314	$EER = 1$ 0.520	Odum (1996) CONAB (2022)
Sector 4	K_{41}: The employment generation estimated from the labor directly involved in production (owner, registered employees, sporadic employees and technical assistance), birds/person.year. This indicator was suggested as an effort to measure the contribution of the production system to local income generation. K_{42}: Ratio between the emergy of labor performed by the labor directly involved in poultry production and the emergy of the payment received for services rendered by the labor. Measured based on real wealth, this indicator aims to identify the main beneficiary in the exchanges between producers and agribusiness.	Employees/1000 t of live weight sej/sej	*Max* *Max*	24 78.862	5 261.340	$\overline{k_{41}} + \sigma(k_{41})$ 147.522	This study Miele et al., 2010
Sector 5	K_{51}: Equitable price suggested as payment for the live weight of the chicken produced, considering the contributions of the environment. Obtained from the Emergy Exchange Ratio (*EER*) and expressed, the suggestion of the equitable price aims to obtain an ideal value estimated in the exchange of real wealth between the money paid by the consumer and the product delivered by the agro-industry. In other words, $EER = 1$. K_{52}: The Emergy Sustainability Index ($ESI = EYR/ELR$) measures the potential contribution of resources or processes to the economy per unit of environmental load. It accounts for the ability of the process to exploit local resources by balancing the use of renewable and non-renewable energy inputs.	R$/kg of live weight sej/sej	*Min* *Max*	18.428 1.965	5.766 0.187	14.920 5.00	This study* Brown and Ulgiati (2004)

UPrO is the production system for commercial broilers raised in organic system; *UPc* is the production system for commercial broilers raised in conventional system.
Sector 1: Environment as provider; Sector 2: Environment as receiver; Sector 3: Production system; Sector 4: Society as provider; Sector 5: Society as receiver.
*The target price for live organic chicken (R$/kg of live weight) was estimated from Embrapa (2007) database and obtained from the following equation.
$P - (1 - P \times v) \times 70\%$
Where: *P* is the average spot price paid for whole processed chicken in June/2021 (R$ 26.77/kg); *v* is the sum of operational costs of the slaughterhouse (10.85%), operational cost of the commercial area (8.44%) and operational cost of the administrative area (1.09%); and 70% is the average yield estimated for broilers with average weight of 2.5 kg live weight, according to Nacimento et al. (2021).
**The objectives for each indicator were inserted as the best values found for each indicator, according to the scientific literature.

$$EER_2 = \frac{R + N + F_{1,2,3,4,5,6,7,8}}{TC_p \times Fl \times EMR}$$

where ^{1} is firewood, ^{2} is bedding, ^{3} is fuel, ^{4} is electricity, ^{5} is paddock, ^{6} is mechanical equipments, ^{7} is labor, ^{8} is buildings; TC_p is total producer cost (R$/flock); *Fl* is the number of flocks produced per year; *EMR* is the estimated emergy/cash ratio for Brazil in the year 2021 (sej/$). The superscript numbering in the items refers to Supplementary Material 2.

K_{32} is the total cost for the producer (R$/kg of live weight). The minimization of this indicator is justified since the objective of production systems is to operate with minimum cost. Moreover, from the production costs, it is possible to infer about the compatibility between costs and prices obtained for the product. By verifying the compatibility between costs and prices, it is possible to indicate the economic feasibility and attractiveness of the activity (Santos Filho et al., 2014).

$$\mathrm{TC} = \mathrm{VC} + \mathrm{FC}$$

where *TC* is the total cost (R$/kg of live weight); *VC* is the variable cost (R$/kg of live weight); *FC* is the fixed cost (R$/kg of live weight).

K_{41} is the number of people directly involved in chicken production (employees/1000 t of live weight.yr). The maximization of this indicator is justified since the intention is to get greater involvement of the local society as a provider of resources (i.e. labor), as well as the contribution of the production system in the generation of income in its surroundings.

$$\mathrm{Employability} = \frac{\mathrm{Mp}}{\mathrm{P}}$$

where *Mp* is the number of directly employed people (owner and his registered or unregistered employees; un); *P* is the amount of meat produced in broiler live body weight in each system during the year.

K_{42} is the ratio of wage emergy: labor emergy (sej/sej). The higher the quotient, the greater the flow of real wealth received by the producer in exchange for services rendered to the agro-industry. For this purpose, the target was obtained from wage emergy was based on the scientific literature, leading to the following equation:

$$\mathrm{RWw} = \frac{\mathrm{W_Y}}{\mathrm{L_Y}}$$

$$\mathrm{W_Y} = 6.27 \times 1537.27 \times \mathrm{EMR}$$

$$\mathrm{L_Y} = (365\,/\,6.27) \times 8 \times 6.27/24 \times 2500 \times 4186 \times \mathrm{UEV}$$

where W_Y is the emergy of the money; 6.27 is the number of flocks/year; 1537.27 is the average wage paid to a registered employee (R$/flock), according to Miele et al. (2010) for a positive pressure acclimatized shed in the state of São Paulo, run by two people; *EMR* is the Emergia/dollar ratio for Brazil in the year 2021. L_Y is the emergy of the labor; $(365/6.27) \times 8 \times 6.27/24$ is the number of days worked by a wage earner per year; 2500 kcal/day; e 4186 kcal to J; *UEV* is the unit in labor-specific emergy (3.12E+04) (Demetrio, 2011).

K_{51} is the suggested equitable price for the exchange of emergy from the chicken kg and the emergy paid per kg of broiler live body weight, where *EER* = 1. Measured in R$/kg of live weight, the equitable price suggests assessing inequity in terms of the price paid (Cuadra and Rydberg, 2006). Thus, prices charged below the fair price suggest a benefit to the consumer, since the consumer pays lower prices than it should be charged. On the other hand, an estimated price lower than the prevailing price indicates that the producer receives more money than the market should pay. For this purpose, we considered:

$$\mathrm{EER} = \mathrm{Y/Vt} \times \mathrm{EMR} \ldots \forall\ \mathrm{EER} = 1$$

where *EER* is the Emergy Exchange Ratio (sej/sej); Vt is the price charged per kg live weight of chicken. The price of the kg of chilled chicken meat, produced in conventional system, was obtained from specialized media in quotations of agricultural products. For the kg of meat produced in organic system, the price of the kg of chilled chicken meat was obtained from the counter price of the respective brand (spot price) obtained from: $\mathrm{P} - (1 - \mathrm{P} \times \mathrm{v}) \times 70\%$, where *P* is the market price paid per kg of processed organic chicken; *v* is the percentage referring to the cost with slaughterhouse, administration and trade, estimated at 20.4%, according to Figueiredo et al. (2007); 70% is the average carcass yield for a gutted broiler, without feathers, head, neck and feet (Nacimento et al., 2021).

K_{52} is the Emergy Sustainability Index (*ESI*). The *ESI* is the relation between Emergy Yield Ratio (*EYR*) and the Environmental load ratio (*ELR*). In other words, to obtain better sustainability indices, one seeks to obtain higher output with inputs from outside the system with the lowest possible environmental load. According to Brown and Ulgiati (2004), *ESI* > 5 values indicate sustainable systems in the long run. Therefore, it is justified to maximize this indicator.

$$\mathrm{ESI} = \mathrm{EYR/ELR}$$

where *EYR* is the Emergy Yield Ratio; *ELR* is the Environmental Load Ratio.

3. Results and discussion

Worldwide, consumers of agricultural commodities are increasingly sensitive to animal welfare (Vanhonacker et al., 2008; Verspecht et al., 2011). To meet this demand, production systems increasingly aim or tend to aim for improvements in this regard (Leinonen et al., 2014). One of the concepts formulated to meet animal welfare is to guarantee the “five freedoms” proposed by the Farm Animal Welfare Council (FAWC). These concepts consist of actions that guarantee that animals are: (i) free from hunger and thirst; (ii) free from discomfort; (iii) free from pain, injury, or disease; (iv) free to express natural behavior; and (v) free from fear and distress (FAWC, 2009). In general, reducing the number of birds per area is the main aspect of meeting welfare in chicken production. In other words, lower stocking density. According to Leinonen et al. (2014), there is an increase in demand for chickens produced in more extensive systems and with lower stocking density. In Brazil, Ordinance No. 52, of March 2021, regulates the production of broilers in organic systems. It established that organic chicken production systems should present a density less than or equal to 30 kg of meat/m^2, which would be approximately 12 birds of 2.5 kg/m^2 (BRASIL, 2021). Beyond the higher economic and lower productivity per area (Estevez, 2007; Verspecht et al., 2011) the higher environmental cost is another consequence of organic chicken production systems (Castellini et al., 2012).

Fig. 3 presents the sustainability performance results for each sector. In this study, the worst results for *UPrO* are closely related to the lower housing density. Although *UPrO* presented worse results for both the environment as a resource provider (Sector 1) and the production unit (Sector 3), the system presented more general sustainability index (GSI) when compared to *UPc* (29.597 vs. 37.590, respectively). These and the other results will be discussed separately in the following sections.

Sector 1 is the ecosystem as resource supplier in which k_{11} is the use of non-renewable resources related to the total emergy (%); k_{12} is the total emergy (sej/kg of live weight) used for production; Sector 2 is the ecosystem as a receiver of negative externalities in which k_{21} is the emission of GHG in CO_2 eq/year per kg of live weight produced (kg CO_2 eq/kg of live weight); k_{22} is the ratio of environmental load (*ELR*; sej/sej); Sector 3 is the unit of production in which k_{31} is the ratio of interchange in emergy related to the producer (*EER*$_2$; sej/sej); k_{32} is the total cost to the producer (R$/kg of live weight); Sector 4 is the society as resource supplier in which k_{41} is the number of people directly involved in the production of broilers (employees/1,000 t of live weight. yr); k_{42} is the ratio Work Emergy: Wage Emergy (sej/sej); Sector 5 is the society as receiver of resources coming from Sector 3 in which k_{51} is the fair price (*em* price) suggested from the exchange between the Money Emergy and Chicken Meat Emergy, where *EER* = 1; k_{52} is the Index of Sustainability in Emergy (*ESI*, sej/sej); GSI is the general sustainability index.

3.1. Sectors 1 and 2: environmental performance

For better understanding, it should be noted that the values presented in Fig. 4 are in reverse order. Thus, values closer to the edges of the radar consist of closer proximity to the target values and, therefore, present better performance for that indicator (see Fig. 5).

According to the results, *UPrO* showed the highest value in Sector 1, indicating a worse performance when compared to *UPc*. Although *UPrO* demonstrated lower use of non-renewable resources in production (K_{11}), the system used more environmental resources overall (K_{12}) (Fig. 4); and emitted a higher volume of GHG per kg of meat produced (K_{21}).

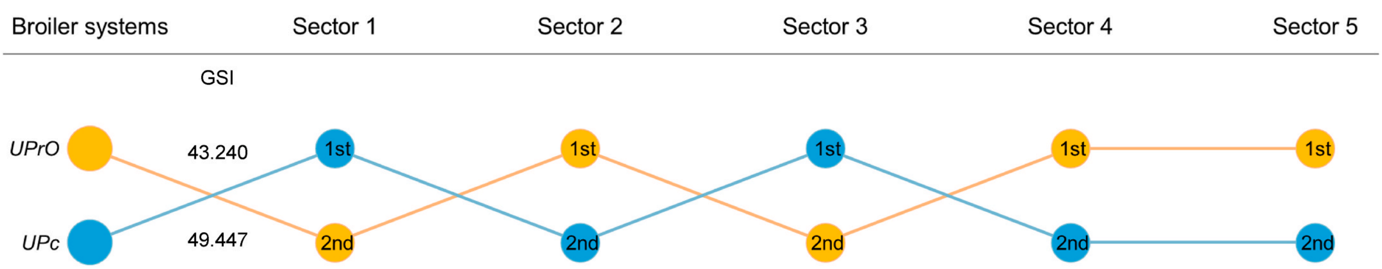

Fig. 3. Comparison of sustainability in the production of broilers in an organic system (***UPrO***) and a conventional system (***UPc***).

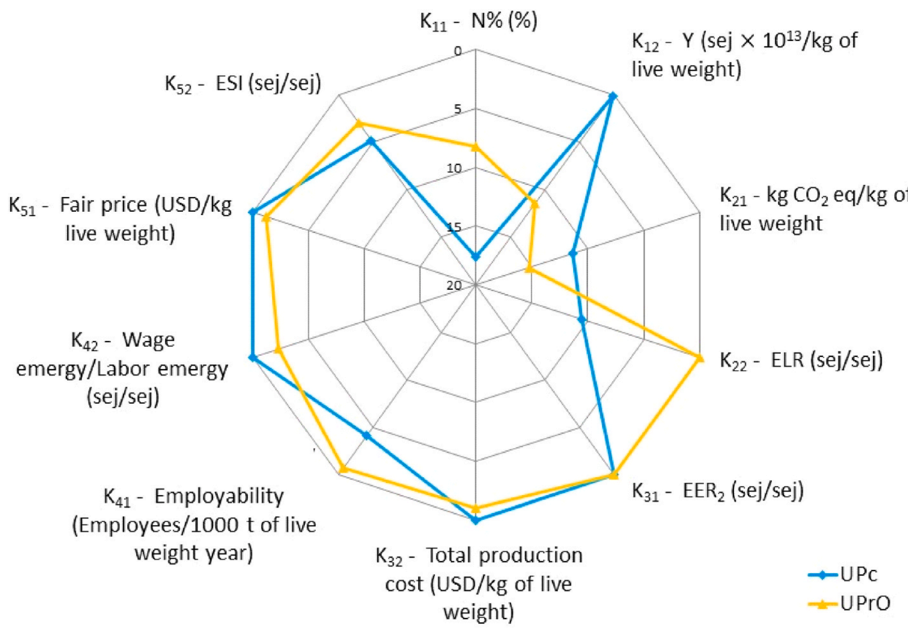

Fig. 4. Performance of the unit of production of organic broilers (*UPrO*) and comparison with conventional production (*UPc*) from a set of selected indicators.

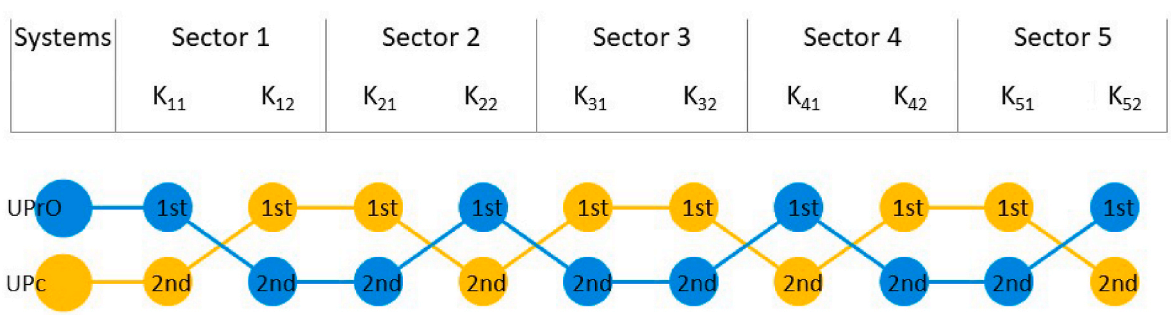

Fig. 5. Comparison of sustainability performance of broiler production in organic (*UPrO*) and conventional system (*UPc*).

In Sector 1, the relationship between stocking density and environmental cost can be explained by the optimization of inputs used in production. In *UPc*, the higher volume of meat produced per area optimizes the use of inputs which, in turn, dilutes the environmental cost, measured in this study from the emergy used. According to Vermeij (2004), the use of energy inputs required for heating is expected to be doubled in organic systems when compared to conventional systems due to the lower stocking density. Furthermore, input optimization goes far beyond energy inputs. One can also observe optimization for "fixed assets" such as buildings, equipment, etc., in which the emergy of these inputs is diluted as the scale of production in the system gets larger. Thus, *UPrO*, to ensure greater comfort for the birds, limited its ability to dilute the emergy required in production. Few studies in the scientific literature use indicators that aim to measure the environmental cost to compare organic and conventional chicken production.

Sector 1 is the ecosystem as a resource provider, where k_{11} is the use of non-renewable resources in relation to total emergy (%); k_{12} is the Total Emergy (sej/kg live weight) used for production; Sector 2 is the ecosystem as a recipient of negative externalities, where k_{21} is the GHG emission in CO_2 eq/year per kg of live weight produced (kg CO_2 eq/kg live weight); k_{22} is the environmental load ratio (*ELR*; sej/sej); Sector 3 is the production unit, where k_{31} is the exchange ratio in producer-related emergy (*EER*$_2$; sej/sej); k_{32} is the total cost to the producer (R$/kg live weight); Sector 4 is the society as a provider of resources, where k_{41} is the number of people involved directly in the production of chickens (employees/1000 t live weight. year); k_{42} is the ratio Labor Emergy:

Wage Emergy (sej/sej); Sector 5 is the society as receiver of resources coming from Sector 3, where k_{51} is the suggested equitable price (*emprice*) from the exchange between the Emergy of money and Chicken meat Emergy, where *EER=1*; k_{52} is the Sustainability Index in Emergy (*ESI*, sej/sej).

According to Castellini et al. (2012), the greater use of the area for the production of organic chicken was pointed as one of the factors that led the production system to present the highest ecological footprint. Despite the differences concerning the evaluation of an organic production system with different characteristics from those of this study (i.e., late slaughter age), it can be observed that similarly, the lower stocking density was one of the causes of the higher environmental cost.

Similarly to the indicators in Sector 1, the higher production of GHG/kg of live weight (K_{21}) is closely related to the higher welfare conferred to the birds. According to Williams et al. (2006), when compared to conventional chickens, organic chickens emit 50% more GHGs (in CO_2 eq/kg meat produced) and consume 30–59% more energy from fossil fuels (i.e., feed transport; in MJ). For Bokkers and de Boer (2009), the use of organic diets as well as the higher volume of feed transported, as a result of higher feed conversion, may explain the higher GHG emissions in organic chicken production. However, differently from the cited studies, *UPrO* and *UPc* were similar, both in terms of technology and husbandry performance. In this study, the spatial boundary adopted for the evaluation was the production unit (farm level). With this, external factors were considered constant, such as the radius of the agribusinesses, which limited possible differences between the emissions related to feed transportation. Also, since both systems use nutritionally similar diets (Bokkers and de Boer, 2009), as well as the same strain of birds (fast-growing), GHG emissions per bird were assumed to be similar. Therefore, the only factor suggesting the worse result in K_{21} corresponds to the lower volume of product produced per area. When compared to *UPc*, the total annual volume of GHG emitted by *UPrO* was lower. However, when considering the emission per unit of product, the result is inverted and *UPrO* starts to emit higher volumes of GHG. According to Crosson et al. (2011) intensification of production can reduce GHG emissions/kg of product through accurate feed and/or fertilizer inputs. Also, for Dourmad et al. (2014), the degree of intensification is inversely correlated with the environmental impact per kg of product, while the opposite is observed when the impact is measured per ha of land used.

On the other hand, in spite of the fact that organic chicken production presented a higher environmental cost, *UPrO* showed a lower environmental load than *UPc*. Since industrial broiler production systems are extremely intensified, being dependent on *F* resources, and since the main source of emergy corresponds to the energy/emergy flows for feeding the animals, the lower environmental load results from the lower input of non-renewable resources into the system from the feed. In intensive production systems of broiler chickens, the main source of emergy comes from the feed (Castellini et al., 2006). In Brazil, besides defining aspects related to stocking density aiming at the welfare of the birds, aspects contained in Ordinance 52, such as the use of 80% organic ingredients in the diet, helped reduce the inclusion of non-renewable resources. In turn, different sources of ingredients, conventional and organic, affect differently the emergy of the chicken production system. For example, conventional corn production employs a large amount of emergy from chemical fertilizers, pesticides, and irrigation (Giannetti et al., 2013a). These are resources with low renewability. Consequently, practices that adopt such inputs will confer lower renewability to conventional corn when compared to organic corn that would not adopt such practices (Castellini et al., 2006). Thus, organic chicken production systems tend to present greater sustainability by presenting a lower environmental load due to the lower use of non-renewable resources (Castellini et al., 2006).

3.2. Sector 3: economic performance

EER_2 is an indicator that seeks to propose a possible beneficiary in the relationship between the producer and its raw material suppliers. According to the results, both *UPrO* and *UPc* showed EER_2 (K_{31}) values close to the target ($EER_2 = 1$). This indicates that there is equity in the exchange relationship between producers and their raw material suppliers. Therefore, producers receive the same amount of real wealth in raw materials as they provide in cash, favoring the development of both parties (Odum, 1996).

Comparing the cost of production, in *UPrO* the cost of production for producers was 44% higher than *UPc*, driven mostly by the fixed cost (K_{32}). Several authors point out the higher production cost for organic chicken compared to conventional production (Bokkers and de Boer, 2009; Cobanoglu et al., 2014; Van Horne, 2020). However, works in the scientific literature that differentiate production costs from responsibilities between producers and agro-industry are scarce. Among producer costs, labor was the factor that most impacted the total production cost for *UPrO*. Data from the National Supply Company point out that, in the first months of 2022, labor was the cost that most impacted the total cost for the chicken producer in the conventional system (CONAB, 2022). For Cobanoglu et al. (2014), the labor cost in organic chicken production tends to be even higher when compared to conventional chicken production, since, in organic systems, the number of birds handled per employee is lower.

3.3. Sectors 4 and 5: Social performance

While on the one hand, the higher labor requirement in organic chicken production increases the cost of production, on the other hand, society can benefit as there is a higher employment generation. In addition, the level of family labor involvement may be one of the factors that contribute to the labor cost in organic chicken production (Cobanoglu et al., 2014). According to the results, the higher involvement of family labor in *UPrO* resulted in better performance when considering society as a resource provider for the system (Sector 4). *UPrO* showed almost 5 times more labor per 1000 t of live weight chicken produced when compared to *UPc* (K_{41}). In this study, while for *UPc* the registered labor plus the producer made up all the labor directly involved in the production of the chickens, for *UPrO* the labor was family-based and composed of four people. According to Reissig et al. (2016), several studies show that organic productions require more labor than conventional productions. Furthermore, for Hall and Mogyorody (2007), alternative productions have the potential to create a more equitable distribution of labor by gender. Also, programs and initiatives that incorporate organic production practices for the fixation of family labor in the field have gained ground in recent years (Dosch, 2011). Thus, if on the one hand the greater need for labor negatively impacts the cost of organic chicken production, on the other hand, organic systems confer a greater need for labor and can promote greater engagement of local society.

However, the results show lower real wealth received by *UPrO* producers when compared to *UPc*. The K_{42} indicator correlated the trade-off between the emergy from money as payment for services rendered with the emergy from services provided by labor. In other words, the real wealth received by the producer was closely related to the contract value paid for the execution of the production service and, consequently, the number of birds housed and the stocking density. Thus, as far as the lower number of housed birds is concerned, the real wealth from the payment for services provided by family labor was also lower than for *UPc*. Thus, it can be inferred that society as a resource provider received less real wealth in *UPrO* when compared to *UPc*.

Although society as a resource provider received less real wealth in *UPrO*, society as a resource recipient came out as the main beneficiary in the exchanges. According to the results, *UPrO* provides a product with a lower equitable price (K_{51}) and more sustainable (K_{52}) considering *ESI*. In this study, the suggestion of the equitable price considered the ratio between emergy delivered in the form of product to society and emergy received in the form of money, with the condition of equality in the exchange, i.e. $EER = 1$. For the study, the target was considered as the price paid for the organic chicken in R$/kg of live weight in June/2021. The suggested equitable price was 43% and 33% higher than the target, respectively. The higher suggested equitable price for organic chicken indicates that society benefited more in the exchange between product emergy: cash emergy for organic chicken, since it received more real wealth from the product than it provided in cash. Studies in the scientific literature have used emergy as a tool to assess the fairness of the price charged in the exchange of different commodities (Cuadra and Rydberg, 2006; Giannetti et al., 2011). For Cuadra and Rydberg (2006) a way to reach the most equitable exchange price would be from the processing of the commodity before its commercialization. In this study, the prices used were estimated on a kg live weight basis. In addition, when processed, poultry has an economic gain in added value (Bell, 2002). Thus, it is possible that the exchange ratio of product emergy: cash emergy from processed chicken meat exceeds the value of its emergy content. As a result, the producer would benefit from the exchange. Commonly, consumers receive more emergy from products, originating from agriculture and extraction, than they give from money as payment (Odum, 1996). However, according to Giannetti et al. (2008), products that undergo many processes tend to show a tendency to decrease the advantage of the buyer over the producer in the exchanges. Thus, the further, along the supply chain, the product is, the more distant it is from the environment-economy interface, and the more the consumers will pay for the emergy received. So, it is possible that the added value from processing poultry into cuts could compensate for the difference between the price charged, and could come closer to the suggested fair price.

Another aspect that indicates the advantage of *UPrO* for society as a receiver is represented by its sustainability. According to the results, *UPrO* showed short-term sustainability, while *UPc* proved to be unsustainable. The higher sustainability of *UPrO* was directly related to its lower environmental load as a consequence of the lower use of non-renewable resources, mainly in its raw materials. Measured from the Emergy Sustainability Indicator (*ESI*; K_{52}), this indicator is a relationship between the emergy yield and the environmental load imposed on the ecosystem to obtain that yield. In turn, emergy yield considers the contribution of energies from resource inputs external to the system over local resources (Brown and Ulgiati, 1997, 2002). Since the energy sources used in chicken feed are poorly concentrated and similar in quality, the best way to make a chicken production system more sustainable comes from reducing its environmental load, which can be observed in *UPrO*.

3.4. Increased stocking density and producer remuneration: a simulation

Based on the observed results, a simulation was conducted based on (i) adoption of the maximum stocking density for broilers in Brazil (12 broilers/m^2) (BRASIL, 2021); and (ii) an increase in the price paid to the producer per bird delivered. The results are shown in the Figs. 6 and 7, and in the Table 3 (see Table 4).

As main positive consequences of the increase from 9 birds/m^2 to 12 birds/m^2 housed would have: a 6% reduction in GHG emissions in kg CO_2 eq/kg of live weight; a 24% reduction in production costs for the producer; a 1% reduction in the use of non-renewable resources per kg of live weight; a 5% increase in *ESI*; and a 3% reduction in environmental cost (measured in emergy; sej/kg of live weight). Regarding the increase in producer income, from R$1.10/bird to R$1.95/bird, the main impact of the adjustment was observed in the exchange ratio emergy of salary: emergy of labor (K_{42}). Since the objective was to increase direct labor, the most feasible option to reach the goal of the tradeoffs between wage emergy and labor emergy was to increase the remuneration of producers. In this sense, the increase of R$ 0.85/bird provided a 46% increase in the emergy received by the producer.

For the increase in the amount to be paid to the producer, one could consider meeting the equitable price for the adjustment. According to the results, there is a difference of R$8.60/bird between the nominal price and the fair price. This difference could be considered as a bonus to be directed to the agribusinesses that commit to producing animals with higher levels of animal welfare. An example that can be given is the Norwegian government bonuses given to organic livestock producers for almost 20 years (Koesling et al., 2012). Through financial policies, legal and communication instruments, the Norwegian government has provided financial support for organic production as part of a policy aimed at increasing the production and consumption of organics (Koesling et al., 2012). Hence, there is a suggestion for the pricing of animals produced with high levels of animal welfare. For the authors, if the environmental aspects used in organic systems are efficient in promoting animal welfare (i.e., lower stocking density and the guarantee of outdoor areas for the expression of their natural behavior), it is valid to use *SE* for the suggestion of an equitable price between the real wealth exchanges of product emergy and money emergy. The use of the resources obtained as a bonus could also be reversed in public-private actions that aim to implement direct environmental actions (i.e. restoration of native forests, permanent preservation areas) and indirect (etc., promotion of awareness events on the importance of environmental preservation and animal welfare).

Sector 1 is the ecosystem as a resource provider where k_{11} is the use of non-renewable resources in relation to total emergy (%); k_{12} is the Total Emergy (sej/kg live weight) used for production; Sector 2 is the

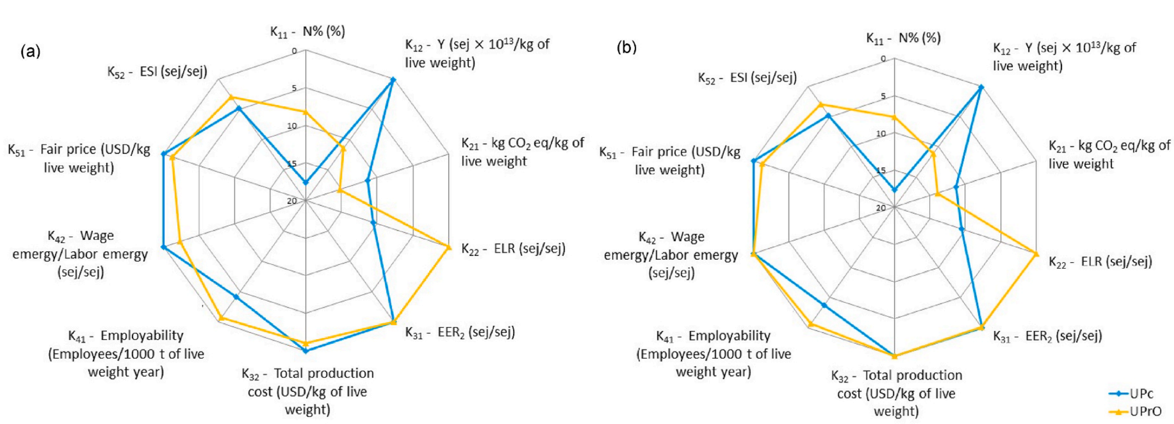

Fig. 6. Performance of the unit of production of organic broilers (***UPrO***) and comparison with conventional production (***UPc***; a). Simulation based on ***UPrO*** evaluating the impacts of increasing the stocking density from 9 to 12 broilers/m^2 and the remuneration of the producer in R$ 0.85/bird on the sustainability from the 5SE$_N$SU model (b).

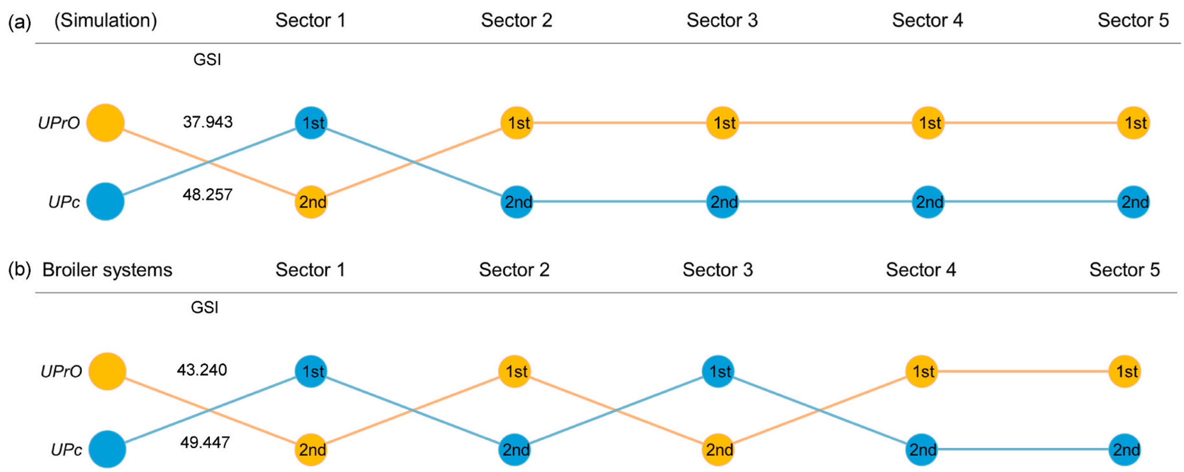

Fig. 7. Simulation based on ***UPrO*** evaluating the impacts of increasing the stocking density from 9 to 12 broilers/m^2 and producer remuneration in R$ 0.85/bird on sustainability from 5SE$_N$SU model (a). Comparison of sustainability results in broiler production in organic system (***UPrO***) conventional (***UPc***) and simulated from ***UPrO*** using the 5SE$_N$SU model (b).

Table 3
Indicators of Sustainability Goals to each selected indicator.

Systems of production	Sector 1		Sector 2		Sector 3		Sector 4		Sector 5	
	(environment as supplier)		(environment as receiver)		(unit of production)		(society as supplier)		(society as receiver)	
	ISG^-_{k11}	ISG^-_{k12}	ISG^-_{k21}	ISG^-_{k22}	ISG^+_{k31}	ISG^-_{k32}	ISG^+_{k41}	ISG^-_{k42}	ISG^-_{k51}	ISG^+_{k52}
UPrO	8.237	11.422	15.292	0.005	0.044	0.997	0.704	2.327	1.176	3.035
UPc	17.658	0.117	12.208	10.527	0.001	0.004	4.105	0.008	0.006	4.813

Table 4
Indicators of Sustainability Goals to each selected indicator and simulation.

Production systems	Sector 1		Sector 2		Sector 3		Sector 4		Sector 5	
	(Environment as provider)		(Environment as receiver)		(Production system)		(Society as provider)		(Society as receiver)	
	ISG^-_{k11}	ISG^-_{k12}	ISG^-_{k21}	ISG^-_{k22}	ISG^+_{k31}	ISG^-_{k32}	ISG^+_{k41}	ISG^-_{k42}	ISG^-_{k51}	ISG^+_{k52}
UPrO	8.237	11.422	1.649	0.005	0.044	0.997	0.704	3.664	1.176	3.035
UPrO$_{simulation}$	7.905	11.129	13.994	0.005	0.150	0.000	0.651	0.013	1.176	2.920
UPc	17.658	0.117	11.331	10.527	0.001	0.004	3.792	0.008	0.006	4.813

ecosystem as a recipient of negative externalities, where k_{21} is the GHG emission in CO_2 eq/year per kg of live weight produced (kg CO_2 eq/kg live weight); k_{22} is the environmental load ratio (*ELR*; sej/sej); Sector 3 is the production unit where k_{31} is the exchange ratio in producer-related emergy (*EER*$_2$; sej/sej); k_{32} is the total cost to the producer (R$/kg live weight); Sector 4 is the society as a provider of resources, where k_{41} is the number of people involved directly in the production of chickens (employees/1000 t live weight. year); k_{42} is the ratio Labor Emergy: Wage Emergy (sej/sej); Sector 5 is the society as receiver of resources coming from Sector 3, where k_{51} is the suggested equitable price (*emprice*) from the exchange between the Emergy of money and Chicken meat Emergy, where *EER=1*; k_{52} is the Sustainability Index in Emergy (*ESI*, sej/sej).

Sector 1 is the ecosystem as a resource provider, where k_{11} is the use of non-renewable resources in relation to total emergy (%); k_{12} is the Total Emergy (sej/kg live weight) used for production; Sector 2 is the ecosystem as a recipient of negative externalities, where k_{21} is the GHG emission in CO_2 eq/year per kg of live weight produced (kg CO_2 eq/kg live weight); k_{22} is the environmental load ratio (*ELR*; sej/sej); Sector 3 is the production unit, where k_{31} is the exchange ratio in producer-related emergy (*EER*$_2$; sej/sej); k_{32} is the total cost to the producer (R$/kg live weight); Sector 4 is the society as a provider of resources, where k_{41} is the number of people involved directly in the production of chickens (employees/1000 t live weight. year); k_{42} is the ratio Labor Emergy: Wage Emergy (sej/sej); Sector 5 is the society as receiver of resources coming from Sector 3, where k_{51} is the suggested equitable price (*emprice*) from the exchange between the Emergy of money and Chicken meat Emergy, where *EER=1*; k_{52} is the Sustainability Index in Emergy (*ESI*, sej/sej); GSI is the general sustainability index.

4. Conclusions and suggestions

The main conclusions are listed below:

(i) A trade-off between animal welfare and economic and environmental costs was observed. The lower stocking density in *UPrO* raised the animal welfare by providing more area/animal, but increased the resource consumption, GHG emission and the production cost. However, *UPrO* presented higher benefits to society both as a provider and as a receiver of resources, from the better exchanges between product emergy (chickens and inputs) and money emergy, greater use of direct labor, as well as access to a more sustainable product. These results allowed *UPrO* to be presented as more sustainable when compared to *UPc* (*GSI* = 43.2 and 49.4 to *UPrO* and *UPc*, respectively).

(ii) The study suggests *ES* as a tool for product pricing based on the inclusion of environmental resources used to promote animal welfare. For the authors, if the environmental features used in organic systems are efficient in promoting animal welfare (i.e., lower stocking density and the guarantee of outdoor areas for the expression of their natural behavior), it is valid to use them to suggest an equitable price between the real wealth exchanges of product emergy and money emergy. The difference between the nominal price practiced and the suggested equitable price could be used to remunerate the producer, who actively participates in the production and promotion of animal welfare, as well as foster the implementation of direct (i.e. restoration of native forests, permanent preservation areas) and indirect (etc., promotion of awareness events on the importance of environmental preservation and animal welfare) environmental actions.

5. Limitations of the study

Although it was analyzed as a whole, it is not possible to state which system is more sustainable, since the performances were observed through a prism restricted to a few indicators. Thus, it does not consider the systems in their magnitudes. As an example, one can cite the intangible values obtained by farmers in *UPrO*, which is a system based on the Nature Farming model. The Nature Farming model, in turn, is based on the writings and guidances left by Mokichi Okada (1882–1955), a Japanese philosopher who produced extensive works related to agriculture, among others. Mokichi Okada considered agriculture as a supporting pillar for an ideal society free of disease, poverty, and conflict. The philosopher emphasized in his writings the important role that farmers have in society, contributing to the health and social welfare by producing food in accordance with the principles and functions of nature, making it possible to build a society in which health, peace, and prosperity prevail. As for its underlying values, the Nature Farming model has a theoretical basis that favors human health, social responsibility, environmental preservation, and nature-based practices in order to meet the expectations of a growing number of consumers worldwide (Xu, 2001).

Although the $5SE_NSU$ model is able to consider intangible values for sustainability assessment, the other tools used in this study did not make it possible to capture such values obtained by producers. Thus, future studies could consider using the $5SE_NSU$ model and intangible value indicators to determine the sustainability of animal production systems.

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CRediT authorship contribution statement

Rafael Araújo Nacimento: Methodology, Validation, Investigation, Writing – original draft. **Vitória Toffolo Luiz:** Methodology, Writing – original draft. **Cecília Mitie Ifuki Mendes:** Investigation, Writing – original draft. **Biagio Fernando Giannetti:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Supervision. **Augusto Hauber Gameiro:** Conceptualization, Writing – original draft, Supervision, Project administration.

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.jclepro.2022.134297.

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