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BROILER PRODUCTION FROM THE PERSPECTIVE OF EMERGY ANALYSIS – ENVIRONMENTAL IMPACT SCENARIOS

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ABSTRACT: Poultry meat consumption is a significant element in Poland's overall food consumption. Economic considerations mean that both nationally and globally, conventional intensive rearing dominates. Nevertheless, environmental and health aspects or the will to treat animals humanely make pro-environmental rearing systems increasingly common. The purpose of this article is an environmental analysis of an example farm engaged in intensive rearing of slaughtered poultry (so-called baseline production). For the analysed production, the following scenarios of changes were proposed: (a) conventional rearing based on the use of own fodder, and (b) organic rearing using free range and own organic fodder. An emergy approach was applied in this analysis. Comparison of different production systems using emergy analysis made it possible to show the scale of environmental resource commitment for baseline and scenario-based productions, and to determine the amount of renewable and non-renewable emergy consumed per unit of production. Through the use of selected emergy indicators, e.g.: Environmental Loading Ratio (ELR), Emergy Yield Ratio (EYR), the environmental impact for each case was determined. For the ecological system scenario, the need to change production parameters (stocking rate, maximum poultry house area, free range) was taken into account. The results of the emergy-based indicators showed that the baseline production places the greatest burden on the environment and is the least sustainable. The organic system is the opposite; however, due to production limitations and the lower production efficiency achieved, it may not be economically viable to orient a farm exclusively to the organic system. In an environmental assessment, the information obtained can provide valuable guidance to agricultural producers. They can help make informed decisions on natural resource management to achieve environmental security. The results are also important for political decision-makers in creating policies for more sustainable agricultural production. The results obtained are discussed, pointing out the importance of the analysis used mainly from an environmental point of view.

KEYWORDS: broiler production, conventional farming, organic farming, emergy analysis, environmental impact

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Introduction

Intensive rearing systems for slaughter poultry are the subject of much discussion, mainly due to the problem of livestock welfare involving various aspects: the genotype of birds, the possibility of disease, access to free range, light, density of birds in poultry houses, and others (Elson, 2015; Morris, 2009; He et al., 2023). Despite the high efficiency of such production, it leads to a significant increase in the environmental footprint, including emissions of NH_3, N_2O or CH_4, soil and water pollution, and affects animal and human health (Gržinić et al., 2023). As some studies indicate, it is not so much the scale of poultry production that has an impact on the environment but precisely the degree of intensiveness, especially the production, preparation and consumption of fodder. A significant problem is deforestation, which is associated with the need to acquire new land for fodder production (da Silva et al., 2014; Abín et al., 2018; Mostert et al., 2022).

In response to these negative environmental impacts, there are voices of consumers seeking food products produced with respect for the environment and animal welfare. Their preferences are changing; their pro-environmental awareness is growing, as is their willingness to pay a higher price for better-quality products. This is gradually increasing the demand for higher-quality products, including organic ones (Rizzo et al., 2023; Mesas et al., 2022; Smoluk-Sikorska, 2022).

Producers also have the opportunity to benefit from support for production that takes into account the needs of the environment and animal welfare. It is intended to compensate for additional costs and lost income resulting from the introduction of practices related to increased welfare, including broilers kept for meat production. This is envisaged in the Strategic Plan for the Common Agricultural Policy for 2023-2027 (European Commission, 2023).

Poultry meat is readily consumed due to its nutritional value, and in many countries, for cultural reasons, it is an alternative to other meats. The demand for poultry meat consumption is also increasing annually. According to FAOSTAT data (FAO, 2023), there has been an increase in production of more than 25% from 2011 to 2021. Globally, the largest producers of broiler meat are Asia (35% of global production) and South America (18.5%). Europe's production is 16% of the world's broiler meat production. Here, too, there are upward trends in poultry production. From 2011 to 2021, it increased by 25%. Poland is a significant producer of poultry meat and supplier to both domestic and foreign markets. In 2022, the country produced more than 3.5 million tons of slaughter poultry livestock (in live weight); there was a 5% increase compared to 2021 (GUS, 2023a).

Although there is an emerging trend toward producing broilers with higher welfare requirements, using slower-growing breeds, using reduced stocking rates, or providing environmental benefits, intensive rearing systems for slaughter poultry dominate the world. Alternatively, medium-intensive or extensive rearing systems are characterised by slower weight gain. Especially in the latter – own fodders are used, and access to free range is often applied. Extensive rearing is characteristic of organic production, based on very strict standards resulting from the Regulation of the European Parliament and the Council (EU) (Rozporządzenie, 2018).

Different broiler-rearing systems may also be characterised by different environmental uses and impacts. This is largely due to the principles of a given production. For example, in organic farming, it is necessary to use your own organic fodder, prohibit the use of antibiotics, provide access to free range, or rely primarily on renewable local environmental resources. Conventional agricultural production systems have far more negative impacts on the environment (Guillaume et al., 2022; Abín et al., 2018; Leinonen et al., 2012; da Silva et al., 2014). They rely more on non-renewable resources for the production of industrial fertilisers, crop protection products or fodder (Zentner et al., 2011; Li et al., 2021; Zhang et al., 2019). Various studies confirm that fodder production is the largest contributor to egg production, and direct energy inputs can account for up to 50% of total non-renewable energy consumption in the supply chain (Bengtsson & Seddon, 2013). The poultry industry is therefore facing increasing expectations for sustainable production, i.e., using fewer resources and having less impact per unit of food produced.

Many methods are used to assess the environmental impact of a given agricultural production. These range from the traditional, based on agro-ecological metrics and indicators (OECD, 2013; Kelly et al., 2018; Payraudeau & van der Werf, 2005), to the more complex, including those that take into account the flow of energy in agro-ecosystems. Commonly used are Life Cycle Assessment analysis (Grout et al., 2018; Fan et al., 2022; Goglio et al., 2015), cumulative energy intensity analysis (Pelletier

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et al., 2011; Maysami & Berg, 2021), exergy analysis (Zhang et al., 2019; Ahamed et al., 2011; Hoang & Alauddin, 2011), carbon footprint (Jaiswal & Agrawal, 2020; Holka et al., 2022; Pandey & Agrawal, 2014) or emergy analysis (Wang et al., 2021; Houshyar et al., 2018; Lewandowska-Czarnecka et al., 2019). We used the last one to make an environmental assessment of broiler production in a small-scale intensive production (a real object which is called baseline production).

The purpose of the article is the emergy analysis (EmA) of broiler production, for which data were obtained directly from a sample production farm, located in southwestern Poland. In addition, based on data and information from the farm, the results of the analysis and other literature data, alternative scenarios for baseline production were proposed: (a) a conventional system based on the use of own fodder, and (b) an organic system using free range and own organic fodder. Production conditions, expenditure and production effects were compared. The comparison showed the scale of the use of renewable and non-renewable environmental resources in the different broiler production systems. The emergy calculation allowed the determination of the magnitude of extracted emergy (Em) and selected emergy indicators, among others: ELR and EYR. The volumes of emergy taken for the production of a unit of production (kg) were additionally determined. In analysing scenario (b), attention was paid to production limitations, production efficiencies and livestock prices. The analysis covered one production year: 2022.

The results obtained were discussed, pointing out the applications of the analysis from an environmental point of view. To our knowledge, based on a study of the literature, the analysis presented is the first of its kind for domestic conditions.

Research method

Emergy analysis – description and examples of application of the research method

Emergy analysis forms a very useful tool for assessing the environmental effect associated with a given production. It takes into account all the components that affect a given activity. These include the relevant flows of substances, energy, labour input, financial resources used in the production process, and renewable resources. The essence of the analysis is to determine the scale of involvement of renewable resources (renewable emergy (EmR)) and non-renewable resources (non-renewable emergy (EmN)) in the production process. On this basis, the degree of its sustainability in relation to the environment is assessed using emergy indicators. Flows are reduced to the amount of solar energy that was directly or indirectly used at each stage of production or service. The flows entering the production process are most often expressed in different units, and the unit of solar transformity τ_i is also expressed differently. Transformity expresses the actual scale of energy transformations that led to the creation of a service or final product. Its numerical value is the result of analyses of the process of obtaining a given good, substance, or service. Goods and services that require the most work (energy) and are characterised by high complexity, at the same time, have the highest transformability (Odum, 1996). The emergy of a given product or service is therefore expressed in common units of sej (solar joules) for all flows and defined by the following Equation (1):

$$Em = \sum E_{xi} \cdot \tau_i, \tag{1}$$

where: E_{xi} the exergy of a given independent component (flow) put into production, expressed in J, τ_i – solar transformity of an independent component, expressed in seJ/J.

Many flows are often expressed not only in J, but also in financial terms or using other units. Thus, a slightly different notation of τ_i, as UEV_i can also be encountered. Using this approach, Equation (1) can take the notation (Su et al., 2020; Zhai et al., 2018) (2):

$$Em = \sum f_i \cdot UEV_i, \tag{2}$$

where: f_i – input of exergy flow, which is also expressed in units of mass or money, which allowed to express transformity in, for example, seJ/$; UEV_i – transformity expressed in, for example, sej/J, sej/kg or sej/$.

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For common substances found frequently in nature and used in practice, their solar transformity is given in terms of the exergy of the substance (Odum, 1996). For energy delivered in fuel, the units of measurement are J, and for electricity, kWh. In cases of more complex substances, such as crop protection products or mineral fertilisers, the transformity can be referred to as the mass of input production means.

EmA has a wide range of applications; it is very often used in the evaluation of various agricultural productions and even entire agricultural systems of countries (Kuczuk et al., 2017; Kuczuk et al., 2023; Enayat et al., 2023; Zhao et al., 2019; Chen et al., 2006; Ghisellini et al., 2014). In agricultural production, it is relatively easy to estimate the flows of renewable resources, i.e., sun, wind, and precipitation. For the fuels used, their exergy can be given (Szargut, 2007); similarly, for a pure fertiliser ingredient or active substance or seed. For machinery and equipment and other technically advanced goods, only approximations can be used. In such cases, another approach is also used, by determining the annual emergy consumption of renewable and non-renewable resources on a national scale. Dividing its volume by the value of GDP yields the so-called emergy monetary equivalent (P1) expressed in sej/$ (Jankowiak & Miedziejko, 2009; Kuczuk et al., 2023; Odum, 1996; NEAD, 2023). It thus fulfils the function of solar transformity. It takes into account the flow of goods and services between countries and can be used especially wherever goods and services are purchased. This is how the emergy of purchased human labor, for example, can be estimated. P1 is also used in other methods for determining environmental impacts, such as calculating the thermo-ecological cost of a given production (Stanek, 2009). For the purpose of the calculations in this article, we use the P1 value determined by NEAD (2023) at 6.09E+12 sej/$.

To determine the magnitude of EmR and EmN, each of the emergy flows is further assigned a value for the renewability index REN, in the range of 0-1. It determines the share of renewable and non-renewable sources in the creation of a given flow. For the purposes of this study, we use NEAD (2023) data for any purchased flows. The REN value for Poland's economy is 0.00616. At the same time, this means that the country's economy relies little on renewable resources.

In order to more precisely determine the environmental impact in the process under analysis, EmA uses various emergy indicators, such as ELR, EYR, ESI, for example, which we also use in our analysis (Table 1) (NEAD, 2023; Brown & Ulgiati, 2004).

Table 1. Emergy indicators used in emergy accounting

Indicator	Formula	Description
Environmental Loading Ratio	ELR = (LN+FN)/(LR+FR)	It determines the potential pressure on the environment, resulting from the share of use of non-renewable resources (flows). A higher value means higher pressure on the environment.
Emergy Yield Ratio	EYR = Em/(FN+FR)	It represents the ratio of total emergy to purchased energy flows. The higher the score, the lower the dependence of the system on purchased emergy, and the more competitive the system is.
The sustainability index	ESI = EYR/ELR	It is a measure of sustainability in terms of minimizing the burden on the environment while promoting development. An ESI of less than 1 indicates pressure on the environment, which is indicated by basing production on non-renewable energy resources.
Renewability	REN = R/Em	It determines the fraction of renewable resources used in the production process.

Notes: LR – local renewable; LN – local non-renewable; FR – purchased renewable; FN – purchased non-renewable; R – total renewable; Em – emergy.

EmA has a tradition of more than 30 years (Odum, 1996; Odum, 2007). However, it still seems niche and undervalued compared to other methods gaining popularity. Quite commonly, its initial use has encountered criticism and challenges from physicists, engineers or economists (Cleveland et al., 2000; Mansson & McGlade, 1993; Amaral et al., 2016). The economists claim that the emergy theory of value, like other energy- and exergy-based theories of value, focuses on the supply side (the environment as a donor of goods), ignoring human preferences and demand (Cleveland et al., 2000).

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Consequently, this method is used in a rather narrow circle of academics, mainly in the US, Brazil, China or Italy (Ulgiati et al., 1994; Chen et al., 2006; Xu et al., 2023; Brown et al., 2022; Nacimento et al., 2022). In Poland, few academics have addressed the problem of applying emergy estimation, mainly in the area of agriculture (Kuczuk, 2017; Kuczuk et al., 2023; Jankowiak & Miedziejko, 2009; Lewandowska-Czarnecka, 2019).

As a measure of true wealth, emergy can be the basis for analysing a wide variety of manufacturing processes or service provisions, whether at the micro-scale (Lei et al., 2008; Cavalett & Ortega, 2008), cities (Liu et al., 2009), or entire economies of countries (Lomas et al., 2008). There is a relatively large amount of documented research devoted to emergy analysis of different types of agricultural production. They show that the more intensified agricultural production is, the results of emergy indicators indicate lower environmental sustainability. Similar conclusions were reached by Brown et al. (2009), concluding that more developed countries have less sustainable economies (low ESI and EYR values and high ELR). Developing countries are more sustainable. In various studies, EmA of agricultural production or agriculture shows clear changes in the values of indicators depending on the development and industrialisation of agriculture. Chen et al. (2006) indicate that China, as a developing country with a huge population, is highly dependent on agricultural development. At the same time, the transition to intensive agriculture requires large energy inputs, particularly those associated with increased use of pesticides, mineral fertilisers and machinery. The verification of the state of agriculture for 1980-2000 showed an increase in the ELR index from 1.74 to 2.72, a decrease in the EYR from 2.28 to 2.08, and a decrease in the ESI from 1.32 to 0.77. In turn, the EmA for Poland's agriculture was designed to show changes in the exploitation of the environment and its loading before and after Poland's accession to the EU. The results of the study showed a slight increase in EYR (1.81; 1.86), a decrease in ELR from 6.53 to 6.15, and an increase in ESI from 0.30 to 0.32 (Lewandowska-Czarnecka et al., 2019). Referring to the definitions of emergy indicators (Brown & Ulgiati, 2004), it can be concluded that Polish agriculture is characterised by medium environmental loading. The low ESI shows that agricultural production is not sustainable in the long run. Similar results were obtained for Italian agriculture. Ghisellini et al. (2014) emphasize that the current and future sustainability of agriculture is based on a difficult balance of food production and environmental impact. An emergy analysis of 25 years of agricultural production in two representative regions showed that they are heavily dependent on non-renewable environmental resources and purchased emergy flows as evidenced by low EYR. The authors noted that in both regional agricultural systems human labor and services accounted for about 50% of the total emergy flow. They noted a fairly high ELR (long-run average for both regions of 8.38). ESI was, on average, very low: 0.14. This indicates, as in the case of Polish agriculture, that the tendency towards low ESI values means a less environmentally friendly production model. It is consumer-oriented and consumes a relatively large percentage of total emergy in its non-renewable form (Brown & Ulgiati, 1997).

Description of the analysed farm

The farm analysed is located in south-western Poland, defined by the following coordinates: 50°43'00.2"N 17°56'52.0"E. Currently, intensive broiler production is carried out in one poultry house with an area of 890m^2. The poultry house is equipped with forced, electrically controlled ventilation. It has tinted windows and electric lighting. Fodder and water are dispensed through a system of feeders and drinking troughs (Figure 1). The poultry houses are heated with coal during the period when the birds are small.

Ross 308 broilers are kept on bedding 8-10 cm deep, deeper bedding is used in the winter season. Day-old chicks come from purchase, and the breeding cycle lasts 42 days. During the year, production includes 5 cycles, between which a minimum of two weeks are spent cleaning and disinfecting the poultry house. Chicken mortality mainly affects very young birds and averages about 5% of the chickens per year. Fallen chickens are transferred under contract to a fox farm. Chicken manure is collected by a local farm and exchanged for straw.

The farm does not produce its own fodders; it purchases ready-made mixtures, or grain is purchased from local farmers, and the owner then composes mixtures. The analysis covered the year 2022. The plant's basic production data is shown in Table 2.

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Figure 1. Seven-day-old chicks, fodder, water, ventilation and lighting system

According to the regulations (Regulation, 2010), in conventional systems, the permissible stocking rate in a poultry house must not exceed 33 kg/m^2, with a final weight of 2-2.5 kg. In order to meet these standards, the farm uses a so-called "sifting". Six days before the end of the cycle, some of the birds that weigh slightly less are selected and sold. Overall, the analysed production meets the standards, and the final average weight of a bird before slaughter is about 2.7 kg.

Table 2. Basic production information on the facility's baseline production

Item	Unit	Raw data
Production area of the hall	m^2	890
Overall maximum number of birds inserted per year	pcs/year	81,530
Number of broilers inserted*	pcs/cycle/hall	16,306
Total number of birds for sale	pcs/year	76,963
Number of broilers for sale*	pcs/cycle/hall	15,392.6
Sales	kg/year	204,314
Stocking rate *; **	bird/m^2/cycle; m^2/bird/cycle	17.30; 0.06
Weight of broilers at the end of the cycle*	kg	2.65
Mortality*	%	5.6
Fodder consumption per cycle*; **	kg/bird/cycle	4.43
Water consumption*	liters/bird/cycle	5.6
Sales value***	$	249,229.59

*average; **calculation for birds meant for sale; ***$ exchange rate in 2022: 4.4598 PLN.

Production data extracted for farm emergy analysis

For the emergy analysis of baseline production, data and information were obtained through direct interviews with the farm owner. Data on purchases, sales and consumption of inputs were based on the owner's business records. Information on the production process system itself was obtained through interviews and visits to the farm.

For input production means from purchase (F, including FR – renewable part from purchase and FN – non-renewable part from purchase), it was assumed after NEAD (2023) that their renewable part is 0.00616 for Poland. Since EmA also includes the determination of the share of local environmental resources, renewable (LR) and non-renewable (LN) ones, those involved in the production

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process and their share were indicated. The data necessary for the emergy analysis of the poultry house finally includes:

a) purchased inputs (F): chicks, fodder, veterinary care (including vaccination of chicks), water consumption (as tap water purchase) for watering purposes, disinfectants, labour, electricity (ventilation, lighting, etc.), diesel, coal, other,
b) local renewable inputs (LR): solar energy, wind, rain.

In the case of baseline production, there is no use of local non-renewable inputs (LN) – soil.

Assumptions made for scenarios (a) and (b) of on-farm production

Alternative production scenarios were proposed for the baseline poultry production analysed:

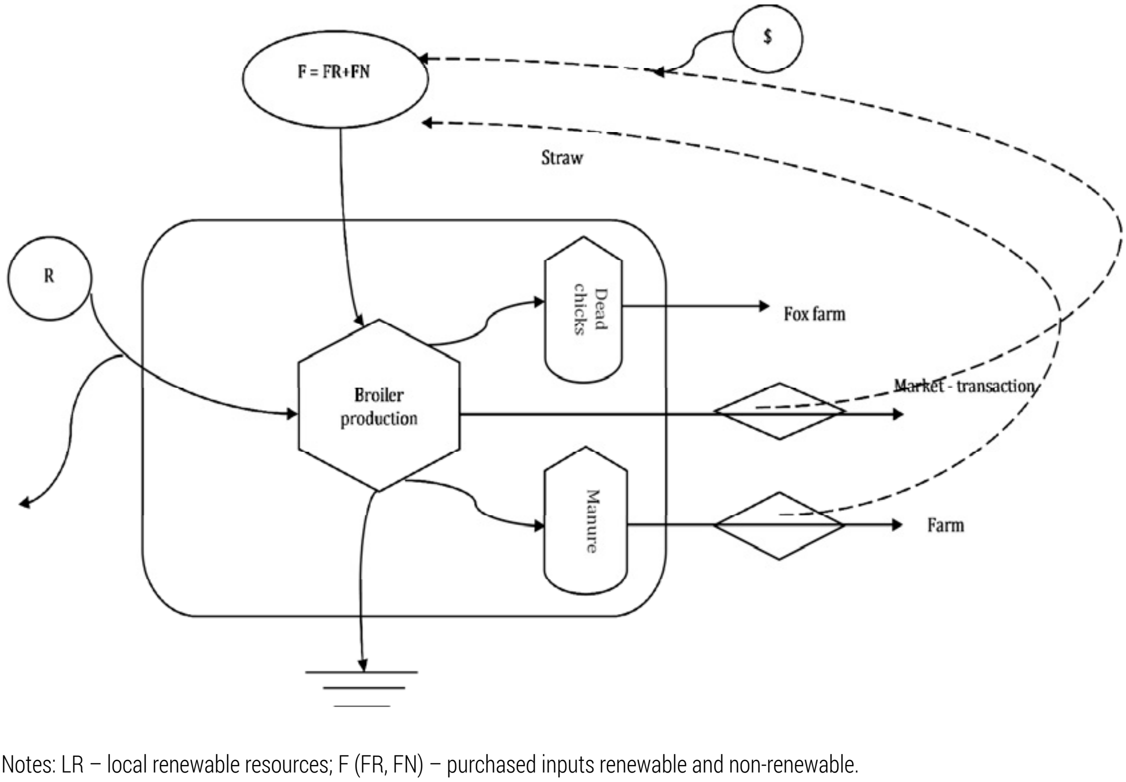
conventional system based on the use of its own fodder. We are introducing the feeding of poultry with own fodder; in the calculation of the fodder emergy, we use the available literature data on the emergy of winter wheat as an example of own fodder,

organic system; in this scenario, we include the necessary requirements for organic broiler production: access to free range (4m^2/bird), the total area of the poultry house(s) on the farm must not exceed 1,600 m^2, a stocking rate of a maximum of 21 kg/m^2 and a maximum number of animals per poultry house of no more than 4800 animals; at the same time, a minimum slaughter age of 81 days applies (Rozporządzenie, 2018; Rozporządznie, 2020); similar to scenario (a), we use literature data on the emergy of organically produced winter wheat in the calculation of own fodder; we take into account market prices for organic poultry at PLN 25/kg, converted to dollars; we assume a similar percentage of mortality as on the conventional farm.

Results and discussion

Graphic presentation of production systems

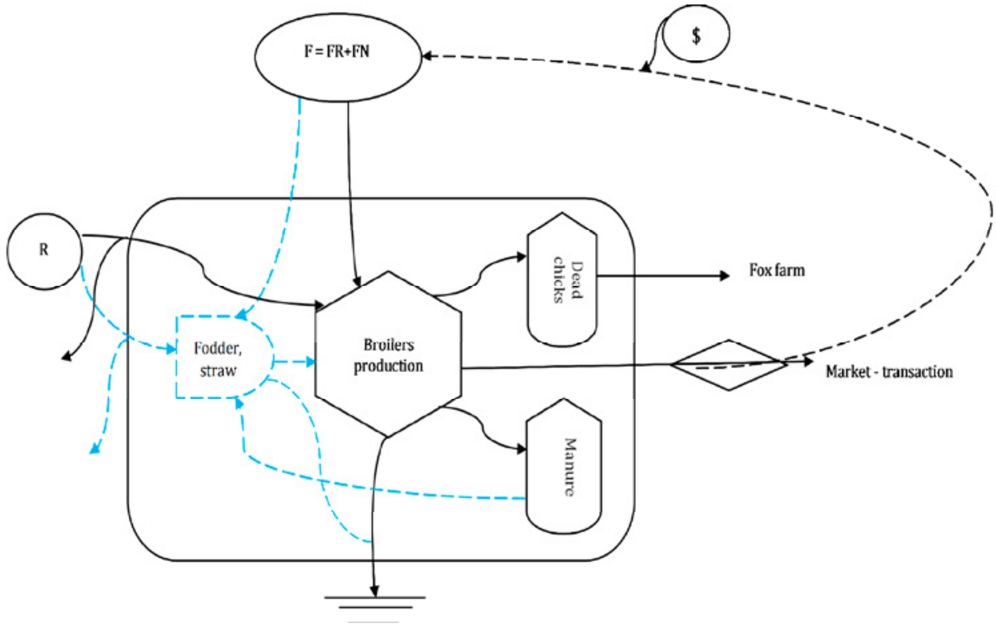
According to the procedure of emergy accounting described by Sciubba and Ulgiati (2005), the production on the farm and the type of resources involved are shown in Figure 2.



Notes: LR – local renewable resources; F (FR, FN) – purchased inputs renewable and non-renewable.

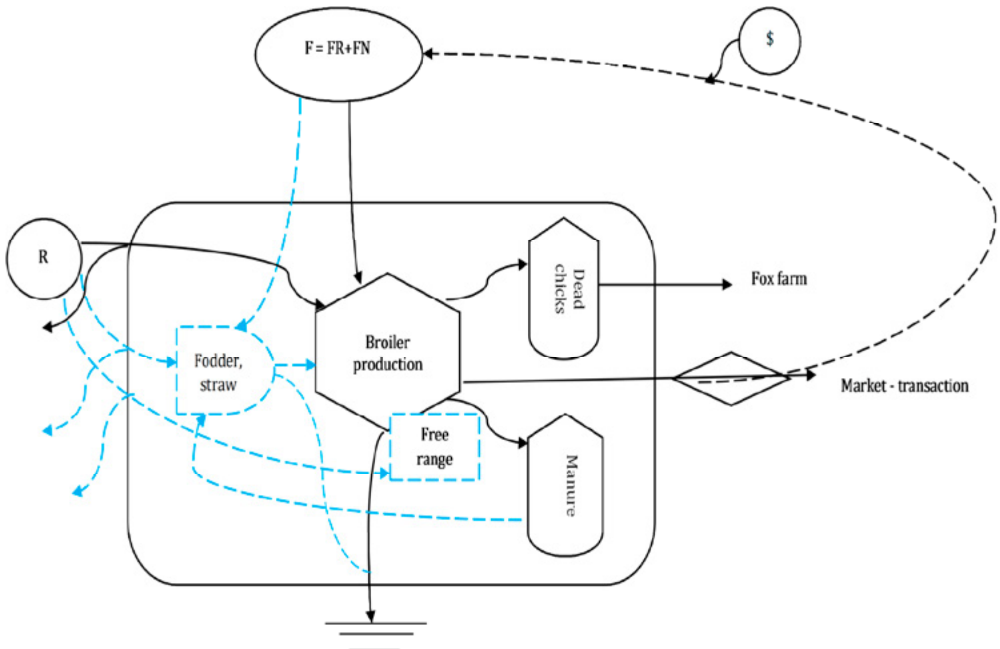
Figure 2. Emergy diagram of baseline production

An energy system diagram shows the relationships between components and processes occurring within the boundaries of the system. In our analysis, the baseline production system and its boundaries are defined by the area of the poultry house. LR and purchased inputs (F) flow into the system. Figure 3 shows the emergy flows for variant (a), taking into account the use of own fodder. Figure 4 shows, in turn, the proposed organic scenario (b), based on the use of own fodder and additionally including a free-range area for broilers. Blue dashed lines show changes from baseline production. In scenarios (a) and (b), straw and manure remain on the farm to be used for bedding and fertiliser.



Notes: LR – local renewable resources; F (FR, FN) – purchased inputs renewable and non-renewable; dashed line – own production of feed and straw and use of own chicken manure for plant production.

Figure 3. Emergy diagram of production for (a) scenario



Notes: LR – local renewable resources; F (FR, FN) – purchased inputs renewable and non-renewable; dashed line – own production of feed and straw and use of own chicken manure for plant production.

Figure 4. Emergy diagram of production for (b) scenario

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Baseline broiler production vs scenario (a)

The figures and calculated Em of baseline production for scenario (a) are shown in Table 3. In baseline production, all production inputs come from purchase. Water for animal watering and other purposes is tap water. We treat it in our calculations as a purchased input, and therefore, with a REN of 0.00616. The straw used for bedding comes from exchanges. A local farmer collects chicken manure from the producer in exchange for straw for bedding. As straw is traded but not directly purchased, the proportion of its renewable fraction (0.107) was determined using literature data (Kuczuk, 2016; Sun et al., 2021).

Table 3. Baseline production and scenario (a) production

Inputs	REN	REN: 0-1	Refer. RF	Unit	Raw data	τ*	Refer. τ	EmR (sej/y)	EmN (sej/y)	EmT (sej/y)
Sun	LR	1	Odum (1996)	J	3.30E+12	1	Odum (1996)	3.30E+12	0.00E+00	3.30E+12
Rain	LR	1	Odum (1996)	liters	5.79E+05	2.59E+04	Odum (1996), Jankowiak and Miedziejko (2009)	7.40E+13	0.00E+00	7.40E+13
Wind	LR	1	Odum (1996)	J	4.81E+08	2.50E+03	Odum (1996), Brandt-Wiliams (2002)	1.20E+12	0.00E+00	1.20E+12
Total LR								7.8518+13	0.00E+00	7.8518E+13
Chicks	FN, FR	0.00616	NEAD (2023)	pcs.	81,530	6.09E+12	NEAD (2023)	1.51E+15	2.43E+17	2.44E+17
Fodder	FN, FR	0.00616	NEAD (2023)	kg	340,623	6.09E+12	NEAD (2023)	6.39E+15	1.03E+18	1.04E+18
Potable water	FN, FR	0.00616	NEAD (2023)	m^3	435	6.09E+12	NEAD (2023)	1.30E+13	2.10E+15	2.11E+15
Water-social	FN, FR	0.00616	NEAD (2023)	m^3	15	6.09E+12	NEAD (2023)	1.16E+12	1.88E+14	1.89E+14
Straw	FN, FR	0.107	Kuczuk (2016)	kg	12,500	6.09E+12	NEAD (2023)	1.16E+15	9.71E+15	1.09E+16
Coal	FN	0	Odum (1996)	kg	32,000	6.09E+12	Odum (1996)	0.00E+00	7.58E+16	7.58E+16
Electricity	FN	0	Odum (1996)	kWh	17,862	6.09E+12	Odum (1996)	0.00E+00	1.99E+16	1.99E+16
Disinfectants	FN, FR	0.00616	NEAD (2023)	kg	200	6.09E+12	NEAD (2023)	1.26E+14	2.71E+16	2.73E+16
Labor	FN, FR	0.00616	NEAD (2023)	pers.	1	6.09E+12	NEAD (2023)	2.53E+14	4.08E+16	4.10E+16
Diesel	FN	0	Odum (1996)	liters	417	6.09E+12	NEAD (2023)	0.00E+00	4.10E+15	4.10E+15
Veterinary services	FR, FN	0.00616	NEAD (2023)	pcs.	5	6.09E+12	NEAD (2023)	1.26E+14	2.04E+16	2.05E+16
Total F								9.6198E+15	1.4738E+18	1.4834E+18
Total LR+F								9.6983E+15	1.4738E+18	1.4835E+18
Own fodder(a)	LR, LN	0.107	Kuczuk (2016)	kg	340,623	2.86E+12	Kuczuk (2016)	1.04E+17	8.70E+17	9.74E+17
Own straw (a)	LR, LN	0.107	Kuczuk (2016)	kg	12,500	5.07E+12	Own calculation	6.79E+15	5.66E+16	6.34E+16
Total LR+F+ Own (a)**								**1.1317E+17**	**1.3598E+18**	**1.4730E+18**

Notes: REN – renewable fraction; LR – local renewable; LN – local non-renewable; FN – purchased non-renewable; FR – purchased renewable; EmR – renewable emergy; EmN – non-renewable emergy; EmT – total emergy; (a) calculation for own fodder (wheat), and straw; ** excluding purchased fodder and straw from the calculation; *τ – transformity. (for LR sej/Unit; for F sej/$; for Own fodder and straw sej/Unit).

Annual inflows of local renewable emergy include solar emergy, wind emergy and water from precipitation. Their total emergy was 7.8518E+13 sej/year. The total renewable emergy of the baseline production was 9.6198E+15 sej/year and represented 0.65% of the total emergy consumed in the production process. Very low involvement of LR is evident.

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The literature gives few examples of emergy in intensive poultry production and the results of the analyses are mixed. In the work of Castellini et al. (2006), conventional and organic poultry production was compared. Emergy flow was estimated at 7.42E+16 sej/cycle and the share of renewable flow was 16%. In China, on the other hand, conventional systems were the subject of research, but with a much smaller intensification and scale of production. The results provide different information about the exploitation of the environment, which is linked to the different contribution of emergy flows. Chen et al. (2017) studied extensive production carried out under natural conditions. Renewable emergy accounted for more than 80% of the total emergy production, amounting to 4.61E+15 sej/year. Another example (Hu et al., 2012), shows a share of renewable emergy of nearly 23%, with a total emergy of production of 9.61E+16 sej/year. In the work of Su et al. (2020), a duck-rearing system and an integrated rice-duck system were analysed. In the first, the total emergy was 3.83E+17 sej/year and the renewable emergy inflow accounted for 7.3%. In the integrated system, where in particular the share of human labor was dominant, the total emergy was 9.19E+15 sej/year and renewable emergy accounted for more than 49%. The treatment and determination of the level of renewability of human labour are debated in the literature. Much depends on whether it is a paid service or part of integrated family farming.

The proposed scenario (a) assumes inflows of the same local renewable resources. It was assumed that the own fodder was wheat. This is, of course, quite an oversimplification. However, we mainly wanted to show how the magnitude of the EmR share, as well as the values of the emergy indicators, change significantly and for the better under conditions of using own-produced fodder. To determine the emergy of winter wheat production, we assumed, following Kuczuk (2016), that REN is 0.107. The REN used already takes into account the share of LN-soil use. From the data shown in Table 3, it can be seen that after applying fodder of own production and using own straw, the total EmR increased to 1.1317E+17 sej/year. The share of renewable emergy therefore represents 7.7% of total emergy (EmT). The latter drops slightly to 1.4730E+18 sej/year. In both production systems, however, the size of the total emergy is determined by the large share of the non-renewable fraction. For baseline production, fodder emergy was determined based on the P1 monetary factor. In scenario (a), a comprehensive emergy calculus was used to determine the EmT of grain for feed (Kuczuk, 2016). Very similar values of EmT in baseline production and scenario (a) prove the high complementarity of both calculation methods.

Additional conclusions arise for the proposed scenario (a). The production of fodder creates on-farm opportunities to obtain their own straw for bedding, and chicken manure can be used in crops (see Figure 3). Assuming the same amount of fodder is required (340,623 kg) and the assumed wheat yield of about 7 tons/ha (average for Opole voivodeship in 2022) (GUS, 2023b), 49 hectares of land are needed for fodder production.

The impact of both productions on the environment is more accurately determined by the commonly used emergy indicators. Table 4 shows their values and, at the same time, the results of emergy consumption calculations related to a unit (kg) of poultry meat produced. The very high ELR for the baseline production (151.96) indicates a very high environmental load. Low values of EYR (1.0001) and ESI (0.0066) – there is a very low degree of use of local renewable resources, and production relies mainly on purchased inputs. The change to introduce its own fodder improves the performance of the indicators. ELR drops to 12.02. In scenario (a), the relatively high value of renewable emergy is influenced by the REN of winter wheat production. ESI and EYR also increase significantly.

In the work of Castellini et al. (2006), ELR was at 5.21, which is due to a higher share of the renewable emergy flow than in our examples. In the work of Cheng et al. (2017), the ELR was 0.23, which is associated with the previously mentioned very high share of renewable emergy (more than 81%), with higher values for ESI (2.23) and EYR (2.37). Similar results can be found in the analysis of Hu et al. (2012) – ELR at 3.44, ESI at 0.32, and EYR at 1.11.

During the year, the baseline production used 7.2608E+12 sej/kg of meat, while scenario (a) used 7.2094E+13 sej/kg of product. However, in scenario (a), by far more EmR is used per kg of product unit produced.

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Table 4. Chosen emergy metrics and indicators characterising baseline and scenario (a) production

Indicator/metric	Unit	Value
Broiler production	kg/year	204,314
Production value	$/year	249,229.59
EmT/production value	sej/$	5.9523E+12
EmT/production value (a)	sej/$	5.9101E+12
EmT	sej/year	1.4835E+18
EmT (a)	sej/year	1.4730E+18
EmR	sej/year	9.6983E+15
EmR (a)	sej/year	1.1317E+17
EmT/production	sej/kg	7.2608E+12
EmT/production (a)	sej/kg	7.2094E+12
EmR/przoduction	sej/kg	4.7468E+10
EmR/production (a)	sej/kg	5.5390E+11
ELR		151.96
ELR (a)		12.02
EYR		1.0001
EYR (a)		3.3839
ESI		0.0066
ESI (a)		0.2816
REN		0.0065
REN (a)		0.0768

Notes: scenario with own fodder and straw; EmR – renewable emergy; EmT – total emergy.

Scenario (b) – conversion of baseline production to an organic system and emergy implications

In an organic unit, the total area of the poultry house(s) must not exceed 1,600 m^2. In addition, in one poultry house, there must not be more than 4,800 birds in one cycle. The stocking rate on the floor area of the poultry house(s) should not exceed 21 kg of live weight per m^2. Access to open space, 4 m^2 /bird, is necessary. We assumed, following Gornowicz et al. (2015), that the average body weight on the 81st day of rearing is 2.3 kg. Chick mortality is assumed at the baseline production level. From the basic data and the assumptions for scenario (b), we derive the information shown in Table 5.

With a basic poultry house area (890 m^2), it is possible to produce broilers organically in only three cycles per year. Comparing the two productions, the organic one will account for only 15.3% of the volume of baseline production. To increase efficiency, it is possible to divide the analysed area into two separate halls (445m^2 each). Under this assumption, organic production can account for 25.5% of the volume of baseline production. These alternatives are due to the aforementioned restrictions on the maximum number of birds in a poultry house and their density per m^2. With two poultry houses, the need for a free-range area may also increase. As you can see, the efficiency of organic production is much lower. However, higher livestock prices play an important role here. This gives the possibility of achieving satisfactory results. These considerations are also included in Table 5.

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Table 5. Estimated production data for organic production scenario (b)

Specification	Unit	Data	Data origin
One poultry house 890 m^2			
Permissible number of birds per poultry house	pcs/cycle	4800	Rozporządzenie (2018)
Maximum density of birds in one cycle	pcs/m^2	5.3	Own calculation
Average weight of a bird in organic production at 81 days of age	kg	2.3	Gornowicz et al. (2015)
Maximum possible stocking rate in one cycle	kg/m^2	12.4	Own calculation
Number of full cycles per year	pcs.	3	Own calculation
Maximum number of birds in three cycles*	pcs.	13,594	Own calculation
Fodder consumption	kg/pc.	5	Gornowicz et al. (2015)
Mortality	%	5.6	Assumption
Fodder needs for total broiler production	kg/year	67,970	Own calculation
Space needs for free range	m^2	18,125	Own calculation
Production for sale	kg/year	31,266	Own calculation
Sales value (at PLN 25/kg)**	$	175,266.82	Own calculation
Two poultry houses with areas of 445 m^2 each			
Permissible number of birds per one poultry house	pcs/cycle	4,000	Own calculation
Maximum density of birds in one poultry house per cycle	pcs/m^2	8.9	Own calculation
Average weight of a bird in organic production at 81 days of age	kg/m^2	2.3	Gornowicz et al. (2015)
Maximum possible stocking rate per area in one poultry house per cycle	kg/m^2	20.47	Own calculation
Number of complete cycles in one poultry house	pcs.	3	Own calculation
Maximum number of birds in three cycles in both poultry houses*	pcs.	22,656	Own calculation
Fodder consumption	kg/pcs.	5	Gornowicz et al. (2015)
Mortality	%	5.6	Assumption
Fodder needs for total broiler production	kg/year	113,280	Own calculation
Space needs for free range	m^2	30,208	Own calculation
Production for sale	kg/year	52,109	Own calculation
Sales value (at PLN 25/kg)**	$	292,102.8	Own calculation

* after taking into account mortality; ** average dollar exchange rate in 2022: PLN 4.4598.

The value of organic production, taking into account the higher market price per kg of livestock, is lower than conventional production by nearly 30%. However, assuming two-hall production, its value can be higher than conventional by 17.2%. However, our considerations do not include a detailed analysis of the economic implications of converting conventional to organic production, but only the impact of these changes from the point of view of the use of environmental resources.

Table 6 shows the variant calculations for scenario (b) and the variant with one poultry house of 890 m^2. On the side of local environmental flows, we consider precipitation, sun, and wind. We relate their share to the area increased by the area of the free range (18,125 m^2). We assume the purchase price of chicks is the same as that of conventional production, and the same consumption of electricity and coal is the same. We leave the value of veterinary service at the same level. We assumed fodder consumption following Gornowicz et al. (2015) at an average of 5 kg/bird. We recalculated straw requirements for bedding and water consumption according to the number of birds and their extended rearing time. As in scenario (a), some of the straw from wheat production can be used as bedding, and the birds' own chicken manure can be used as fertiliser.

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The ecological variant is characterised by lower environmental impact. The introduction of the free-range area increased the share of LR to 1.6762E+15 sej/year. The EmR is 5.9329E+16 sej/year and represents a 12.1% share of the total emergy of the process. Similar results are presented by Hu et al. (2012), where the share of renewable flows in a family-operated organic rearing systemic counts for more than 24%. Also in the study of Castellini et al. (2006) – nearly 29% of the total emergy of poultry production under organic conditions is renewable emergy.

Table 6. Renewable and non-renewable resource inflows and emergy of organic broiler production (b) – for production in one poultry house 890 m^2

Inputs	RF	REN: 0-1	Refer. REN	Unit	Raw data	τ*	Refer. τ	EmR (sej/y)	EmN (sej/y)	EmT (sej/y)
Sun	LR	1	Odum (1996)	J	7.05E+13	1	Odum (1996)	7.05E+13	0.00E+00	7.05E+13
Rain	LR	1	Odum (1996)	liters	1.24E+07	2.59E+04	Odum (1996), Jankowiak and Miedziejko (2009)	1.58E+15	0.00E+00	1.58E+15
Wind	LR	1	Odum (1996)	J	1.03E+10	2.50E+03	Odum (1996), Brandt-Wiliams (2002)	2.57E+13	0.00E+00	2.57E+13
Total LR								1.6762E+15	0.0000E+00	1.6762E+15
Chicks + vaccination	FN, FR	0,00616	NEAD (2023)	pcs.	14,400	6.09E+12	NEAD (2023)	2.66E+14	4.30E+16	4.33E+16
Potable water	FN, FR	0,00616	NEAD (2023)	m^3	173	6.09E+12	NEAD (2023)	5.17E+12	8.33E+14	8.39E+14
Water-social	FN, FR	0,00616	NEAD (2023)	m^3	15	6.09E+12	NEAD (2023)	1.16E+12	1.88E+14	1.89E+14
Coal	FN	0	Odum (1996)	kg	32,000	6.09E+12	Odum (1996)	0.00E+00	7.58E+16	7.58E+16
Electricity	FN	0	Odum (1996)	kWh	17,862	6.09E+12	Odum (1996)	0.00E+00	1.99E+16	1,99E+16
Disinfectants	FN, FR	0,00616	NEAD (2023)	kg	76	6.09E+12	NEAD (2023)	6.39E+13	1.03E+16	1.04E+16
Labor	FN, FR	0,00616	NEAD (2023)	pers.	1	6.09E+12	NEAD (2023)	2.53E+14	4.08E+16	4.10E+16
Diesel	FN	0	Odum (1996, 2007)	liters	417	6.09E+12	NEAD (2023)	0.00E+00	4.10E+15	4.10E+15
Veterinary services	FR, FN	0,00616	NEAD (2023)	pcs.	5	6.09E+12	NEAD (2023)	1.26E+14	2.04E+16	2,05E+16
Total F			NEAD (2023)					7.1577E+14	2.1526E+17	2.1598E+17
Own fodder	LR, LN	0,21	Kuczuk (2016)	kg	67,970	2.86E+12	Kuczuk (2016)	4.08E+16	1.54E+17	1.9439E+17
Own straw	LR, LN	0,21	Kuczuk (2016)	kg	15,000	5,11+E12	Ow calculation	1.61E+16	6.06E+16	7.67E+16
Total Own								5.6937E+16	2.1419E+17	2,7113E+17
Total LR+F+Own								**5.9329E+16**	**4.2945E+17**	**4.8878E+17**

Notes: REN – renewable fraction; LR – local renewable; LN – local non-renewable; FN – purchased non-renewable; FR – purchased renewable; EmR – renewable emergy; EmN – non-renewable emergy; EmT – total emergy; *τ – transformity (for LR sej/Unit; for F sej/$; for own fodder and straw sej/Unit).

The above translates into the values of emergy indicators (Table 7). ELR at 7.24 is lower by 21 times compared to the baseline production and nearly twice – to the production according to scenario (a). In the study of Castellini et al. (2006), this indicator was at 2.04. In the family-operated organic system in China – 3.10 (Hu et al., 2012), and in the backyard organic rearing system in China – 2.34 (Zhang et al., 2013). Also, the values of other indicators take the value in favour of organic production.

Table 7. Emergy metrics and indicators characterizing production in the organic scenario (b)

Indicator/metric	Unit	Value
Broiler production	kg/year	31,266
Production value*	$/year	175,266.82
EmT/production value	sej/$	2.7888E+12
EmR/production value	sej/$	3.3851E+11
EmT	sej/year	4.8878E+17
EmR	sej/year	5.9329E+16
EmT /production	sej/kg	1.5633E+13
EmR /production	sej/kg	1.8975E+12
ELR		7.24
EYR		2.26
ESI		0.3127
REN		0.1214

Notes: EmR – renewable emergy; EmT – total emergy; *at a price of 25 PLN/kg.

Implications of the study

Emergy methodology is a very useful tool in comparing different agricultural systems in terms of their environmental impact. The analysis of different poultry production systems directly shows that more extensive and organic production systems have less environmental impact, rely more on the use of local renewable environmental resources, and, in general, their share of production is increasing.

EmA-based results can influence the design of incentive policies targeting production systems that enhance environmental sustainability and food quality (Castellini et al., 2006). EmA also provides important information for agricultural producers and consumers, being a tool for educating these groups operating in food and natural resource markets. This is important because the modern consumer today also looks at a food product through the lens of how it was produced and how much production has affected the environment.

Moving towards more sustainable agricultural production, it therefore becomes necessary to reduce the share of non-renewable resources coming from outside the system (Cheng et al., 2017). Emergy analysis makes it possible to indicate the magnitude of their use and shows what services are provided by the environment in the creation of goods and services. Thus, it is advisable to use it, although generalisations in the calculations may not accurately reflect the transformations taking place in ecosystems, productions or economies. In particular, the use of emergy monetary conversion can overstate or understate the emergy of introduced substance flows. The emergy value shaped by the market may not correspond to the emergy determined based on exergy and solar transformity. The renewability of REN is analogous, which, using a monetary conversion factor, is an averaged renewability that characterises the entire economy of a country. EmA is a very useful and interesting method for assessing the environmental impact of production, educating the public, and showing the scale of resource use.

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Conclusions

The research conducted and the analysis of the results allows the following conclusions:

- The presented analysis shows that intensive poultry farming is a production with a significant environmental impact. Virtually all inputs come from purchase, so assuming a REN of 0.00616. This ultimately results in an ELR of 151.96. Such a high value implies a low involvement of local renewable resources in the generation process.
- Production scenario (a), based on the use of in-house fodder, reduced the ELR to 12.02. In this scenario, the still high value of EmN is influenced by the REN of wheat production in the conventional system (0.107). At the same time, in scenario (a) the EYR increases from 1 (the value characterising production based on purchased inputs), to 3.38. This higher value is due to the involvement of own fodder emergy in the poultry rearing process.
- Organic poultry farming further reduces both environmental pressure (ELR = 7.24) and total emergy used. The value of the emergy indicators is significantly affected by the REN of fodder produced under organic conditions. The data taken for calculation was 0.21.
- At the same time, the conditions of the organic system reduce the volume of production, which is at only 15.3% of the baseline production. In order to increase productivity, it is possible to divide the analysed area into two separate premises. The organic production can account for 25.5% of conventional production. The economic viability of organic meat poultry farming is, therefore, dependent on the market price of organic poultry meat and the demand for such products.
- Few literature data exist on emergy analysis of poultry farming, including broilers. The results of the available analyses vary due to the use of different conventional production systems. For the most part, however, the results show, as in our analysis, that where there is intensive production, the environmental load factor is high.
- However, the scale of organic production (scenario (a)) does not allow for a direct comparison of the values of the emergy indicators with those characterising extensive, family-run Chinese farms. The latter, presented in the discussion, are very small farms with a low number of poultry kept.

The contribution of the authors

Conceptualization, A.K. and J.P.; literature review, A.K.; methodology, A.K. and J.P.; formal analysis, A.K. and J.P.; writing, A.K.; conclusions and discussion, A.K. and J.P.

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PRODUKCJA BROJLERÓW Z PERSPEKTYWY ANALIZY EMETGETYCZNEJ – SCENARIUSZE ODDZIAŁYWANIA NA ŚRODOWISKO

STRESZCZENIE: Spożycie mięsa drobiowego stanowi istotny element ogólnego spożycia żywności w Polsce. Względy ekonomiczne powodują, że zarówno w kraju, jak i na świecie dominuje konwencjonalny chów intensywny. Niemniej jednak środowiskowe i zdrowotne aspekty oraz chęć humanitarnego traktowania zwierząt sprawiają, że proekologiczne systemy chowu stają się coraz powszechniejsze. Celem artykułu jest analiza środowiskowa przykładowego gospodarstwa prowadzącego intensywny chów drobiu rzeźnego (tzw. produkcja bazowa). Dla tej produkcji zaproponowano scenariusze zmian: (a) chów konwencjonalny oparty o wykorzystanie pasz własnych oraz (b) chów ekologiczny z wykorzystaniem dostępu do wolnego wybiegu i własnej paszy organicznej. W analizie zastosowano podejście emergetyczne. Porównanie różnych systemów produkcyjnych za pomocą analizy emergetycznej umożliwiło pokazanie skali zaangażowania zasobów środowiska w produkcji bazowej i scenariuszach oraz określenie ilości emergii odnawialnej i nieodnawialnej zużywanej na jednostkę produkcji. Poprzez wykorzystanie wybranych wskaźników emergetycznych, np.: Environmental Loading Ratio (ELR), Emergy Yield Ratio (EYR), określono wpływ na środowisko dla każdego scenariusza produkcji. W scenariuszu systemu ekologicznego wzięto pod uwagę konieczność zmiany parametrów produkcji (obsada, maksymalna powierzchnia kurnika, wybieg). Wyniki wskaźników pokazują, że produkcja bazowa stanowi największe obciążenie dla środowiska i jest najmniej zrównoważona. System ekologiczny – odwrotnie, jednakże ze względu na ograniczenia produkcyjne i niższą osiągniętą efektywność produkcji, zorientowanie gospodarstwa wyłącznie na system ekologiczny może nie być ekonomicznie opłacalne. Uzyskane informacje mogą stanowić cenne wskazówki dla producentów rolnych. Mogą pomóc w podejmowaniu świadomych decyzji dotyczących zarządzania zasobami naturalnymi, aby osiągać bezpieczeństwo środowiskowe. Wyniki analizy są również ważne dla decydentów politycznych przy tworzeniu polityk na rzecz bardziej zrównoważonej produkcji rolnej. Otrzymane wyniki omówiono, wskazując na wagę analizy stosowanej głównie z punktu widzenia ochrony środowiska.

SŁOWA KLUCZOWE: produkcja brojlerów, rolnictwo konwencjonalne, rolnictwo ekologiczne, analiza emergetyczna, wpływ na środowisko