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EMERGY ANALYSIS OF POND FISH FARMING – A CASE STUDY FOR A LARGE FISH FARM IN POLAND

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ABSTRACT: The immediate goal of the article is an emergy analysis of fish production on an exemplary fish farm. Additionally, it was compared, in terms of environmental burden, with other exemplary agricultural productions. On the basis of the calculated emergy inflows, selected emergy indicators (ELR, EYR, REN) were calculated, showing the scale of use of renewable and non-renewable resources. The results show that the analysed fish production does not burden the environment and largely uses renewable resources, unlike other intensive agricultural productions. The ELR value was compared with its values for other exemplary agricultural production. In fish farming, this indicator is most often lower than 1. It is assumed that such activity does not burden the environment. Animal production requires the involvement of additional space for fodder production. Therefore the differences in the area necessary for the production of a food unit (GJ) of exemplary plant and animal products are also shown. Emergy analysis and its results can provide valuable information for decision-makers in terms of the direction of a given production.

KEYWORDS: emergy account, environment, inland aquaculture, emergy indicators

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Introduction

Fishing is an important part of the global economy, consisting in acquiring fish, seafood and other aquatic organisms for consumption and processing. The scope of fishing also includes breeding or rearing that is based on the breeding of fish and other aquatic organisms in aquaculture (Hryszko et al., 2018). According to FAO data (FAO, 2022), global fisheries and aquaculture production in 2020 amounted to 177.8 million tonnes, including inland aquaculture comprising 54.4 million tonnes. Compared to 2000, the total production volume increased by more than 32%, and for inland aquaculture by over 20%. At the same time, 157.4 million tonnes of fish were used for consumption in 2020 (an increase of 44% compared to 2000), and consumption per person was 20.2 kg/year on average (an increase by approx. 20% compared to 2000). The greatest number of aquatic products per person per year are consumed in Asia (24.6 kg on average), the lowest – in Africa (10 kg), and in Europe – 21.1 kg. Unfortunately, in Poland, the consumption of aquatic products is still at a very low level (13.1 kg/person on average – data for 2019 (EUMOFA, 2021). The consumption of fish and seafood is recommended due to their high nutritional value (Januszko & Kałuża, 2019).

Polish aquaculture has a long history, with the first records of activity from around the 11th–12th century (Guziur, 2018), and Poland uses the largest areas of ground carp ponds in the European Union (Lirski & Myszkowski, 2022). Currently, aquaculture in Poland consists mainly of terrestrial freshwater fish farming and is limited to the rearing of about forty species of fish. There are three main types of activity specialising in the production of fish for consumption: low-intensity carp farming in polycultures, intensive farming of salmonids and high-intensity farming of fish in recirculating systems with water filtration and purification. Among these groups, the production of consumption carp has a significant share. In 2020, it accounted for 48% (21.15 thousand tonnes) of the total weight of produced fish for consumption (Lirski & Myszkowski, 2021a; Lirski & Myszkowski, 2021b).

The global production of aquaculture has increased in recent decades, while aquaculture systems are becoming more energy-intensive, mainly based on non-renewable sources (Kim & Zhang, 2018). Sustainable aquaculture production is the subject of intense discussion (Naylor et al., 2021), and for this to be a sustainable trend, it is necessary to combine local resources and human capital in the best possible way while reducing or eliminating negative environmental impacts (Diana et al., 2013). Fish production in freshwater ponds, like any other activity, has an impact on the environment, and without concern for sustainable development, it leads to ecological disadvantages, an increased number of diseases of farming fish, and consequently to a decrease in the economic profits of fish farms (Mavraganis et al., 2020).

Since aquaculture is closely related to the environment, the authors shall analyse the problem of its impact on the environment. Freshwater aquaculture, an example of which is the subject of analysis in the paper, is often a very complicated form of activity, including not only the farming of specific species, but a number of adaptations related to the necessary infrastructure and creating value chains. In many countries, it is most often in the form of family fish farms, which produce a variety of fish species for local and regional consumption (Hernandez et al., 2018; da Silva Maciel et al., 2022; FAO, 2018).

The immediate goal of this study is an emergy analysis of fisheries production in freshwater aquaculture (carp rearing and accompanying production of additional species) in an exemplary family fish farm located in south-western Poland. On the basis of the calculated emergy inflows (renewable and non-renewable) to the system, selected emergy ratios have been calculated (NEAD, 2022; Haden, 2003), showing the scale of using renewable and non-renewable resources. Additionally, we compare the analysed production with other exemplary agricultural types of production, which constitute the crucial basis for food consumption in many countries (e.g. wheat, buckwheat, corn, chicken, and pigs, examples of aquaculture). The purpose of these comparisons is to show the differences in the environmental load of these different types of productions. Due to the fact that animal production (including aquaculture) requires the involvement of additional land for fodder production, we also show the differences in the area actually required to produce a food unit (GJ) of sample plants and animal products.

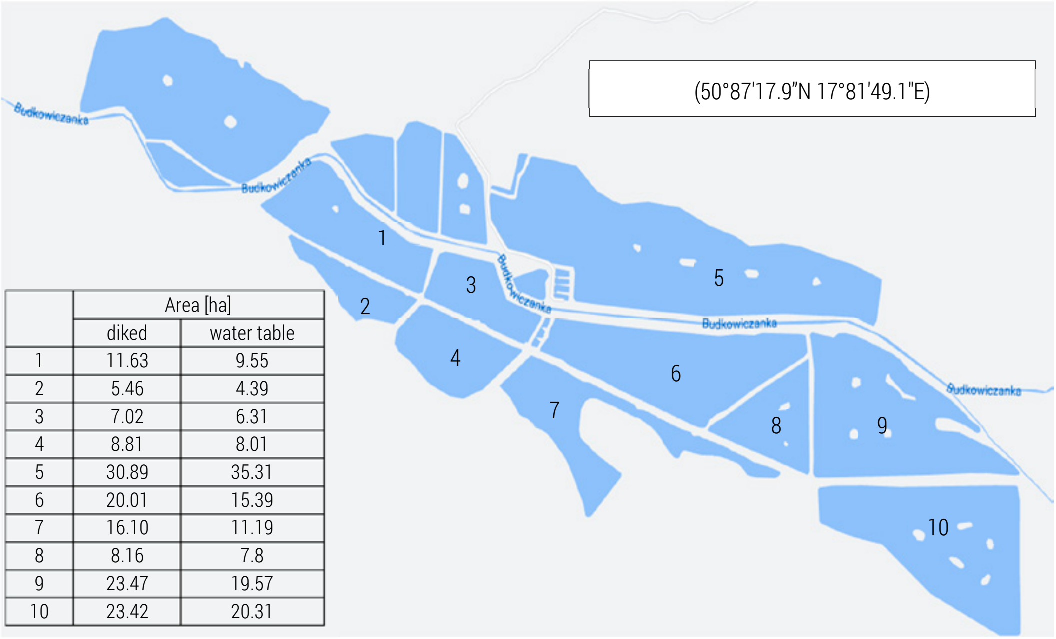
Data and Methods

Description of the studied object

The subject of the analysis is the production of a fishing farm: the production results achieved, the amount and type of expenditures incurred, taking into account the extent of the use of renewable and non-renewable environmental resources. The analysis includes the two production years, 2020 and 2021.

The farm was established in 1985; it is located in south-western Poland, in the Opole Voivodeship (50°87’17.9”N 17°81’49.1”E). In the vicinity of the farm, there is the Stobrawa Landscape Park. The proximity of the farm’s fishing ponds and the running production blend in with the landscape, enrich biodiversity and do not disturb the natural environment. The vicinity of the ponds is also a great place for hiking.

The most important and valuable assets of the farm are fish ponds with a diked area of 162.77 ha and a water surface area of 137.83 ha. The farm has a total of 10 ponds with an area of 5.46 ha to 38.89 ha with an average depth of 1.3 m (Figure 1).



	Area [ha]	
	diked	water table
1	11.63	9.55
2	5.46	4.39
3	7.02	6.31
4	8.81	8.01
5	30.89	35.31
6	20.01	15.39
7	16.10	11.19
8	8.16	7.8
9	23.47	19.57
10	23.42	20.31

Figure 1. Illustrative map of the location of fish ponds and their area

Source: authors' work based on Google Maps [04-08-2022]. The data on the area of the ponds come from the analysed farm.

The Budkowiczanka River, which is the longest left tributary of the Stobrawa River, flows through the central part of the pond area. The river supplies the ponds with water. The intake of surface water from the river is in accordance with the decision of the water permit and amounts to 10,833,960 m^3 per year. This environmental resource and the amount consumed make up the main share in the use of renewable natural resources in production. Other renewable resources included in the emergy analysis of fish production are: solar energy, wind, rainfall, and wild fish that appear in ponds with the water let in the ponds. Most ponds are filled with water each year in the spring (from March to April) and drained in the fall (from October to November) when fish for sale are harvested. The selected ponds intended for the so-called lagoon of winter-breeding (fingerlings materials), which are the basis for further production, remain flooded all the time. After being harvested, fish for sale are kept in fish warehouses until the Christmas period, when they are sold. Ponds no. 3, 6 and 8 – with a total diked area of 35.19 ha and water surface area of 29.50 ha – are intended for wintering stocking material.

In addition to the production ponds, the farm is equipped with machines, devices, means of transport and buildings necessary to run production. Equipment characterised by a high level of wear and tear and the needs of the farm aimed at the improvement of working conditions and efficiency, also having an impact on animal welfare, prompted owners to purchase new equipment and machines with the use of external support in the form of EU funds. At the end of 2020, the farm obtained funds from the Fish Operational Programme (FOP) in the amount of PLN 172,013.65 (about $ 44,120.77), which was 1/3 of the net value of the new equipment purchased. Equipping the farm with modern machinery and equipment should improve the conditions, safety and organisation of work (e.g. mowing dikes, feeding fodder, and transport). It may also affect the efficiency of the production process and translate into the production results achieved. Until the end of 2020, some of the farm work was done by hand, which consumed a lot of time for the employees involved in the production process.

The type and volume of production on the farm

The analysed facility is a large commercial farm which has specialised in the production of commercial fish – carp (*Cyprinus carpio)* from the very beginning of its activity. The production is of a low-intensive rearing character. For such farms, the scope of production ranges from 500 to 1500 kg/ha, the share of natural food in the ration is high, and depending on the fertility of the pond and the stocking density, may reach up to 50%. This level of production intensification currently covers the vast majority of Polish pond farms (Guziur, 2008; Lirski & Myszkowski, 2021a; Raftowicz & Le Gallic, 2020; Lasner et al., 2020). Currently, in fishing practice, low-intensity farming is recommended as the most profitable.

The production of fish for consumption on the farm in question is carried out in a two- or three-year cycle. The two-year cycle consists in producing heavy fingerlings (at least 60 g/pc.) in the first year, which is stocked in commercial ponds in the second year. In a three-year cycle, in the first year, light fingerlings with a unit weight of up to about 60 g are produced. After overwintering in the second year, the light fingerlings are used to produce two-year-old stocking material, called steplets, with a unit weight of 200-400 g, which is used in commercial ponds in the third production season.

The current final products of the farm are commercial fish ("tradeish"), such as carp grown from stocking material as well as pike (*Esox Lucius)* and tench (*Tinca tinca*) flowing in with water when the ponds are filled. Additionally, fingerlings and stocking material are produced, but mainly for the farm's own production needs. Carp is the main, so-called intended production of the farm. Tench and pike flow into the filled reservoirs "by the way", along with water feeding the ponds. Owners benefit from the mercy of the environment and the gift of nature, and these species that migrate ultimately increase production, increase diversity and affect the economic result of the farm.

Every year, nearly 100% of adult commercial fish production is sold. The farm obtains the largest part of its revenues from the sale of commercial fish. Its share in total sales was over 80% in both years. The total sale of stocking material and fingerlings in the years 2020–2021 accounted for 18–19% of the total sales of the farm's production. In 2020, the production volume was 1.80E+05 kg. According to the owners, the increase in main production by 6.50E+03 kg in 2021 (see Table 2) resulted, among others, from improving work related to equipment purchased under FOP.

Data for emergy calculations of a farm production

Information on the production was obtained from the records conducted on the farm, other documents (water abstraction permits) and, additionally, through direct discussions with the owners. Data included:

- production volume,
- sold production value,
- expenditure (purchase and own) and costs related to production: own and external human labour, fodder, young stocking material, consumption of fuel and spare parts, consumption of materials for repairs, lime consumption, fees and taxes, depreciation, and insurance.

Additionally, for the needs of emergy analysis of the conducted production, the use of renewable environmental resources taken into account, such as solar energy, precipitation supplying water to ponds, wind, surface water flowing from the Budkowiczanka river and other fish species supplying ponds with inflowing water.

Using available references data on other agricultural productions (plant and animal, extensive and intensive), the ELR of these productions was compared with the fish production analysed in the article. In addition, in order to show the real scale of the area involved in a given type of production (including feed production), the total necessary area per energy unit (GJ) of the final product was calculated for selected productions. Such an analysis also shows a much greater scale of environmental load in many different productions.

The energy value (GJ) of fish production was calculated using the tables of the composition and nutritional value of food (Kunachowicz et al., 2020).

Emergy analysis and emergy indicators

There are several approaches allowing to measure the impact of a given type of production on the environment, e.g. Cumulative Energy Intensity (CEI), Life Cycle Assessment (LCA) or Emergy Analysis (EMA) (Wang et al., 2020; Wardal et al., 2021; Flaten et al., 2019; Wilfart et al., 2013; Kim & Zhang, 2018). The method that allows to measure the relation of involvement of renewable and non-renewable resources in the production process is emergy analysis. Its application, along with the estimation of environmental loading ratios (e.g. EYR, ELR, REN) (NEAD, 2022; Haden, 2003), may allow for more optimal decision-making in the sphere of using resources available for production (Lomas et al., 2006; Sciubba & Ulgiati, 2005).

The emergy approach in the assessment of the use of the environment is based on the analysis of the use of the environment as a donor of available energy (exergy) (Wang et al., 2020; Brown & Ulgiati, 2004b) and the analysis of the path of thermodynamic transformations of energy: resources, products manufactured, services (Wang et al., 2020; Hau & Bakshi, 2004; Odum, 1996). Emergy measures the work done by both nature and people in the process of creating a product or service, and the starting point is the focus on the energy available in the environment (energy of the sun, wind, tides, etc.), which is the source and basis for the functioning of the biosphere and the creation of economic goods.

The natural environment is the provider of energy needed to produce goods and services. Accumulated in renewable and non-renewable resources, it constitutes energy available for use in the production process. From the point of view of conserving natural resources and sustainable development, it is important that the production in question uses a greater proportion of renewable resources.

The concept of emergy, introduced by Odum (1996) as the measure of the manufactured product (service) and its quality, expresses the energy of solar radiation used directly or indirectly in the production of a product or service. It is expressed in solar joules [seJ]. In EMA, solar energy has been assigned particular importance in the process of creating resources and goods. The vast majority of products and services are characterised by considerable complexity and the use of different materials, intermediate products and labour inputs. Monetary flows are also largely used. Therefore, the emergy account is often very complex, similar to the determination of cumulative energy or exergy consumption (Stanek, 2009).

The emergy of a given product (production process) or service can be expressed by the equation (1) (Sciubba & Ulgiati, 2005):

$$U = \sum_i P_i \times \tau_i, \qquad (1)$$

where: U – emergy, P_i – expresses a component used in production, expressed by its exergy in [J], mass [g] or monetary value, e.g. in [\$], τ_i – solar transformity of component P_i expressed in [seJ/J], [seJ/g], or [seJ/\$].

The exergy of most substances or various products can be precisely estimated. It concerns their mass and price as well. However, it is difficult to accurately determine the solar transformity. Often its values are inaccurate, which raises a number of controversies, e.g. in the work by Hu et al. (2012).

The emergy account also has a number of advantages. It makes it relatively easy to determine the emergy of financial outlays in production. Data on national monetary equivalents (P1) (NEAD, 2022) and the share of renewable sources of emergy in their value make it possible to divide the emergy of goods obtained from purchase into a renewable and non-renewable part. In our calculations, we use the value of the monetary equivalent (P1) derived from (NEAD, 2022) for 2015 (latest available value), which is 6.09E+12 seJ/$.

The emergy account brings the contribution of all inputs to a common reference quantity, which is solar energy. At the same time, it enables the separation of components into a renewable (or partially renewable) and non-renewable part. This allows for the determination of the share of renewable components in the production process and the total level of its renewal, as well as for determining its impact on the environment (environmental loading).

The emergy account also gives the opportunity to compare different types and techniques of production in terms of their impact on the environment. This is achieved by appropriately defined emergy indicators. The most important are ELR, EYR, REN. The Environmental Loading Ratio (ELR) is a measure of the environmental pressure of a given production. It expresses the use of environmental services by a system, indicating a load on the environment. It is the ratio of the total emergy of the non-renewable inputs to the emergy of the total renewable inputs. The lower the ratio, the lower the stress to the environment, and any production for which ELR>1 begins to load the environment. Emergy Yield Ratio (EYR) is an index measuring the ability of a system to use the available local resources. It shows the ratio of the output of a system to the external inputs from outside (purchased). The higher the ratio the higher is the relative contribution of the local sources of emergy to the system. In the productions where the streams of emergy of goods and services from purchase definitely dominate, EYR aims at the value of 1. The renewability (REN) indicator determines the ratio of emergy from renewable sources to the total emergy consumed in the production process. The higher the score, the greater the use of local renewable environmental resources in the production process (NEAD, 2022; Ciotola et al., 2011; Jankowiak & Miedziejko, 2009; Chen et al., 2006; Pérez-Soba et al., 2019; Su et al., 2020; Vassallo et al., 2007; Brown & Ulgiati, 2004a). An additional description of the indicators is presented in Table 2.

Often some resources used in production are partially renewable and sometimes difficult to estimate precisely. The share of renewal is described differently in the literature on the problem. The renewal of human labour can be an example. In the production analysed in this paper, labour and services are fully paid. Therefore, its renewal was assumed at the level determined by the monetary conversion factor (P1) (National Emergy Money Ratio) (NEAD, 2022).

Results and discussion

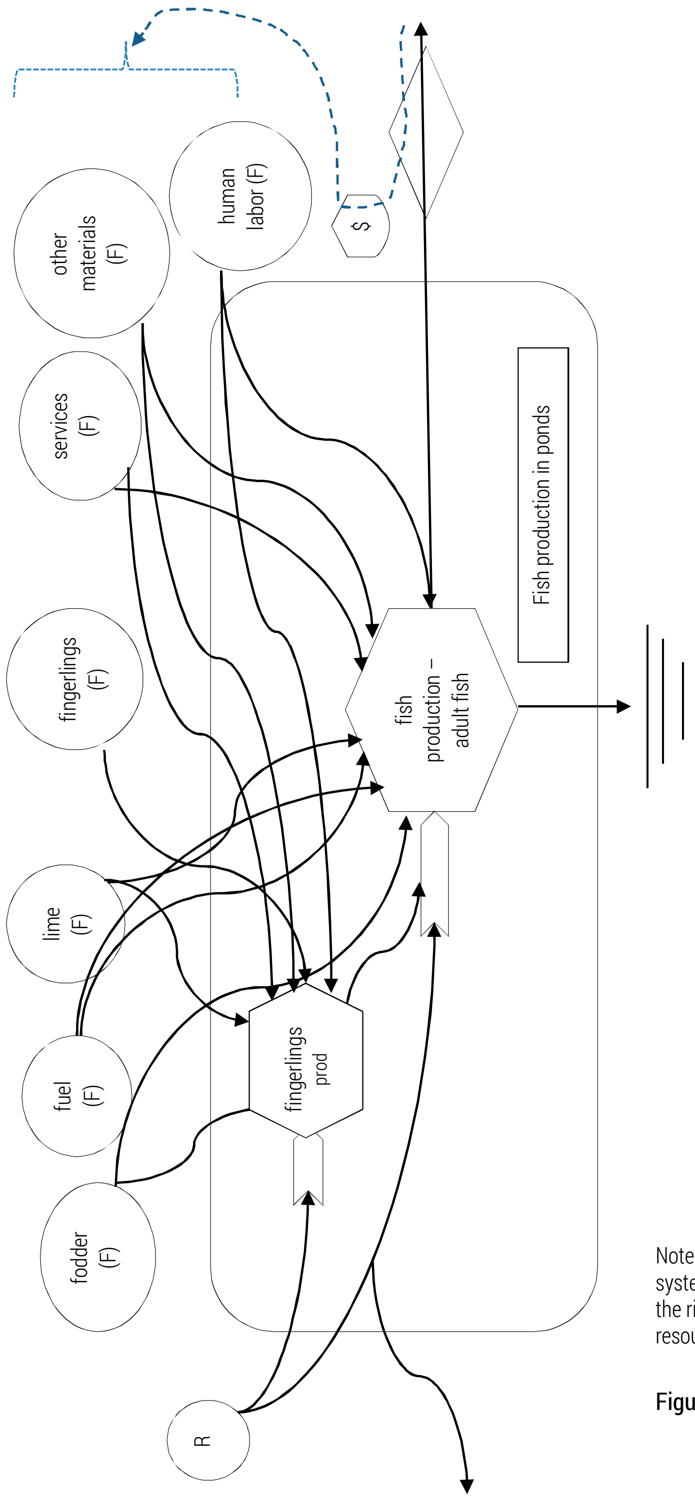
In accordance with the procedure of emergy account described by Sciubba and Ulgiati (2005), the production on the farm and the type of resources involved are presented in Figure 2. It is a diagram of an energy system that shows the relationship between components and processes within the system boundaries. The production system and its boundaries are determined by the area of the rearing ponds. The resources related to the production process, shown on Figure 2, include:

- renewable from natural sources (R): sun, rainfall, wind, surface water from the river feeding the ponds, wild fish flowing into the ponds,
- purchased (F): including the share of renewable (FR) and non-renewable (FN) parts, e.g. fodder, lime, services, fuel, purchased stocking material.

Further below, Tables 1 and 2 show exactly the types of expenditures and costs involved in the production of fish in 2020–2021, production results and the calculated selected emergy indicators. Table 1 summarises the share of renewable and non-renewable resources, both from beyond the system and from purchase, used in production (including their renewable and non-renewable part of resources). They are shown in energy and monetary terms. Financial costs of the conducted activity were also taken into account, including depreciation, taxes and fees, insurance.

Looking at the emergy share, the large area of rearing ponds and the area required for the manufacture of a production unit (ha/t or m^3/kg) means that the share of renewable sources is clearly greater (1.532E+18 seJ in 2020 and 1.534E+18 seJ in 2021) in relation to the share of non-renewable resources (1.163E+18 seJ and 1.269E+18 seJ). This makes the production environmentally beneficial, which is reflected in the emergy indicators discussed later.

Due to the fact that practically all the remaining resources necessary for the discussed fish farming come from purchase, their emergy shares are con-



Notes: R – renewable resources available to the system, e.g., wind, sun, rain, surface water from the river flowing into the ponds; F–purchased resources (FR and FN parts).

Figure 2. Emergy flow diagram of pond fish rearing

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veniently expressed by the use of a monetary conversion factor (P1). Among these components, the largest part is expenditure on fish fodder (45.22% in 2020 and 58.22% in 2021), labour and services (26.49% and 20.62%), depreciation of fixed assets (6.32% and 9.45%) and fuel (7.06% and 4.43%).

The amount of fodder given is a consequence of the scale and type of the farming process, as well as the experience of employees. It is difficult to reduce these costs in the analysed fish farm. In the literature dealing with the analysis of emergy fish farming, there are examples of a smaller scale of production compared to the discussed farm. In these examples, fish fodder is often a by-product or waste from other production, sometimes aggregated with ongoing fish farming. Such a situation is described in (Liu et al., 2018), where silkworm larvae are used as fodder. In small family farms, fish fodder also uses various leftover food and harvested grass (Zhang et al., 2012). On the farm, which is the basis for our analysis, the fish are fed with grain fodder, mainly wheat.

At the end of 2020, the farm received funds from the FOP, and a number of purchases of fixed assets were made, the purpose of which was to improve production activities. The effect of these measures was a reduction in spending on wages and services by over 20% and a reduction in fuel consumption by about 38% in 2021. The investments implemented also increased the value of depreciation, which influenced the overall financial result and total energy in 2021.

Emergy monetary conversion factors are often used alternately with conversion factors (solar transformities) based on energy (exergy), such as seJ/J or mass seJ/g units (Sun et al., 2021). Since financial conversion factors and a calculation based on the purchase prices of raw materials depend on fluctuations in market prices, the values of emergy of selected goods or services determined in this way may differ from the values based on energy conversion factors (Jankowiak & Miedziejko, 2009). Therefore, additionally, our analysis contains a recalculation (for the year 2021) of the streams of emergy for fodder and fuel. At that time, they accounted for over 62% of production costs. In the case of fodder, data from the study by Kuczuk (2016b) regarding the conditions of wheat cultivation were used for the calculations. We assumed that it is the basis of the fodder mixture for farmed fish. Solar transformity for conventional wheat production presented in Kuczuk (2016b) amounted to 2.96E+12 seJ/kg, and REN = 0.107. For organic wheat production 2.95E+12 seJ/kg, and REN = 0.249. The recalculations provided a similar emergy stream with different shares of the renewable and non-renewable parts. In the case of fuels, the cumulative exergy consumption of diesel oil in the amount of 47.4 MJ/kg after Stanek (2009) and the solar transformity of τ = 11.088E+4 seJ/J, adopted after Brandt-Williams (2002) were used. The emergy stream of 2.849 seJ was obtained, for which REN = 0 was assumed.

Table 1. Emergy analysis: local renewable and purchased (FR and FN) inputs

No	Input	Renewability share	Unit	Quantity, value per production cycle (2020)	Quantity, value per production cycle (2021)	UN seJ (2020)	UN seJ (2021)	τ	UR seJ (2020)	UR seJ (2021)	Refer. τ
1	Solar energy	1	J	4.74E+15	4.74E+15			1	4.74E+15	4.74E+15	Odum (1996)
2	Rain	1	m³	1.02E+06	1.02E+06			2.59E+04	1.31E+17	1.31E+17	Jankowiak and Miedziejko (2009)
3	Wind	1	J	5.35E+11	5.35E+11			2.50E+03	1.34E+15	1.34E+15	
4	Water in ponds from river tributaries	1	m³	5.35E+13	5.35E+13			2.59E+04	1.39E+18	1.39E+18	
5	Wild fingerlings	1	kg	1.80E+02	2.88E+02			8,44E+12	1.52E+15	2.36E+15	Own calculation
	Total renewable								1.525E+18	1.526E+18	
6	Purchased fingerlings	0.00616	$	1.86E+03	1.14E+03	1.12E+16	6.89E+15	6.09E+12	6.97E+13	4,27E+13	NEAD (2022)
7	Fodder	0.00616	$	8.69E+04	1.22E+05	5.26E+17	7.39E+17	6.09E+12	3.26E+15	4.58E+15	
	Fodder*	0.107					1.42E+18	2.86E+12		1.70E+17	Kuczuk (2016b)
	Fodder**	0.249					1.19E+18	2.85E+12		3.96E+17	
8	Calcium	0.00616	$	1.99E+03	1.05E+03	1.20E+16	6.34E+15	6.09E+12	7.46E+13	3.93E+13	NEAD (2022)
9	Fuel and grease	0.00616	$	1.36E+04	9.11E+03	8.21E+16	5.51E+16	6.09E+12	5.09E+14	3.42E+14	
	Fuel and grease***	0					2,85E+16	11.09E+04		0,00	Odum (1996) (corrected by 1,68)

No	Input	Renewability share	Unit	Quantity, value per production cycle (2020)	Quantity, value per production cycle (2021)	UN seJ (2020)	UN seJ (2021)	τ	UR seJ (2020)	UR seJ (2021)	Refer. τ
10	Spare parts	0.00616	$	6.99E+03	3.64E+03	4.23E+16	2.21E+16	6.09E+12	2.62E+14	1.37E+14	NEAD (2022)
11	Other materials	0.00616	$	1.07E+04	2.42E+03	6.50E+16	1.47E+16	6.09E+12	4.03E+14	9.10E+13	
12	Depreciation	0.00616	$	1.22E+04	1.98E+04	7.36E+16	1.20E+17	6.09E+12	4.56E+14	7.43E+14	
13	Taxes and fees	0.00616	$	3.20E+03	3.26E+03	1.94E+16	1.97E+16	6.09E+12	1.20E+14	1.22E+14	
14	Social insurance	0.00616	$	3.88E+03	3.93E+03	2.35E+16	2.38E+16	6.09E+12	1.46E+14	1.47E+14	
15	Purchased services	0.00616	$	2.70E+04	1.70E+04	1.64E+17	1.03E+17	6.09E+12	1.01E+15	6.36E+14	
16	Full-time human labour	0.00616	$	8.00E+03	8.69E+03	4.84E+16	5.26E+16	6.09E+12	3.00E+14	3.26E+14	
17	Full-time human labour	0.00616	$	1.59E+04	1.76E+04	9.63E+16	1.06E+17	6.09E+12	5.97E+14	6.60E+14	
	Total purchased					1.163E+18	1.269E+18		7.211E+15	7.866E+15	
	TOTAL					1.163E+18	1.269E+18		1.532E+18	1.534E+18	
	TOTAL: *and ***						1.923E+18			1.699E+18	
	TOTAL: **and***						1.697E+18			1.924E+18	

Notes: U – emergy used; R – renewable part; N – non-renewable part; τ – transformity; No. 15 – the purchased services, e.g. desludging, service, transport, mowing, contract work for the time of catching fish; No. 16 – Full-time human labour – farm work, physical work on dikes (mowing), feeding, taking care of the physical condition of machines and devices, manual work on catching fish, guarding; No. 17 – Full-time human labour – administration and physical work by the owner; *calculation from solar transformity for conventional fodder (wheat); **calculation from solar transformity for organic fodder (wheat); ***fuel calculation taking into account cumulative exergy intensity.

This methodology is more difficult to apply to labour and service outlays. In the case of the fish farm analysed in the study, they differ seasonally in terms of scope and duration. These are often specialised services, simple jobs also performed by family members. As the accounting documents do not reflect the exact man-hours, it is difficult to calculate their total number. Hence, in the case of work, the monetary emergy conversion factor was used. As a consequence, for the analysed fish farming, for the year 2021, also three values of selected emergy indicators (ELR, EYR and REN) were given as an alternative. The first of the values is the result of taking into account only the monetary conversion factor for fodder and fuel, and the second and third values – are the solar transformity of wheat production and the exergy consumption of the accumulated fuel. We assess the environmental sustainability of the analysed production on the basis of selected, generally used emergy indicators, listed in Table 2 (NEAD, 2022; Haden, 2003). Their estimated values have been supplemented with additional information that may be helpful for comparisons with other aquaculture systems as well as with other agricultural activities.

In 2021 in the analysed fish farming, the ELR = 0.827, EYR = 2.195, and REN = 54.7%. The value of ELR<1 proves the favourable relations between production and the natural environment. The consequence of the relatively high renewal of the analysed process is the value of EYR>2. The higher the EYR value, the higher the relative contribution of local emergy sources to the system. Therefore, this indicator shows the system's ability to use the available local resources. The values quoted above relate to calculations taking into account the monetary conversion factor.

On the other hand, when using the conversion of fodder and fuel emergy, taking into account the solar transformity of wheat grain and the cumulative exergy consumption of fuels, some differences in the values of the indicators (REN, ELR, EYR) calculated for 2021 can be noticed. Taking into account the feeding of fish with conventional fodder, the ELR value increased slightly to 1.132. On the other hand, the use of organic fodder lowered the ELR again to a value below 1, which is a result similar to the calculation taking into account the monetary conversion factor. In general, the results for both calculation methods are similar, and the differences that appear in the emergy account are acceptable. Especially if you take into account the various assumptions you make, comparing data and the values of indicators in 2020–2021, it can be seen that the completed investment (FOP) allowed reducing the share of labour and fuel-related emergy streams. However, a significant increase in depreciation made the value of the REN slightly lower in 2021. The ELR increased by 9% in 2021 but was still below 1. The changes in the prices of goods and services in those years also influenced the values of the indicators. The slight increase in production (by approx. 6 tonnes) was probably the result of various environmental impacts, but it was not a direct result of economic activities.

Table 2. Emergy measures and indicators of production on the analysed farm

Measures and indicators	Symbol/Formula/Unit	2020	2021
Total production	Y [kg]	1.80E+05	1.86E+05
Total production – energetic value	Y [GJ]	820.61	766.18
Sold production	Y[kg]	1.50E+05	1.53E+05
Value of production sold	Y[$]	5.46E+06	7.90E+06
Total emergy used	$U = U_R + U_N$ [seJ]	2.695E+18	2.803E+18
Total emergy used*			3.621E+18
Total emergy used**			3.621E+18
Share of renewable emergy (including U_{FR})	U_R [seJ]	1.532E+18	1.534E+18
Share of renewable emergy (including U_{FR})*			1.699E+18
Share of renewable emergy (including U_{FR})**			1.924E+18
Share of non-renewable emergy (including U_{FN})	U_N [seJ]	1.163E+18	1.269E+18
Share of non-renewable emergy (including U_{FN})*			1.923E+18
Share of non-renewable emergy (including U_{FN})**			1.697E+18
The purchased emergy (services and raw materials for production)	$U_F = U_{FR} + U_{FN}$ [seJ]	1,17E+18	1.277E+18
The purchased emergy (services and raw materials for production)*			2.096E+18
The purchased emergy (services and raw materials for production)**			2.096E+18
Renewability	$REN = (U_R/U) \cdot 100$ [%]	5.68E+01	5.47E+01
Renewability*			4.69E+01
Renewability**			5.31E+01
Environmental Loading Ratio	$ELR = U_N/U_R$	7.594E-01	8.276E-01
Environmental Loading Ratio*			1.132E+00
Environmental Loading Ratio**			8.819E-01
Emergy Yield Ratio	$EYR = U/U_F$	2.303E+00	2.195E+00
Emergy Yield Ratio*			1.728E+00
Emergy Yield Ratio**			1.728E+00
National Emergy Money Ratio (P1) – monetary conversion factor	P1 = U/GDP [seJ/$]	6.09E+12	6.09E+12
Total emergy used per 1 kcal of production	U/GJ [seJ/GJ]	3.28E+15	3.66E+15
Total emergy used per 1 kg of production	U/Y [seJ/kg]	1.501E+13	1.509E+13

Measures and indicators	Symbol/Formula/Unit	2020	2021
Renewable part of emergy (including U_{FR}) per 1 kcal of production	U_R/kcal [seJ/kcal]	7.832E+09	8.389E+09
Renewable part of emergy (including U_{FR}) per 1 kg of production	U_R/Y [seJ/kg]	8.533E+12	8.257E+12
Consumption of cereal fodder (wheat)	kg	476645.0	537160.0
Cereal consumption per 1 kg of fish production	kg	2.65	2.89
Fodder consumption per production area	kg/ha	2928.33	3300.12
Average wheat yield in Poland	kg/ha	4470.00	4570.00
Arable land area required for fish production on 1 ha	ha	0.66	0.72
Total production/area	Y/ha [kg/ha]	1103.09	1140.96

Notes: *calculation from solar transformity for conventional fodder (wheat) and fuel with cumulative exergy consumption taken into account; **calculation from solar transformity for organic fodder (wheat) and fuel, taking into account the cumulative exergy intensity.

Figure 3 shows the compared values of ELR indicators for various agricultural production: plant and animal, including aquaculture. It can be noticed that the extensive and medium-intensive fish farming system is characterised by the lowest ELR indicators presented. It is also beneficial to combine farming with other production that can be a source of fodder (Liu et al., 2018). The remaining productions shown have an ELR>1. In the case of plant production, the intensive use of mineral fertilisers and plant protection products affects (often significantly) the increase of the value of the indicator (Jankowiak & Miedziejko, 2009). The work of the machines used and fuel, treated as streams of non-renewable emergy, also play a significant role. Examples of organic production often show lower ELR ratios compared to conventional production. However, in organic production, higher labour inputs and lower production efficiency are more common. Figure 3 also shows the so-called theoretical production (light gray color) under domestic conditions (Poland). In that case all goods and services necessary for production are purchased. This would mean the lack of direct participation of renewable emergy streams in the production process. An example of such production can be very intensive, caged poultry farming.

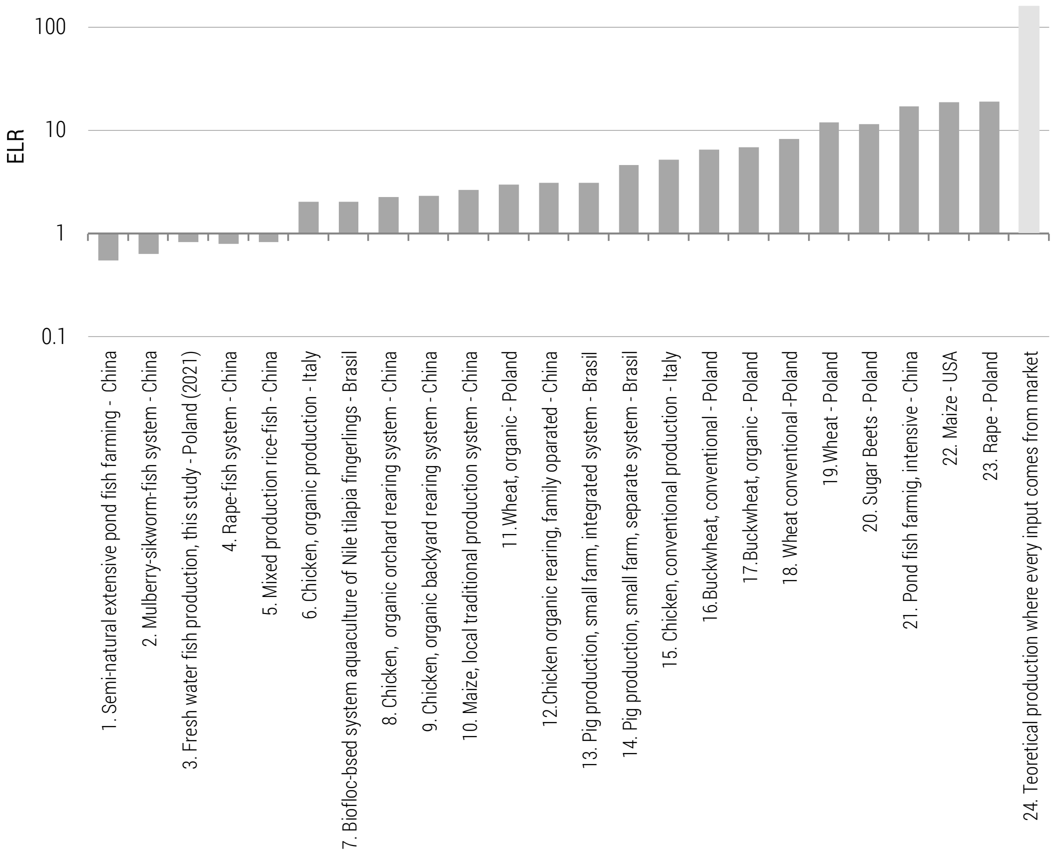

Figure 3. ELR values for typical agricultural and fishing productions

Source: authors' work based on Zhang et al. (2012; 2013); Liu et al. (2018); Su et al. (2020); Castellini et al. (2006); David et al. (2021); Kuczuk (2016a; 2016b); Hu et al. (2012); Cavalett et al. (2006); Jankowiak and Miedziejko (2009); Miedziejko & Jankowiak (2010a; 2010b); Martin et al. (2006).

Each agricultural production requires the involvement of a specific area of land. At a given scale of the production, the area is the greater, the more extensive or ecological production is. Land, especially in densely populated and urbanised countries, is expensive, which has an impact on potential plans for the development of agricultural production. Using data available in the literature, in Figures 4 and 5, there are estimated areas marked (dark gray colour – basic production area, the light gray colour of bars – additional area needed for fodder production) occupied by exemplary plant and animal production, including aquaculture, related to 100 GJ of final products. It can be seen that by far the smallest area is occupied by the plant production shown in the chart and intensive animal husbandry (poultry, pond fish farming), which often takes place with extremely limited livestock areas. Virtually in all of the larger-scale animal productions shown, the basic cost is fodder (most often cereals and cereal mixtures), which requires the involvement of additional space. Therefore, Figure 5 also presents the added approximate size of the areas necessary to meet the fodder needs (light gray part of the bars). Verified in such a way, Figure 4 highlights the possible total area used for a given type of livestock production. It is clearly visible that plant production requires a much smaller area per 100 GJ of consumer product produced. The production of animal products for consumption requires not only livestock buildings or ponds but also a forage area. This exemplifies how large the scale of animal production is.

Pig and fish farming requires relatively the largest total area for production. In the case of poultry, it depends on the type of system: organic or conventional. The organic way of poultry farming significantly increases the area necessary for keeping the livestock. In the pond farm analysed in the study, it was estimated that for the production of 100 GJ of fish product, approximately 14 ha of forage area is required. It should be noted that in the low-intensity pond fish farm analysed in this study, the fodder provided constitutes about 50% of the nutritional requirement of the fish. The rest is supplemented by organic matter in the ponds.

In the case of the analysed fish production, one should pay attention to other aspects. The areas with ponds are often facilities for various forms of recreation and generate biodiversity. However, the ecosystem services provided by this type of production are more difficult to measure than a typical production-focused service, which is the provision of a consumer product. (Turkowski, 2021; Mathé & Rey-Valette, 2015; Hill et al., 2021). Moreover, as noted by Silvano et al. (2005), “a landowner with incomplete knowledge of the ecosystem services provided may therefore give them less weight than direct market benefits”.

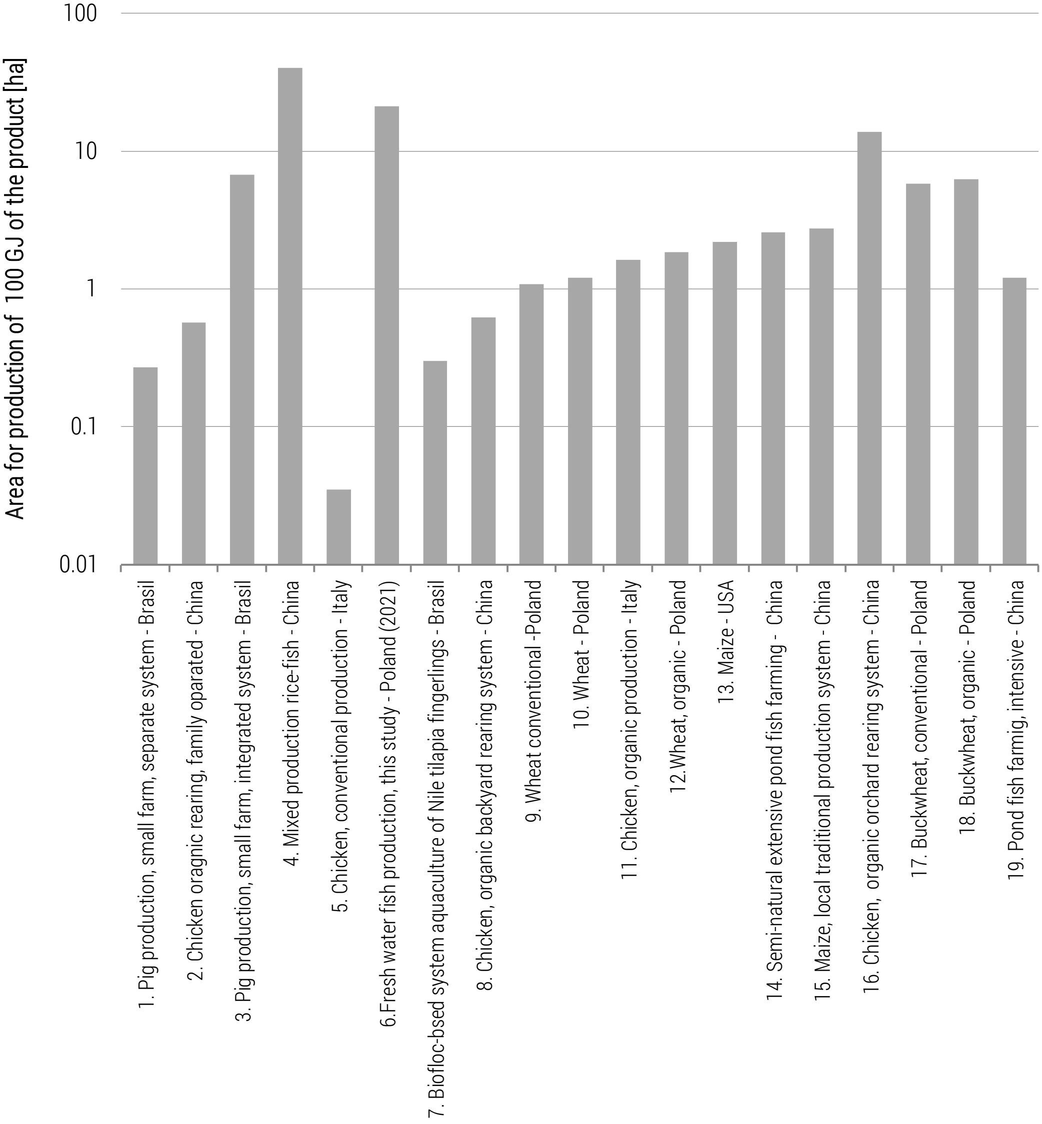

Figure 4. Main area for 100 GJ of the selected final products

Source: authors' work based on Cavalett et al. (2006); Hu et al. (2012); Su et al. (2020); Castellini et al. (2006); David et al. (2021); Zhang et al. (2012; 2013); Kuczuk (2016a; 2016b); Jankowiak & Miedziejko (2009); Martin et al. (2006).

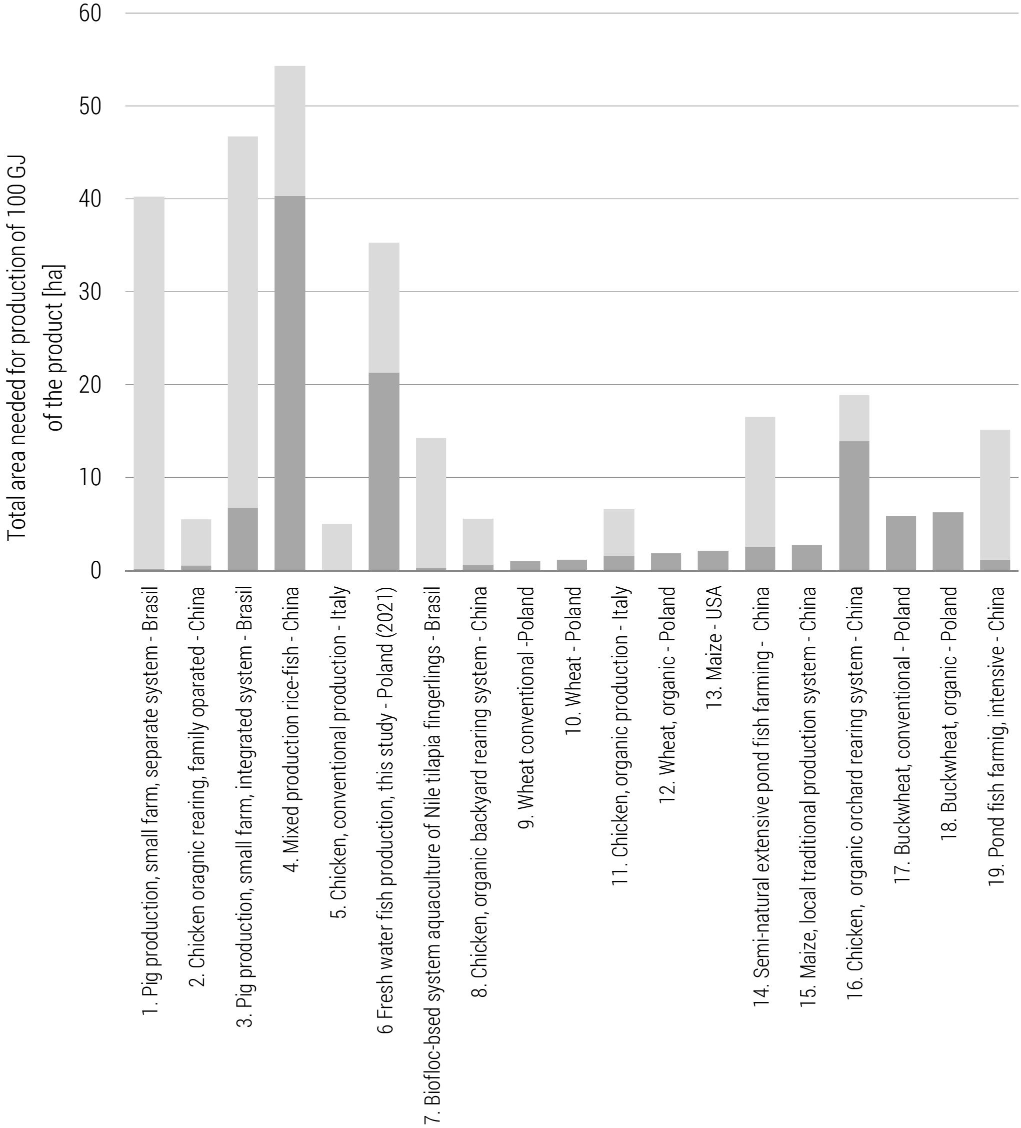

Figure 5. Area for production of 100 GJ of chosen final products, including additional area needed for fodder production purposes (light gray color)

Source: authors' work based on Cavalett et al. (2006); Hu et al. (2012); Su et al. (2020); Castellini et al. (2006); David et al. (2021); Zhang et al. (2012; 2013); Kuczuk (2016a; 2016b); Jankowiak & Miedziejko (2009); Martin et al. (2006).

Conclusions

The conducted research allows for the formulation of the following conclusions:

Fish farming is an environmentally beneficial production due to the high involvement of renewable resources. This is indicated by the ELR parameters obtained: 0.7594 in 2020 and 0.8276 in 2021, EYR: 2.301 in 2020 and 2.193 in 2021 and REN: 56.8% in 2020 and 54.7% in 2021. The ELR value of the analysed production was compared with its values for other, exemplary agricultural products. It can be seen that for the fish farms used as an example, the ELR is usually lower than 1. It is assumed that such activity does not negatively impact the environment.

Determination of emergy streams based on monetary conversion factor provides results vulnerable to fluctuations in the prices of goods and services. Therefore, for the production analysed in the study, additional alternative values of the above indicators were determined. The emergy of fodder and fuels was additionally determined by the use of solar transformity and renewability in wheat production (as a fodder base) and cumulative exergy consumption for fuel. The obtained results differ slightly from those obtained from monetary conversion factor. Despite these differences, they also show the environmental benefits of fish production.

The basic surfaces (without forage) necessary to produce 100 GJ of final products were compared. The smallest areas are related to intensive poultry production and intensive fish farming. Pig farming also requires a relatively small area. Extensive and ecological productions cover an area relatively larger, usually more than 1 ha per 100 GJ of production. The production of fish discussed in the paper requires about 21 ha per 100 GJ of fish produced.

If the area needed to secure fodder for the livestock is added to the areas dedicated to livestock production, the actual need for an area for livestock production can be noticed. The plant production itself requires much less space. Animal production, along with the fodder area, often requires the involvement of more than 10 ha per 100 GJ of the final product. The pond fish farm analysed in the study also requires over 30 ha/100 GJ of the product.

The practical significance of such an analysis is important information for producers, public administration and decision-makers in terms of undertaking rational production activities that take into account the problem of the use of environmental resources.

The contribution of the authors

Conceptualisation, A.K., J.Pospolita; methodology, A.K., J. Pospolita; data validation, A.K., J. Pospolita; literature review, A.K., J. Pieczonka; investigation, A.K., J. Pieczonka; data acquisition, J. Pieczonka; analysis and interpretation of data, A.K., J. Pospolita and J. Pieczonka.

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