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Analysis of Sustainability Performance of Different Farming Types Using Life Cycle Approach*

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Abstract:

Purpose: *The article aims to present and discuss the results of environmental and economic analysis of the activities of the main production types of farms in Poland.*
Approach/Methodology/Design: *The theoretical assumptions of the article concern environmental protection and the problem of shaping a low-carbon economy in the EU. In this context, it is presented how the production effects in the agricultural sector influence various types of environmental risks. The methodology of product life cycle analysis (LCA) and life cycle costing (LCC) were proposed for a comprehensive analysis of the impact of agricultural production on the environment and for the diagnosis of farm functioning according to sustainable development criteria.*
Findings: *Based on the analyses carried out, differences in the environmental impact of different types of agricultural activities were found. The negative influence of farms with animal production was higher than that of farms with field crops type. In farms with animal production, different environmental impact areas were found between dairy farming and pig farming. The dairy farming had the strongest environmental impact through production processes. The acidification category turned out to be an important environmental problem in farms with livestock production.*
Practical Implications: *The article brings a number of valuable information that can be a base material and a reference for further research, programs and studies for professionals - practitioners and scientists dealing with the environmental impact of agricultural production, its eco-efficiency, or more broadly ecology and sustainability.*
Originality/Value: *The results of the analysis and theoretical considerations contained in this article complement existing research in the field of agricultural sustainability.*

Keywords: *Farming types, sustainability, environmental impact, LCA, LCC.*
JEL classification: *Q01, Q51, Q56.*
Paper Type: *Research study.*

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1. Introduction

Agricultural activity, like other areas of economy, should be guided by the principle of sustainable development. In addition to production and economic objectives, the term also refers to ecological and social objectives. Agriculture, using the basic resources of the environment, which are its means of production, pursues its main goal of food production (Fleury *et al.*, 2010). Maintaining production resources for future generations can only be achieved through rational management. The intensification of agricultural production by simplifying the structure of agro-ecosystems and increasing the input of agricultural means has led to many threats to the agricultural environment in recent years (Godfray and Garnett, 2014; Tilman *et al.*, 2011). Economic policies that aim at shaping a low-carbon economy play a major role in environmental protection, both globally and in European countries. The understanding of the risks of ecosystem degradation is gradually introducing changes in production systems, combining production and social objectives. Currently, the basic research issue is to determine the future course of development of societies and economic conditions aimed at reducing the pressure exerted on ecosystems by civilization's development (Millennium ..., 2005).

In the agricultural sector, production effects are functionally related to the simultaneous occurrence of various types of environmental threats. Examples of such factors are greenhouse gas emissions (GHG), ammonia emissions (NH_3), pesticide damage, airborne dust pollution, eutrophication, or smog formation (Vermeulen *et al.*, 2012; Aneja *et al.*, 2009). In the EU's sustainable development strategy, minimizing the environmental impact of a product across the entire production chain is a key point of current environmental policy. The general idea is to create conditions for a gradual increase in the environmental quality of products and services from a life-cycle perspective (COM, 2012).

The challenge facing commercial farms today is to shift to sustainable land use and to manage production processes in an environmentally friendly way. The spread of ecological standards in agricultural production creates the need to consider environmental effects in agricultural activity. The most realistic option for farms, within the framework of the eco-development strategy, is to increase the efficiency of management through more economical use of inputs and reduction of emissions to the environment (Gadanakis *et al.*, 2015). The assessment of farms' activity in the aspect of sustainable development should be of a multi-criteria nature, taking into account the ecological and economic functioning of farms to the same extent (Baum and Bieńkowski, 2019; Day *et al.*, 2008; Andreoli and Tellarini, 2000).

In solving the presented problems (holistic approach), a Life Cycle Analysis (LCA) is useful (Guinée *et al.*, 2002, De Benedetto and Klemeš, 2009). Originally, the LCA method was developed for industry to consider many types of environmental effects of various production technologies. Currently, using this method, work is being developed to assess the environmental effects of agricultural production (Goglio *et al.,* 2018; Caffrey *et al.,* 2013).

The main objective of the research was to carry out environmental and economic analysis of the activity of farms in Poland (their main production types) using the methodology of product life cycle analysis (LCA) and cost accounting (LCC). An additional goal was to integrate environmental and economic assessment indicators in one model - to create a sustainability performance index of production processes.

2. Literature Review

Environmental policies in many countries around the world, including the EU, aim to gradually reduce the environmental footprint of production processes on farms and in the food industry (Omiloloa and Robele, 2017; COM 2011). This is achieved by the development of low-emission technologies for agricultural and agri-food production and their certification systems. Cross-sectional studies by Tukker (2006) published in the report on the environmental impact of products showed that the food and drink consumption accounts for 22-34% of the total life-cycle impacts in all their categories, except for eutrophication, in which the food system accounted for 60%. For many years, the EU has been supporting the process of market development based on integrated product policy (COM, 2003). Its aim is to spread the use of environmental management systems along the entire production chain. Currently, the standards for environmental quality and product impact on the environment are one of the most important issues focusing on product quality both in Europe and in the world.

Studies on the effects of climate change indicate that the main threat to economic development and the performance of the environment in the world are high levels of greenhouse gas (GHG) emissions from the growing global economy, the use of fossil fuel energy and intensive agricultural production. In response to the emerging threats of climate change, numerous programmes have been developed, both global and regional, to slow down the growth of GHG concentration (UNECE, 2010). The result of the increase in global GHG emissions is an increase in the average surface temperature of the Earth by more than 1°C compared to the pre-industrial period. Due to the growing climate threats, EU countries adopted in 2014 an action plan to reduce GHG emissions in sectors not covered by the European Emissions Trading Scheme and to reduce them by 30% by 2030 (COM, 2014).

There is a well-founded fear that maintaining current GHG emission levels over the long term may endanger the lives of most of humanity and even the entire civilization. Hence the measures taken to reduce GHG emissions also in agriculture. This means that the control of GHG emissions should be regarded as an important instrument to support environmental management of agricultural production to mitigate the effects of climate change. The importance of agriculture in the EU climate policy is illustrated by the fact that the European Commission has included emissions and removals of greenhouse gases from land use, land use change and forestry (LULUCF) activities in the new climate and energy policy framework until 2030 (Regulation (EU)..., 2018).

Animal products are relatively heavily loaded with GHG emissions. FAO estimates show that about 18% of global emissions of these gases come from animal production. The projection of a twofold increase in global livestock production by 2050, concentrated mainly in developing countries, stimulated by increased meat consumption, should be seen as a threat to sustainable development (Steinfeld *et al.* 2006, Hristov *et al.* 2013). Of the GHG in the agricultural production and processing of agricultural raw materials, the most important is the emission of three types of chemical compounds: carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Agriculture in Poland generated about 27.7 million tons of GHG (in kg CO_2 eq.) in 2011. Nearly 66% of GHG emissions were related to animal production (Bieńkowski *et al.*, 2016). The source of CO_2 emissions in agriculture is the combustion of fuels (diesel, gasoline) and the generation of heat energy (as a result of fuel oil, gas combustion) and the use of electricity. CH_4 emission occurs during the intestinal fermentation of ruminants and during storage of manure or slurry. On the other hand, significant amounts of N_2O are emitted due to the use of natural fertilizers and mineral nitrogen fertilizers in plant cultivation.

Agriculture is also the main source of ammonia emissions to the atmosphere, accounting for 80-95% of the total emissions of this gas. The total amount of ammonia emitted in Europe is estimated at about 4 million tons per year (EEA, 2019). The volume of this emission is mainly due to animal production (approx. 80% from agriculture) and in the second part to plant production. In plant cultivation, the emission of NH_3 occurs during application of both natural and mineral fertilizers in the field. Control of ammonia emissions plays an important role in international environmental policy. Since ammonia has been proven to be an important factor in soil acidification and eutrophication of European ecosystems, several international agreements on strategies to reduce emissions of this gas have been concluded. The breakthrough in this area was the Directive on national emission levels, adopted in 2001 by the European Union (Directive 2001/81/EC, 2001).

Another important document is Directive (EU) 2016/2284 on the reduction of national emissions of certain atmospheric pollutants (2016). According to this document, the reduction of NH_3 emissions in Poland after 2020 should be 1% per year compared to 2005. Achieving the required levels will require significant innovative undertakings. Precipitation of NH_3 from the atmosphere (previously emitted from ground sources) may contribute to negative effects in both soil and water environments. In sensitive ecosystems, the balance of minerals is disturbed because of soil acidification, which is the result of the nitrification of ammonium ions transferred from the atmosphere. Ammonia is also involved in the formation of fine particles (PM2.5) that travel to large, supra-regional areas. Air pollution by fine particles has a harmful effect on human health (Aneja *et al.*, 2009).

A comprehensive analysis of the environmental impact of agricultural production can be provided by the Life Cycle Analysis method - LCA (Goedkoop *et al.*, 2013). This method serves as an analytical tool to identify and evaluate the potential impacts of the production system or products on various environmental aspects. The method of environmental analysis of products and services, covers the entire life cycle from extraction of raw materials to waste management, i.e. "from cradle to grave." However, it is insufficient to recognize the functioning of farms according to general sustainability criteria, which are currently the dominant paradigm of economic strategy in many countries. A complementary method to the LCA of products is the life cycle costing (LCC) method (Swarr *et al.*, 2011). LCC is an important analytical tool for assessing the economic dimension of economic activity, which is identified with the first pillar of sustainable development. The LCA method, in turn, is an important research technique in assessing the impact of human activity on the environment, which is the second pillar of sustainable development. In the light of the requirements of resource efficiency and low carbon emission, the parallel application of these two methods provides a broader analytical basis for the analysis of sustainable development throughout the life cycle of products, not only during their operation or production.

3. Materials and Methods

3.1 Materials

The research was carried out on a group of 69 commodity farms from Wielkopolskie and Lubelskie voivodeships in Poland in the years 2017-2018. The analyzed farms belonged to 4 types of main agricultural activities: a) milk production, b) mixed livestock production (milk and pig), c) swine production, d) field crops. These are the dominant types of specialist farms in Poland, their share constitutes over 64% of the total number of farms (Sadowski *et al.*, 2013). The selection of the objects to be analyzed was based on the information available on farms in the Regional Agricultural Advisory Centers. The main criteria for selecting the farms were, apart from a specific type of production specialization, the economic size of the farm over 8 ESUs (European Size Unit) and the farm's consent to participate in the survey.

The primary data source was information from questionnaire interviews conducted by agricultural advisors. The scope of information obtained from the plant production department included production, distribution, including sales, annual and fodder plants and purchases of materials for production (e.g. fertilizers, plant protection products, seeds, repair materials). For each crop on the farm, a description of production technology has been drawn up (type of treatment and duration, machines and agricultural tractors used, human labour input, quantity and value of materials used, including diesel and lubricants). In order to achieve the assumed objectives, it was necessary to know the operating costs of tractors and machines. Their calculation includes maintenance costs and costs of use. The components of maintenance costs were depreciation costs and costs of insurance and technical tests as well as maintenance costs, which were a derivative of the machine price in the amount of 1% of its value. The costs of use were dependent on the costs of repairs and the costs of auxiliary materials. The value of repair costs (in PLN/h) was calculated based on the normative repair cost factor and the normative use of machines during their useful life.

The costs of fuels, lubricants and electricity were not included in the operating costs. They were a separate item in the calculation of product costs. Fuel costs were determined based on the declared fuel consumption of tractors and harvesters per one hour of a given type of action. Oil costs depended on fuel consumption. In the case of tractors, the value of lubricants represented 4% of the fuel used, and in the case of combine harvesters - 6%. The animal production department recorded data on purchases of compound feeds for various groups of animals, purchases of animals, medicines and veterinary services, consumption of drinking water by animals, electricity, sales of milk and livestock, production of natural fertilizers and their disposal. The rearing process in different categories of animals was characterized by data on nutrition (feed rations, type of feed and its nutritional value), workload, consumption of hygienic materials, use of machines and tractors and fuels. An integral part of the description of animal production was to collect information about the system of keeping animals in livestock buildings and ways of storing manure. The collection of information was supplemented by data on the type and costs of services and labour costs.

Table 1 presents data characterizing the types of agricultural farms in general. The type of field crops had the largest area of agricultural land and no permanent grassland. Cultivation of fodder crops in agricultural types with cattle rearing constituted a dozen or so percent share in the total acreage. The levels of mineral fertilization were the highest in the types of field crops and pig farming. The production distinctiveness and specialization of agricultural types were emphasized by the differences in the size and structure of animal herds. The preferred method of manure management was litter-based farmyard manure. The highest value of revenues from the sale of agricultural products was observed in the types of pigs and milk farming. In the type of field crops, plant production was the main source of income.

3.2 Methods

The life cycle analysis was carried out according to the methodology of Rebitzer *et al.* (2004). It includes four phases: 1) definition of the aim and scope of research, 2) analysis of a set of relevant inputs and outputs, 3) life cycle impact assessment, 4) life cycle interpretations (results and discussion).

Table 1. *Production characteristics of the analysed farming types of farms*

Specification	Dairying	Mixed livestock	Pig	Fields cropping
Area of agricultural land, of which	53.8	42.1	55.4	60.1
permaent grassland	11.4	7.6	1.1	
arable fodder	15.3	4.7		0.3
NPK (kg ha^{-1})	216.5	205.9	231.5	237,0
Total herd size (head), of which	75.9	114.85	374.4	1.1
cattle and calves	75.15	38.55		1.1
dairy cows	36.57	16.67		
pigs	0.75	76.3	374.4	
breeding sows	0.07	7.3	34.5	
Manure distribution between handling systems (%)				
slurry	7		12	
litter	93	100	88	100
Sales of animal products, of which:				
milk (kg FPCM ha^{-1})	5141.4	2405.1		
live weight cattle (kg LW ha^{-1})	214.3	150.4		4.4
live weight pigs (kg LW ha^{-1})	2.5	386.1	1452.2	
Revenues in total (PLN ha^{-1}), of which:	9528.7	6719.3	9583.9	4145.6
milk sale	6581.0	2669.7		
cattle sale	1384.6	995.7		30.2
pig sale	13.2	1741.6	7536.8	
cash crop sale	1549.9	1312.3	2047.1	4115.4

Note: *FPCM: fat- protein-corrected milk*
Source: *Own elaboration.*

The aim of the first phase is to define the boundaries of the system and its main functions and to define functional units for the analyzed production processes. Based on common functional units, it becomes possible to compare processes and management systems in terms of environmental load. The work in the second phase is aimed at developing a set of inputs and outputs, the so-called Inventory tables, with reference to functional units selected in the previous phase. In the third phase the results of the life cycle impact assessment are presented. This includes the following mandatory steps: selection of impact categories, category indicators, characterization, and classification models. Optional steps are normalization, grouping, weighing and analysis of data quality. All emission types, energy streams and raw materials used are assigned to specific impact categories.

The impact categories considered significant in the LCA of agricultural production processes included: climate change, abiotic resource depletion for minerals and fossil fuels, acidification, eutrophication, photooxidant smog formation, particulate matter formation (De Boer, 2003; Brentrup *et al.*, 2004). The indicators of the above-mentioned impact categories were, respectively: warming potential

(GWP100) expressed in kg carbon dioxide equivalents (kg CO_2 eq.), depletion of abiotic mineral resources (ADP mineral) expressed in kg antimony equivalents (kg Sb eq.), depletion of fossil fuel resources (ADP fossil fuel) in Megajoules equivalents (MJ eq.), acidification potential (AP) in kg sulfur dioxide equivalents (kg SO_2 eq.), eutrophication potential (EP) in kg phosphate equivalents (kg PO_4^{-} ^{3}eq.), photochemistry smog generation potential (POCP) in kg ethylene equivalents (kg C_2H_4 eq.), fine particle dust formation potential below 10 micrometers (PM2.5) in kg particulate matter with a diameter of 2.5 micrometers equivalents (kg PM2.5 eq.). At the characterization stage, the results of inventory table analyses are transformed into indicators for each impact category in relation to the functional unit. This is the sum of the products of emissions or resources used and "characteristic factors". The characterization factor represents the relative potential of an emission to cause a certain type of environmental effect.

Life cycle impact assessment was carried out based on CML methodology (Guinée *et al.,* 2002). Estimation of the amount of GHG and NH_3 emitted to the environment in plant and animal production was based on models and indicators from the literature. (Little et al. 2008, IPCC 2006). The emissions of phosphorus compounds were determined based on the SALCA-P model (Prahsun, 2006). The ILCD model was used to assess the impact of dust pollution (European ..., 2011). PM emissions of less than 2.5 and 10 micrometers in diameter were calculated for each crop and group of animals on the basis of types of cultivation practices and herd structure and animal housing system (EEA, 2013). The whole analysis was carried out in SimaPro® (Goedkoop *et al.,* 2016). For each unit process, specific material and emission streams were introduced, then combined into aggregated process models (referred to as a process tree) and converted into a functional unit. The process parameters included both data at the pre-production and production stages, i.e. directly on the farms. Secondary data relating to industrial unit processes were mostly derived from Ecoinvent® database (2018). The primary data of the model consisted of a set of parameters of all unit processes occurring on the farm (presented in the "material" subsection).

The results of the impact category were subjected to an interpretative analysis. The evaluation element was the reaction of the results of impact assessments to the modification of input data parameters in the set of inputs for individual types of farming. A sensitivity analysis was chosen as the basic procedure for estimating the effects of changes in some parameters. The essence of this analysis was to check the scale of the response of LCA results to the 20% range of changes in parameter values, up and down (in relation to their original values), consumption of mineral nitrogen fertilizers, fuels, and milk and livestock production.

The weighing and standardization procedure were used to present the environmental dimension of the functioning of different types of farms. This made it possible to convert category indicators into one common unit, thus indicating the aggregated dimension of the different impact categories. By weighing, the importance of the impact is determined, while normalization unifies the impact indicators by dividing them by a selected standard size, making them dimensionless. In the above analysis, the reference values were the overall sizes of the various impact categories in Europe (Sleeswijka *et al.* 2008). All impact categories were assigned the same weight factor value of 0.1428.

The calculations of the environmental performance were carried out according to the formula:

$$ENP = \sum_{i=1}^{m} NIC_i, \tag{1}$$

where: ENP = environmental performance of given farming type, per ha,
NIC_i = indicator of the impact category „i" after normalization and weighting,
m = number of impact categories,

$$NIC_i = \frac{AIC_i * WF_i}{IC_{Europe}}, \tag{2}$$

where: WF_i = weighting factor for impact category "i",
IC_{Europe} = reference value of the total impact category „i" determined for the whole of Europe,
AIC_i = indicator of the aggregated impact category „i", per ha:

$$AIC_i = \frac{\sum_{j=1}^{n} ICi_i}{A}, \tag{3}$$

where: IC_i = impact "i" for individual product of a given farming type,
n = number of products,
A = average area of given farming type in ha.

The final stage of the work was the LCC analysis and quantification of the level of general farming sustainability of various types of farms, combining indicators of the environmental performance and the results of the cost life cycle in one model. Thanks to the application of LCC analysis it was possible to assign costs to different products of the farm along their entire life cycle, which so far are most often included collectively in one cost account. This type of analysis also allows for the identification of the so-called leading cost factors along the product life cycle (Swarr *et al.*, 2011). Life cycle costs were established for products and production systems within the same limits as defined in the environmental life cycle analysis.

Evaluation of economic performance of the analyzed farming types was done by summing up the LCC of all products, based on the formula:

$$ECP = \frac{\sum_{j=1}^{n} LCC_j}{A}, \tag{4}$$

where: ECP = economic performance of the given farming type, PLN/ha,
LCC_j = life cycle cost of sold product “j” by a given farming type, PLN
n = number of sold products,
A = average area of a given farming type in ha.

Evaluation of the overall sustainability level was presented by the sustainability performance index which integrated both the environmental and economic indicators as follows:

$$SPI_{f=}\ \left(\left(ENW * \frac{ENP_f}{\sum_{f=1}^{o} ENP_f}\right) + \left(ECW * \frac{ECP_f}{\sum_{f=1}^{o} ECP_f}\right)\right) * 100, \qquad (5)$$

where: SPI_f = sustainability performance index of farming type “f”,
ENW, ECW = weighting factors for environmental and economic performances, respectively (ENW + ECW) = 1, here ENW and ECW were assumed to be equal to 0.5
ENP_f = indicator of environmental performance of farming type “f”,
ECP_f = indicator of economic performance of farming type “f”,
o = number of compared farming types,
100 = conversion to 100-point scale.

Both environmental and economic performances contributed equal share to the value of index because they were ascribed equal weights of 0.5. It means that one of these was treated preferentially.

4. Results

A comprehensive environmental assessment of four main farm types was obtained. The assessment is based on the aggregated values of the environmental impact indicators of the products related to the common UR surface area unit for all types (Table 2). Agricultural types specialized in animal production had higher rates of all analyzed impacts compared to the type of field crops. The final effect of the LCA analysis showed that the environmental load for the milk type is many times higher in the impact GWP100, AP, EP and POCP categories. The type of pig production was characterized by higher values of the ADP min and ADP fuel as well as PM2.5 indicators. Among the types with animal production, the least harmful effects, measured by AP, EP, ADP mineral, ADP fossil and PM2.5 indicators, represented the mixed animal type (consisting of dairy cattle and pigs).

The results presented in Figure 1A show the relative values of the indicators in percentages in relation to the results in a given impact category (considered 100%) achieved by the field crop type. Impact category indicators are presented against the background of stocking density of the analyzed farm types (Figure 1B).

***Table 2.** Impact category indicators for the analysed farming types per 1 ha AL.*

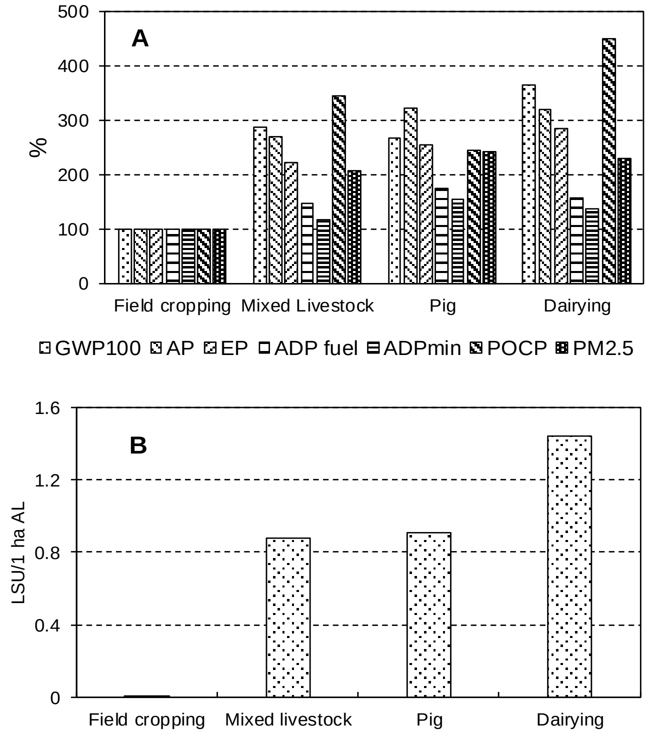
Impact category	Unit of indicator result	Dairying	Mixed livestock	Pig	Field cropping
Climate change (GWP100)	kg CO_2 eq.[1],	8525.2	6745.6	6275.5	2334.7
Acidification (AP)	kg SO_2 eq.[2],	107.5	90.3	107.8	33.5
Eutrophication (EP)	kg PO_4 eq.[3],	35.8	28.1	32.1	12.6
Abiotic resource depletion for fossil fuels (ADP fuel)	MJ[4]	24978.8	23449.9	27833,0	15845.1
Abiotic resource depletion for minerals (ADP min)	kg Sb eq.[5],	0.015	0.013	0.017	0.011
Photooxidant formation (POCP)	kg C_2H_4 eq.[6],	1.89	1.45	1.03	0.42
Particulate matter formation (PM)	kg PM2,5 eq.[7,]	6.77	6.09	7.16	2.94

***Note:** [1]carbon dioxide equivalents, [2]sulphur dioxide equivalents, [3]phosphate equivalents, [4]megajoules, [5]antimony equivalents, [6]ethylene equivalents, [7]particulate matter with a diameter of 2.5 micrometers equivalents.*
***Source:** Own elaboration.*

It can be observed that higher values of indicators in agricultural types with animal production are to a large extent related (conditioned) to stocking density. However, this is not a direct relationship type, because several categories of impact (AP, ADP fuel, ADP min and PM2.5) had the highest values of indicators with a lower stocking density, which was characterized by the pig type, compared to a high stocking density in the milk production type. There was a relatively small differentiation in the indicators of the ADP fuel and ADP min impact categories between agricultural types with livestock production, and especially between agricultural types with cattle, i.e. mixed livestock, and dairying.

At the same time, the mentioned impact categories were the most similar in terms of indicator levels to the type of field cultivation. The structure of the results of the sensitivity analyzes indicated the great importance of changes in the scale of milk and livestock production on the results of the impact category in agricultural types specialized in livestock production (Figure 2). The reaction of the impact category to a 20% change in the volume of animal production in the milk and mixed animal type ranged from 14.9-18.4% depending on the impact type. In the pig type, the results of the impact category were slightly less sensitive to changes in the production volume parameter (14.4-16.5%). In the type of field crop production, the nitrogen fertilization factor had a dominant influence on changes in the value of environmental impacts.

Figure 1. *Relative changes in impact assessment levels (A) versus differences in livestock density (B) for the analysed farming types. Environmental impacts of field cropping type of farming are used as the reference values.*

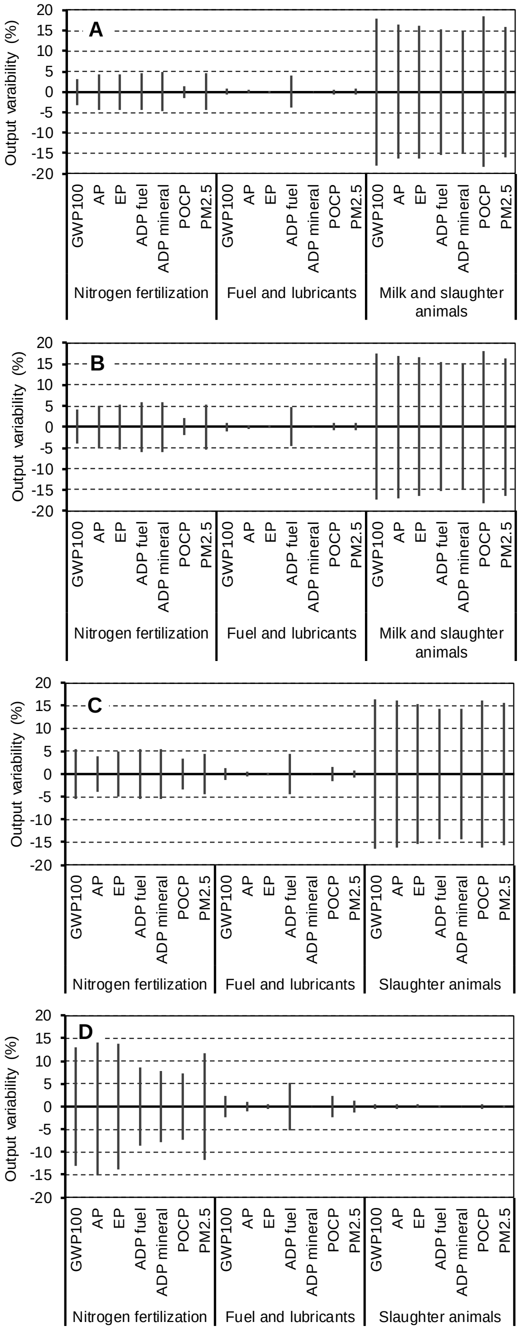


Source: *Own elaboration.*

It was observed that the distinguishing group with the greatest response to the 20% change in nitrogen fertilization were the following impact categories, respectively: AP, EP and GWP100. The effect of nitrogen fertilization on the variability of the analyzed impact categories was many times lower in animal types, compared to the type of field crops. The presence of two subsystems of plant and animal production, and thus also two centers of simultaneous impact on the environment, in these types of farming caused that the general sensitivity of impacts to changes occurring only in the plant section regarding the level of mineral nitrogen fertilization decreased.

Searching for practical ways to reduce the environmental impact of production systems requires the analysis of a wider set of factors, going beyond modifying the intensity of production inputs or reducing the scale of production. Figure 3 shows the results of the scenario assuming the replacement of the existing systems of manure management in the analyzed agricultural types with a system based fully on slurry. The introduction of the slurry system reduced the indicators of the three impact categories (GWP100, AP and EP) and was not relevant for the indicators concerning the use of mineral resources and fossil fuels in all types of agricultural holdings.

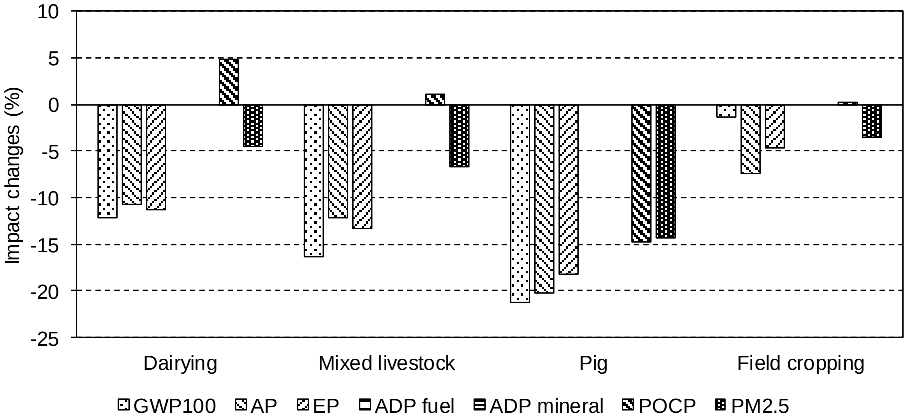
Figure 2. *Sensitivity analysis presenting the range of environmental impact assessment results on changes in the respective input data for the analysed farming types: (A) dairying, (B) mixed livestock, (C) pig, (D) field cropping.*



Source: *Own elaboration.*

Among the analyzed types of farming, the most favorable reaction to the introduction of slurry occurred in the pig type, because the reductions in the values of the impact category indicators in this type were the highest. It turned out that less reduction of environmental effects was caused by the scenario of switching to slurry in a milk type, compared to other animal types, even though this type had the highest stocking density. In the type of field crops, there were also positive changes in the environmental profile (after replacing the bedding system with slurry), although they were not so significant in comparison with other types, certainly due to the marginal size of animal production here. It should be noted that, in contrast to the pig type, the POCP category had a different, unfavorable direction of change, after the introduction of slurry in other types of agriculture.

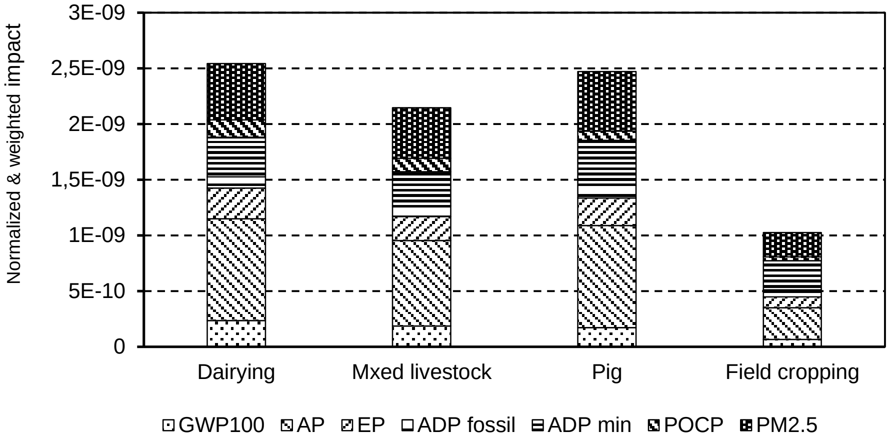
Figure 3. *Changes in the environmental impacts in the scenario where all animals are confined in "slurry systems" in the analysed farming types.*



Source: *Own elaboration.*

The overall environmental assessment, based on a single indicator that includes both the stages of weighing and normalization of the seven impact categories, is shown in Figure 4. The results of the environmental impact indicator determine the level of environmental impact in a numerical manner, without assigning specific metric units. The higher the environmental indicator value, the higher the potential impact on the environment. There is a clear difference in the value of this indicator between field crops and animal production types. The results of environmental indicators of milk and pig type were at a similar level. According to the impact category share structure, it appears that the main source of environmental impact is the acidification category, accounting for between 27.8 and 35.9% of the total environmental impact, depending on the agricultural type. The impact of acidification was more evident in agricultural types with animal production. Figure 4 also shows that the PM2.5 category is important in the overall environmental impact. It is worth noting that from the point of view of the percentage share of the impact category in the environmental indicator, GWP100 was relatively less important, compared to the other impact categories.

Figure 4. *Overall environmental impact indicators of different farming types per 1 ha*



Source: *Own elabotation.*

All processes related to the analyzed types of farming within the defined boundaries of systems and functional units were compared, apart from the physical dimension, also to costs, presenting the assessment of life cycle costs (Table 3). It shows that the lowest LCC value was achieved by field crop type. In terms of the amount of these costs, the dominant type was the pig type, which had almost 2.7 times higher costs than the field crop type. In the context of differences in life cycle costs, the mixed animal type and the dairying type were more favourable than the pig type. The structure of the share of cost groups shows that in animal types, the purchase of fodder was the most important factor influencing the size of costs. In the pig farming, they were the most important cost item, accounting for nearly 47% of total costs. The data indicate that the plant production system was an important center of cost concentration. This was evidenced by the amount of costs in the "other plant production costs group (including, inter alia, cultivation, harvest, seed and insurance costs) as well as the costs of fertilizers and mineral fertilization treatments.

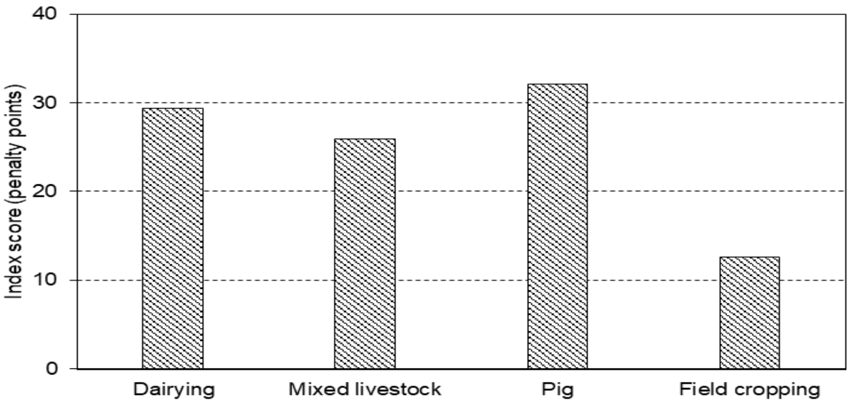
The values of sustainability performance index for the analyzed agricultural types are shown in Figure 5. The environmental and economic performance indicators contributed equally to the development of this index. The index score was the lowest for the field crop type. There was a visible difference in the results of this index between the field crop type and types with animal production (106 to 155%). The highest index value was obtained by the pig type (32.1). According to the adopted evaluation criteria, this means that the pig type operates at the lowest level of sustainability (it has the highest value of scoring points). The average level of sustainability of the production activities can be attributed to the mixed animal type.

Table 3. *Total life cycle costs (LCC) and groups of costs contributing to the results of LCC for the analysed farming types, in PLN per 1 ha*

Specification	Dairying	Mixed livestock	Pig	Field cropping
Fertilisation & mineral ferilizers	978.00	872.38	1092.33	940.91
Organic fertilization	381.63	153.90	318.05	59.55
Chemical crop protection & pesticides	380.59	289.88	478.45	497.38
Other costs of crop production	1462.80	1125.35	1563.7	1408.09
Purchase of amimal feed and feed additives	2123.10	2101.19	3630.68	7.80
dairy cattle	1848.94	1250.93		
fat cattle	268.57	255.46		7.80
pigs	5.59	594.80	3630.68	
Vet services and artificial insemination	202.92	183.52	163.87	0.17
dairy cattle	194.50	97.98		
fat cattle	8.08	6.75		0.17
pigs	0.34	78.79	163.87	
Other costs of animal production	863.33	1134.69	568.7	13.32

Source: *Own elaboration.*

Figure 5. *Overall sustainability performance for the analysed farming types*



Source: *Own elaboration.*

5. Discussion

The study uses the LCA and LCC method to analyze the sustainability of different types of agricultural production. Thanks to this approach, it was possible to link the production and economic sphere with the ecological aspects of production. Studying the relationship between production systems and the environment required a comprehensive analytical approach to the life cycle of production processes. Environmental impact assessments of various types of agriculture were conducted by analyzing the following criteria: climate change, acidification, eutrophication, mineral resource depletion, fossil fuel depletion, photochemical smog creation, particulate air pollution. The presented impact categories are considered suitable for use in the study of agricultural production systems, because they give a clear result of the environmental profile in the form of measurable impact category indicators, a well described calculation procedure, without creating interpretation difficulties (Guinée *et al.*, 2006).

The product differentiation within each system and the directions of production between the systems made it necessary to relate the results of environmental assessments to a common unit for the analysis of the modelled systems, i.e. 1 ha. In this way, a uniform basis for comparative analyses of various systems has been created. If such a solution is not adopted, the comparison of systems would be selective, limited only to single products, if they are produced in each type of farming. Such an analysis would then not be representative for the whole system due to the selectivity of products and production processes. Description of systems based on few parameters would be reductionist and would conflict with the very idea of sustainable management requiring a holistic approach (Finkbeiner *et al.*, 2010; Horrigan *et al.*, 2002).

Among the compared agricultural types, the functioning of the field crop type was the least harmful to the environment. The analyzed type of activity consisted of many commercial plant production processes. Ecological effects from the life cycle perspective, measured by the value of impact category indicators, were similar to the impact indicators in winter oilseed rape cultivation, per 1 ha of cultivation, on a large scale farm (Dąbrowicz *et al.*, 2017). In other studies of the carbon footprint of wheat cultivation, the GWP100 index ranged from d 2378 kg CO_2 eq. ha^{-1} for small farms up to 2759 kg CO_2 eq. ha^{-1} for large farms (Syp et al., 2015). The results of the research show that the size and structure of the environmental impact, averaged for plant-type crops, is similar to the ecological assessments of commercial crops, commonly grown, characterized by production intensity and of high economic importance.

The LCA analysis revealed many times greater environmental impact of agricultural types with pig production and milk production. As it is known from the literature, animal production is associated with several ecological problems related to GHG and ammonia emissions from animal feces (Hristov *et al.*, 2013; Steinfeld *et al.*, 2006). Animal rearing caused the largest jump in the values of indicators for the POCP, GWP100 and AP impact categories. Approximately 44% of the world's CH_4 emissions from animal production, a component of GHG gases, come from ruminant stomachs and the anaerobic biodegradation of their fertilizer (Hristov et al., 2013). This compound is also part of the set of substances responsible for the formation of photochemical smog (Fantin *et al.*, 2012; Castanheira *et al.*, 2010). The high acidification potential was certainly influenced by NH_3. It is one of the main substances introduced into the environment directly from animal production (Guerci *et al.,* 2013).

When analyzing changes in the indicators of the influence category, it is worth considering the intensity of the organization of livestock production, an important determinant of which is the stocking density. The increase in the value of most indicators, to some extent, remained in relation to the stocking density. This relationship could not be seen in the case of impact categories for the use of mineral resources and fossil fuels. Certainly, within the scope of these criteria, the use of raw materials at the stage of field production, including feed production, had a much greater impact on the environmental effects than directly in animal rearing. The lack of a direct relation between indicator values and stocking density indicates a more complex structure of the impact on the type and strength of the researched agricultural types on the environment. In the literature, the differences in environmental loads in animal production are explained by the different biological specificity of the digestion of ruminants and granivores, physiological differences between species, different feeding methods, nutritional requirements, efficiency, ration balance in relation to animal needs, manure management and many other factors (Hristov *et al.,* 2013; Montes *et al.,* 2013; Chianese *et al.,* 2009).

The analyzed agricultural types are characterized by a complex relational structure and many flows of raw materials and by-products between plant and animal production. The assessment of the environmental impact of agricultural production is therefore a result of the intensity of many processes and the level and effectiveness of production. The static description of agricultural production systems does not allow to learn the possible variation of results under the influence of changes in key input parameters. The solution to this limitation was to perform a sensitivity analysis. It was shown that environmental problems showed the greatest sensitivity in relation to assumptions about the change in the volume of milk and live cattle production in agricultural types with livestock production.

The obtained results indirectly show that the most effective way to alleviate environmental problems would be to reduce the stocking density of animals and, consequently, its livestock in the entire livestock sector. The currently recommended protection against excessive concentration of animal rearing is the reduction of nitrogen from mineral fertilizers in the farm, which corresponds to a maximum number of animals 1.8-2.0 LSU/ha UR (Kuś and Jończyk, 2008). It should be added that it is a stocking density between 30 and 60 % higher than the one found in the researched types of farms. In addition to changes in the number of herds, the actions to reduce harmful emissions in livestock production may include modification of the animal housing system (Montes *et al.,* 2013; Chianese *et al.,* 2009). The analysis of the scenario of changing the traditional animal housing system to a litter-less system shows that the environmental effects in many impact categories are clearly reduced, except for the POCP category. Among the ingredients included in this impact category is biogenic CH_4. When animal feces are collected in a liquid form, higher amounts are emitted due to the higher conversion rate of manure to methane than in the litter system (IPCC, 2006).

Based on the analysis of individual impact categories, it is difficult to synthetically demonstrate the environmental preferences of certain types of farming. The solution to this problem was to obtain a cumulative impact index, after summing up the indicators, previously subjected to the process of normalization and weighing. This also made it possible to determine what the relative importance of the individual categories in the overall environmental impact is (potential of impacts to be harmful to the environment). Regardless of the environmental effects, an important measure of sustainable development is limiting inputs on production and reducing its costs.

The framework for the general assessment of agricultural types from an economic perspective was LCC. Aggregate costs were a direct measure of the financial impact (Swarr *et al.,* 2011). The compilation of costs corresponded to the main phases of the LCA, except for the life cycle impact assessment phase. This phase is redundant because all input data is expressed in one monetary unit (Moreau and Weidema, 2015). Using the LCC method, it was shown that the purchase of feed in agricultural types with dairy cattle production was a much lower cost compared to the pig type. Due to the specificity of cattle feeding, own production of roughage was able to secure to a greater extent the nutritional needs of animals, despite a comparable stocking density (mixed type) and nearly 60% more animals (milk type).

The presented sustainability performance index coherently combined environmental and economic assessment from a life cycle perspective of the compared agricultural types. The constructional value of this index was to ensure that both assessment dimensions have an equal impact on the final value of the index. A different concept of combining LCA and LCC results is to show the relationship between them in a two-dimensional arrangement, on the vertical and horizontal axis of the graph (UNEP/SETAC, 2011; Baum and Bieńkowski, 2020).

The visualization of the economic and environmental position is not informative enough for an unambiguous interpretation of the sustainability, where the positioning of the compared agricultural type indicates significant differences in the results of its environmental and economic evaluation. There were differences between the types of agricultural production in the assessment of the degree of sustainability. The lowest level of sustainability was found in the pig type. This was primarily due to higher LCC costs and high environmental impact of emissions. In the traditional Feledyn-Szewczyk and Kopiński (2010) studies on the sustainability of farms in Poland by means of agro-ecological indicators, the problems of lack of sustainability were related to the use of mineral fertilization, high emission potential of nitrogen and phosphorus compounds and low profitability.

6. Conclusions

The type of field crops had the relatively smallest environmental impact compared to agricultural types with livestock production. Different areas of environmental impact appeared between the dairy type and the pig type. The dairy farming had the strongest environmental impact through production processes, in terms of climate change, eutrophication, photooxidant smog, while the pig farming in terms of mineral resource depletion, fossil fuel depletion and air pollution with particulate matter. In both types of farming, the acidification category has proved to be an equally important environmental problem. However, considering the differences in stocking density, this problem is much more serious in the pig type.

In all types of livestock production, changes in the way cattle are kept and manure management, would be fundamental to reducing environmental impact, i.e. transition from manure to slurry. The most measurable ecological benefits would occur in the type of pig production.

The overall environmental impact indicator covered all seven impact categories in cumulative form. The use of standardization, weighting and subsequent aggregation procedures made it possible to determine the impact of each category on the indicator level. In the environmental assessment of analyzed agricultural types using this indicator three impact categories were decisive: AP, ADP min and PM2.5. The highest potential impact on the environment had the milk and pig farming. The clearly outlined problem of acidification in connection with agricultural activity was deepened by recognizing the structure of the share of the main processes contributing to acidification. The results of the research suggest that the area of improvement of production processes to reduce their harmful impact on acidification should be primarily changes in the conditions of animal rearing, use of natural fertilizers and mineral nitrogen fertilizers.

Introducing economic issues into the LCA analysis, i.e. life cycle costs, is important from the point of view of economic efficiency of production processes in different types of farms, which are subject to complex ecological assessments. The issue of cost life cycle from the side of production processes is consistent with the modern strategy of seeking better conditions for economic development by reducing costs.

The presented sustainability analysis shows the possibility of a comprehensive assessment of the sustainability of different types of agriculture, considering all production processes and applying the life cycle method. This analysis requires a detailed knowledge of many data sets about individual processes and the structure of interrelationships between processes characterizing different production systems.

The developed procedure for assessing the sustainability of production processes was based on the mechanism of integrating the composite indicator of environmental performance with the life cycle costing. The strategy to promote better sustainability assessment, included in the index construction model, is to limit negative environmental impacts and reduce life cycle costs. The results of the analysis showed a different level of overall sustainability of production processes between the researched types of agriculture. The best sustainability of production processes was observed in the type of field crops, and the worst in the pig farming.

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