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Eco-Efficiency of Milk Production in Poland Using the Life Cycle Assessment Methodologies

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Abstract:

Purpose: *The main objective of the study was to perform an environmental and economic evaluation of milk production in the main production types pursued by Polish farms. The second objective was to analyze the eco-efficiency of milk production.*

Design/Methodology/Approach: *The study was conducted in a group of 24 farms, among which 15 farms focused on milk production and 9 farms conducted mixed livestock production (milk production and pig fattening). The data for the study concerned the period 2017-2018. Cattle was raised in a closed breeding cycle. Fat stocks was supplied by calves born on the farms. Life cycle assessment (LCA) at the stage from cradle-to-farm gate and LCC were used for environmental impact assessment. The functional unit was 1 kg raw milk corrected for fat and protein (FPCM). The studied environmental profile was applied to five categories of impacts: climate change (GWP100), acidification (AP), eutrophication (EP), abiotic resource depletion potential for fossil fuels (ADP fuel), abiotic resource depletion potential for minerals (ADP min) and photochemical ozone creation potential (POCP).*

Findings: *A farming type specializing in milk production showed a more favourable environmental profile compared to the mixed livestock type. The group of processes responsible for generating direct emissions in cattle raising (enteric fermentation and manure management) had the greatest impact on GWP100 and AP. Imported feed and home grown feed contributed much to ADP fuel, ADP min and EP. The higher eco-efficiency of milk production was recorded for the milk farming type. In the type of mixed livestock farming, both the reduction of total environmental impact and costs should be the primary factors in improving the eco-efficiency of milk production.*

Practical Implications: *Attention should be paid to the practical importance of eco-efficiency analysis, which, so far, has been an insufficiently used measurement tool for achieving targets in sustainable milk production.*

Originality/value: *In the article we propose the evaluation of eco-efficiency of milk production by considering both environmental and economic impacts from the life cycle perspective.*

Keywords: *Sustainability, eco-efficiency, environmental impact, life cycle assessment (LCA), life cycle costing (LCC), milk farming type, mixed livestock farming type.*

JEL classification: *Q01, Q51, Q56.*
Paper Type: *Research study.*

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1. Introduction

Reducing the environmental impact of farming is an essential aspect of sustainable agriculture (EEA, 2019; Scanes, 2018; Rohila *et al.*, 2017). In agriculture, cattle raising contributes most to the formation of various types of pollution. The main substances introduced directly into the environment during animal production are ammonia (NH_3), methane (CH_4), nitrous oxide (N_2O) and nitrogen oxides (NO_x) (Steinfeld *et al.*, 2006; Gerber *et al.*, 2013; Kaufmann, 2015). NH_3 is formed both during natural decomposition processes in nature and during human activity. In Poland 90% of the total NH_3 emission is generated from animal feces (Bieńkowski, 2010). In terms of animal species, cattle generates the highest NH_3 emissions in Poland (45.0%), followed by pigs (38.0%). These two species accounted for 83.0% of total NH_3 emissions from animal production. The main source of this compound is the decomposition of urine, feces and bedding. In areas where nitrogen (N) is scarce, its excess usually leads to serious changes in the ecosystem, resulting in the disappearance of numerous plant species which are displaced by nitrophilous plants. In turn, aquatic ecosystems undergo eutrophication (Stoate *et al.*, 2009; Aneja *et al.*, 2009). Considering all of these aspects preventing excessive NH_3 emissions should be treated as a priority (Guerci *et al.*, 2013). This is evidenced by the Directive of the European Parliament and the Council on the reduction of national emissions of certain atmospheric pollutants (Directive 2016/2284, 2016). In order to meet the objectives, it would be necessary to gradually reduce the current stock of farm animals or reduce the NH_3 emitted from animal production.

Greenhouse gas emissions (GHG) are also associated with cattle raising. In cattle production, the main source of GHG emissions is CH_4 from intestinal fermentation. In order to feed the cattle, fodder crops are grown, which are responsible for about 36% of GHG emissions (FAO, 2010). These crops are associated with a variety of pollutants. The main problem attributed to fodder crops is relatively high N fertilization in the form of mineral N fertilizers and organic fertilizers. N from fertilizers causes changes in the environment identical to ammonia emissions from animal production (Erisman, 2011). Phosphorus (P), also present in mineral and organic fertilizers, contributes to water eutrophication. In a sustainable management system, livestock manure is a good organic fertilizer necessary for the production of fodder, provided that the annual organic fertilizer application rate of 170 kg N per 1 ha of agricultural land (AL) is not exceeded (COM, 2018).

In Poland, the restructuring process in cattle production has aimed at concentrating the herds on larger dairy farms. For many years, we have been witnessing a decrease in the number of dairy cattle in Poland. In terms of the number of milk cows, Poland ranks third among 28 European Union (EU) countries (Eurostat, 2020). The decrease in the number of cows in Poland did not entail a decrease in milk supply, as it was compensated by an increase in cow milk yield. In 2010, the average cow milk yield in Poland was 4487 l/year. In 2019, it was about 5800 l/year (Statistics Poland, 2020). The changes aiming at herd concentration and quality improvement are in line with the trends reported in the EU. Due to its intensity, milk production is considered to be a potential environmental hazard. In the light of this risk, the search for technological and organizational solutions which could effectively reduce the emission of harmful substances into the environment has become a priority.

Over the last few decades, there has been a significant evolution in the approach to the use of the agricultural environment: from ignoring the problem of pollution and treating agriculture as an inexhaustible source of raw materials to recognizing the need to prevent pollution and reduce input consumption. This evolution was propelled by the pressure of awareness that environmental problems in the world may generally become a barrier to further economic development. In response to these problems, the focus was shifted to reducing the negative impacts of production processes in order to cut down on pollution and enable savings of minerals and fossil fuels (Godfray and Garnett, 2014; Tilman *et al.*, 2011; Vermeulen *et al.*, 2012).

More and more consumers have been looking for food produced in a more environmentally friendly way. This forced farmers to change the overall purpose of their production - from maximizing the animal yields obtained to efficient production, while taking into account effective environmental restrictions. It has also become important to take into account the ecological aspects of the products at the various stages of their entire life cycle (Notarnicola *et al.*, 2017). It is therefore necessary to estimate the magnitude of the impact of environmental factors and product costs for different animal production systems. One of the tools applied in the analysis of the environmental impact of products is life cycle assessment (LCA), which links the production sphere with the environment throughout the product life cycle (Gerber *et al.*, 2013; de Vries and de Boer, 2010). Thanks to this method, it is possible to characterize a large set of environmental impacts, e.g., climate warming potential (GWP100), acidification (AP), eutrophication (EP), mineral depletion (ADP min), fossil fuel depletion (ADP fuel), photochemical ozone creation potentials (POCP). This method can be successfully applied for comprehensive environmental impact assessment.

The second pillar of sustainable agriculture refers to the economic conditions of production, which are decisive for its efficiency (Gadanakis *et al.*, 2015). For each agricultural producer, an important goal is to achieve economic efficiency, defined as the ratio of obtained revenues to incurred expenditures. In dairy production, this efficiency depends on the production capacity of the cows, the cost of maintaining and feeding the cattle, the organization and course of the production process, as well as milk prices (Mc Geough *et al.*, 2012; Beukes *et al.*, 2010). The goal of effective milk production should be to minimize costs for a given production volume.

The achievement of this goal is also in line with the idea of sustainable development, which is based on the resource-efficient use of the environment and production inputs. The use of the LCA method in the ecological evaluation of manufacturing processes shows that reducing the environmental effects of production often goes hand in hand with cost reduction, indicating the possibility of improving production processes (Huppes and Ishikawa, 2009; Iribarren *et al.*, 2011).

The incorporation of LCA into the study of the environmental orientation of animal products has so far been most often reflected in the analysis of a single impact characterizing climate change. The complex system of functioning of livestock farms and their interaction with the industrial sphere in terms of obtaining means of production and emission to the environment requires an extended environmental description of products based on various ecological criteria. The characteristics of the product's environmental profile are insufficient if the sustainable production concept is to be taken into account. The cost factor of production is an important element of the sustainability.

However, cost assessment must be synchronized with the environmental life cycle assessment of the product, and must take place within the same limits of production systems. The life cycle costing (LCC) method is particularly useful in solving this problem (Swarr *et al.*, 2011). LCC is considered to be an essential analytical tool in assessing the economic dimension of production processes. LCC analysis, combined with an LCA, provides an opportunity to examine eco-efficiency, which is considered an important measure for assessing progress in sustainable production. These methods provide powerful means to assess the economic and environmental performance of production activities by recognizing the need to minimize the use of production inputs and reduce emissions to the environment (Heijungs *et al.*, 2010). Contemporary trends in research of sustainable production postulate also the inclusion of the social factor in the evaluation of production processes and products (Jørgensen *et al.*, 2013).

The primary objective of the study was to perform the environmental and economic evaluation of milk production in the main production types of Polish farms, applying the methodology of LCA and LCC. An additional goal was to apply the calculated environmental and economic impacts to the analysis of the eco-efficiency of milk production.

2. Materials and Methods

2.1 Research Material

The analyzed farms included farms which specialized in milk production and farms where the branch of milk production was a significant source of income in their overall income structure. The latter belonged to the mixed livestock type (milk and pig production), as they reported different sources of income. Out of the four studied farming types encompassing a total of 69 farms: field cropping, pigs, mixed livestock and milk farming, cattle was kept only in the two latter groups. The analysis was based on 24 farms, 15 of which were of the milk farming type and 9 of which were of the mixed livestock type. These farms were from the Wielkopolska and Lubelskie regions.

The average economic size of milk farms expressed in terms of standard output was about 139 thousand Euros, while in the average economic size of mixed production farms was about 82 thousand Euros. The data concerned the years 2017-2018. The primary data source was information from questionnaire interviews conducted by agricultural advisors. The interview was comprehensive and covered the scope of production and economic data, including plant, milk and livestock sales. Detailed purchase records have been prepared for fodder and cash crops, and their distribution among individual species.

The data concerned mineral fertilizers, crop protection products, seed material, repair materials and purchase of services. The description of fodder growing technology processes also required data on the type of agricultural machinery, tractors and their use, human labour input, tractor material consumption, diesel and lubricants. The register of information pertaining to cattle production included data on the production and purchases of roughage, compound feeds for different age groups of animals, purchases of medicines and veterinary services, electricity consumption, labour input, data on the nutritional needs of different groups of cattle, use of machinery in feeding and fuels.

Data concerning the system of keeping animals in livestock buildings and ways of storing manure was also obtained. The data set was supplemented with information on the consumption of silage foil, disinfectants and potable water. In a situation where it was not possible to determine the consumption of materials or fodder for a given group of animals in a direct way, on the basis of their intended use, the resources and fodder used were distributed among the groups of animals according to quantitative proportions estimated by the farmers. The analysis of economic issues also assumed the necessity to collect information on prices of all production means used in many unit processes. Therefore, the data obtained also concerned the prices of all inputs. In the dairy cattle feeding, nutrition primarily relied on own fodder. The valuation of this fodder was conducted on the basis of its production costs.

Production and economic characteristics of farming types with milk production are given in Table 1. The dairy farms had, on average, a larger area of agricultural land (AL). A greater areal percentage was occupied by roughage crops and permanent grassland, compared to the type of mixed livestock farming. In the milk farming type, the high cattle stocking and nearly 2.2 times larger number of cows resulted in an increased demand for fodder, which required more fodder area, compared to mixed farming. Due to the high degree of specialization of the milk farming, milk production was the main source of revenue, as opposed to the mixed livestock type, where milk sales did not generate most of the revenue.

Table 1. *Production characteristics of the analyzed farming types with milking cows*

Specification	Farming types	
	Milk	Mixed livestock
Area of agricultural land (ha)	53.84	42.13
Permanent grassland (%)	21.2	18.0
Arable fodder (%)	28.4	11.2
Livestock density (LU ha^{-1})	1.4	0.9
Livestock structure:		
Dairy cattle and beef cattle (%)	99.7	74.5
Pigs (%)	0.3	25.5
Cow numbers	36.6	16.7
Manure distribution between handling systems (%):		
Slurry	6.7	0.0
Litter	93.3	100.0
Milk sale (kg FPCM)	276813.9	101327.0
Cattle sale (kg LW)	11539.4	6336.6
Revenues in total (thousand PLN):	499.9	261.3
Revenues of milk (%)	74.6	43.4
Revenues of live cattle sale (%)	14.9	14.4

Note: *LU: livestock unit; FPCM: fat and protein corrected milk; LW: live weight.*
Source: *Own elaboration.*

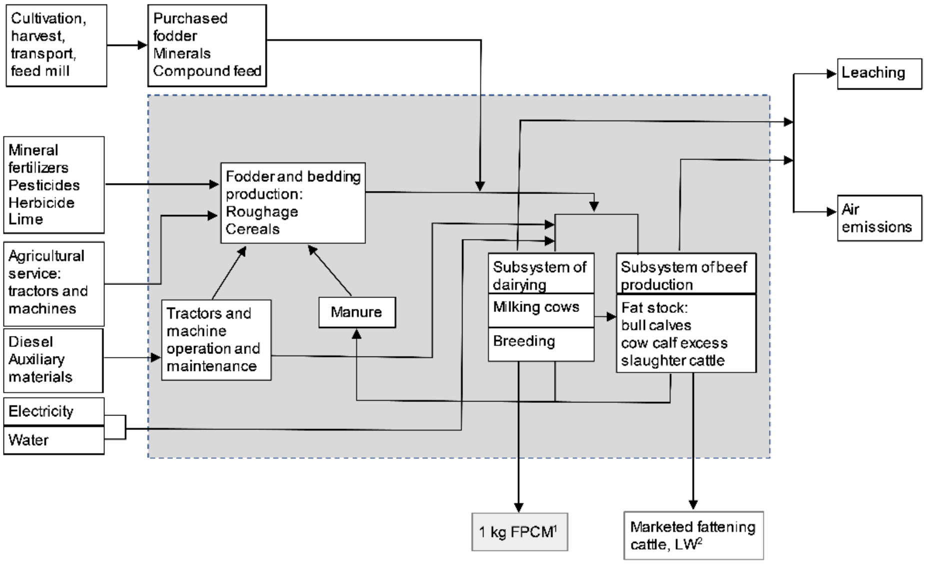
2.2. Methods

The methodological part of the study in the area of environmental impact of milk production was in accordance with the accepted principles of life cycle assessment (LCA) (Cucurachi *et al.*, 2019; Rebitzer *et al.*, 2004). The LCA is four-step procedure executed in a sequential manner. The first step is to define the purpose and scope of the study. The primary purpose of the study was defined earlier, in the first section. The reason for conducting this type of analysis was a relatively poor recognition of environmental aspects in milk production in the local conditions of Poland and in various types of farming. A new element consisted in the evaluation of financial costs, in the form of life cycle costing (LCC) induced during the life cycle of the milk produced. This way, LCA was combined with LCC assessment. The temporal and geographic scope of the analysis is presented in the 'materials' section.

The description of individual processes of milk production should be construed as representative of the type of technology and intensity of milk production in two types of farming, i.e. of the milk and the mixed livestock. The collection of parameters of milk production technology corresponded to the average actual state in the analyzed facilities. The life cycle assessment of milk production included stages from 'cradle-to-farm-gate'. Processes directly related to the production activity of the farm (breeding of basic dairy cattle and cattle for fattening from the basic cow herd, cultivation of plants used for feeding cattle, production of silage, animal nutrition, manure management and storage) have been included within the limits of the system. The system also includes intermediate processes in the industry, related to the production of raw materials and products used as inputs in the production activity of the farm (Figure 1). In a detailed characteristic, these were: production and transport of compound feeds, roughage purchased from farms, pesticides, mineral fertilizers and silage foil, detergents, fuels and repair materials. The scope of the system also included the maintenance and use of agricultural machinery. In order to interpret the results, a number of individual processes have been combined into process groups, distinguishing five main groups: enteric fermentation, manure management, feed import, home grown feeds, bedding, farm operations and others. The group of farm operations includes electricity, machine use and fuel and lubricant consumption in cattle raising. The group of others included: silage foil, disinfectants and insemination and veterinary services. The basic functional unit (FU) was 1 kg of raw milk corrected for fat and protein content (FPCM), respectively 4 and 3.3%. FPCM was calculated using the following equation based on the percentage of fat and protein in milk (IDF, 2010).

$$FPCM\ (kg) = Milk\ production\ (kg) \times (0.1226 \times fat\% + 0.776 \times protein\% + 0.2534) \tag{1}$$

Figure 1. *System boundaries and functional unit of the milk in the investigated faming types. Lines represent product flows and emissions, dashed lines represent range of processes within milk production system*



Note: *[1]Fat and protein corrected milk, [2]live weight .*
Source: *Own elaboration.*

Physical allocation was used as the basis for distribution of the greenhouse gases (GHG) emission streams between co-products that were exported outside the system, based on the option of the second recommendation of ISO 14044 (ISO, 2006). The milk production system is multifunctional. Production processes simultaneously yield two products: milk and livestock (cull cows and fattened cattle), therefore environmental interventions and inputs were allocated in proportion to the physiological feed requirements attributed to milk and physiological livestock production according to the following equation (IDF, 2010):

$$AF = 1 - 5.7717 \times R \qquad (2)$$

where, AF = allocation factor, $R = Mmeat/Mmilk$, $Mmeat$ = sum of live weight (in kg) of all animals sold, $Mmilk$ = sum of milk sold (in kg) corrected to 4% fat and 3.3% protein, according to equation 1.

The second step of the LCA analysis was to draw up a model of the milk production system structure. It consisted of dozens of unit processes connected by material-energy streams, creating a so-called hierarchical process tree. Input and output data was entered for each individual process. Then the unit process data was aggregated and referred to the functional unit. The next step of this analysis was to create an inventory table to compare the quantitative consumption of resources and means of production and emissions released to the environment due to the functioning of the various processes within the system.

The environmental impact assessment of milk production included stages of milk life cycle from the cradle to the gate, i.e. until 1 kg of raw milk is obtained. This meant that upstream processes were included in the life cycle stages, which covered the production of material inputs and energy used in milk production. Data for these processes was obtained from available literature and the Ecoinvent 3.0® and Agribalyse® 1.5 databases (Audsley *et al.*, 2009; Ecoinvent, 2018; Koch *et al.*, 2015). The whole analysis was carried out in SimaPro® (Goedkoop *et al.*, 2016). Foreground processes included technological operations of fodder and cereal crop cultivation, raising replacement cattle and cattle for fattening, storage and export of organic fertilizer to the fields. Calculations of GHG, NO_x and NH_3 emissions from the use of mineral fertilizers on fields were carried out according to the methodology described by the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2019). Phosphorus emissions to surface waters and river runoffs were determined using the Salsa-P model (Prasuhn, 2006).

The IPCC model (IPCC, 2019) was used to calculate the amount of N excretion with feces. Estimation of gaseous emissions to the environment during the cattle rearing process was carried out on the basis of the model and indicators specified by European Environment Agency (EEA) (EEA, 2013). For the estimation of direct emissions from the combustion of fuels by tractors and combines, the emission factors for the respective fuel type have been used in relation to their energy value (EEA, 2013).

The third stage, called life cycle impact assessment (LCIA), serves to link the LCI data in terms of cause and effect with environmental consequences. The calculation procedure was carried out on the basis of characterization models and parameters given in the CML methodology (Center of Environmental Science, Leiden University, the Netherlands) (Guinée *et al.*, 2002). In this stage, the mandatory elements consist in the choice of impact categories, category indicators and characterization coefficients. Using an appropriate characterization model, the LCI results were converted into the results of the impact category indicators, so that the inventory table data can be multiplied by characterization parameters specific to each substance classified in a given impact category. The characterization parameter determines the environmental impact potential of the substance. The indicators units for the analyzed categories of impact, such as: GWP100, AP, EP, POCP, ADP min, ADP fuel were, respectively: kg CO_2 eq., kg SO_2 eq., kg PO_4 eq., kg of C_2H_4 eq., kg Sb eq. and MJ eq.

After the presentation of the environmental profile, the next stage was to interpret the impact category by referring the indicator values to reference values, for Europe (Sleeswijk *et al.*, 2008). Thanks to the standardization of the index values, they were converted into a common unit. Next, the standardized results of the indicators were subjected to a weighting procedure consisting in assigning a degree of importance to a particular category of influence, i.e. weighting factors and multiplying the indicator results by them. For all impact categories, the weighting factors had the same value of 0.1667. It was assumed that due to the lack of internationally recognized coefficients, the components of the environmental profile would not have any preferences in terms of modeled problems. Ultimately, the weighed indicator values were added to one total environmental indicator.

Parallel to the LCA, LCC analysis was realized. LCA does not include the account of costs associated with production systems. When examining a production system from the point of view of eco-efficiency (one of the important criteria of sustainable development), it is necessary to learn the relationship between specific environmental effects and LCC of the analyzed processes. In a general sense, LCC is the sum of internal costs incurred during the product life cycle. It consisted of the following direct costs: production means (mineral fertilizers, seed material, crop protection products), labour costs, energy costs, fuel and lubricant costs, costs of purchase of fodder and disinfectants, and service costs. LCC also included maintenance and operating costs (Muzalewski, 2010). Costs are expressed in the Polish currency, PLN (according to the PLN - Euro exchange rate applicable to the research period: 1 PLN = 4.03 Euro).

Eco-efficiency was derived in two ways. The first way was to calculate the ratio of LCC to total environmental indicator. It was defined as the cost of the environmental effect. The second way was to analyze the eco-efficiency in graphical form in an XY diagram (Michelsen and Fet, 2010). Standardized values for the total environmental indicator were marked on the Y axis and LCC values on the X axis. Objects located closer to the point of intersection of the coordinate system are generally characterized by higher eco-efficiency. A single indicator has no diagnostic value, which could be potentially used to interpret low or high eco-efficiency, or to identify the mutual location of the examined objects in relation to the X and Y axes.

3. Results

Table 2 presents inventory data for the milk production process carried out in two types of farms. It includes all physical quantities of input flows for unit processes found within the structure of the analyzed systems. The data presented has been aggregated and related to the functional unit, i.e. 1 kg FPCM. Due to the complexity of the systems, the collection of data in an aggregate form was conditioned by the prior creation of the unit process tree related to material and energy flows. The overall consumption of imported fodder and feed additives per 1 kg FPCM was lower in the farming type specializing in milk production. In the milk farming, lower amount of imported fodder was compensated to a greater extent with the use of home grown fodder, as opposed to the mixed livestock type. It was also characterized by higher efficiency in the use of other inputs, including human labour.

The values of the indicators of the analyzed impact categories are presented in Table 3. These results show the indicator values for the life cycle stages from cradle to gate. Out of the six impact categories analyzed, four categories referred to environmental output streams in the milk production system: GWP100, AP, EP and POCP, while the other two categories were related to fossil fuel and mineral input streams: ADP fuel and ADP min. In general, the environmental profile for milk production was more favorable in the specialized milk farming. In the mixed type, milk production was associated with a higher environmental load in all impact categories. This was evidenced by higher values of indicators compared to the milk farming (from nearly 0.5% to over 19%). The least highlighted difference in indicators between agricultural types concerned the categories of EP and AP.

Table 2. *Inventory data of inputs for the analyzed farming types with milk production. Inputs values in relation to functional unit of 1 kg FPCM*

Specification	Unit	Farming type	
		Milk	Mixed livestock
Imported feed:			
Compound feed	kg	9.92×10^{-2}	1.53×10^{-1}
Soymeal	kg	5.10×10^{-3}	0
Rapeseed meal	kg	2.33×10^{-2}	3.31×10^{-2}
Rapeseed	kg	4.20×10^{-3}	0
Grass hay	kg	8.6×10^{-3}	0
Cereal straw	kg	2.38×10^{-2}	0
Brewers grains	kg	2.00×10^{-2}	0
Cereal bran	kg	1.50×10^{-3}	3.16×10^{-2}
Sugar beet pulp, pressed	kg	1.34×10^{-1}	1.71×10^{-1}
Dry beet pulp	kg	3.00×10^{-4}	0
Grass silage	kg	4.28×10^{-2}	0
Minerals	kg	7.50×10^{-3}	7.70×10^{-3}
Milk replacer	kg	5.12×10^{-3}	9.20×10^{-4}
Home grown feed:			
Grass/alfaalfa silage	kg	5.69×10^{-1}	8.64×10^{-1}

Maize silage	kg	1.22×10^{0}	7.38×10^{-1}
Grass hay	kg	5.37×10^{-2}	5.02×10^{-2}
Winter cereal grain	kg	7.85×10^{-2}	8.69×10^{-2}
Spring cereal grain	kg	4.63×10^{-2}	4.87×10^{-2}
Green fodder	kg	5.56×10^{-2}	2.78×10^{-2}
Energy use			
Electricity	MJ	9.21×10^{-2}	9.89×10^{-2}
Diesel fuel/engine oil	kg	2.30×10^{-3}	3.40×10^{-3}
Others:			
Labour	hour	4.50×10^{-3}	8.20×10^{-3}
Tap water	l	3.76×10^{0}	3.86×10^{0}
Silage film/polyethylene mesh	kg	1.20×10^{-3}	2.00×10^{-3}
Tractors and machines	kg	1.00×10^{-4}	2.00×10^{-4}
Cereal straw	kg	2.02×10^{-1}	3.83×10^{-1}
Veterinary services/insemination	item	2.00×10^{-4}	3.00×10^{-4}
Disinfectant liquid	kg	6.00×10^{-4}	1.10×10^{-3}

Source: *Own elaboration.*

Table 3. *Impact category indicators for the milk production in the analyzed farming types per 1 kg FPCM*

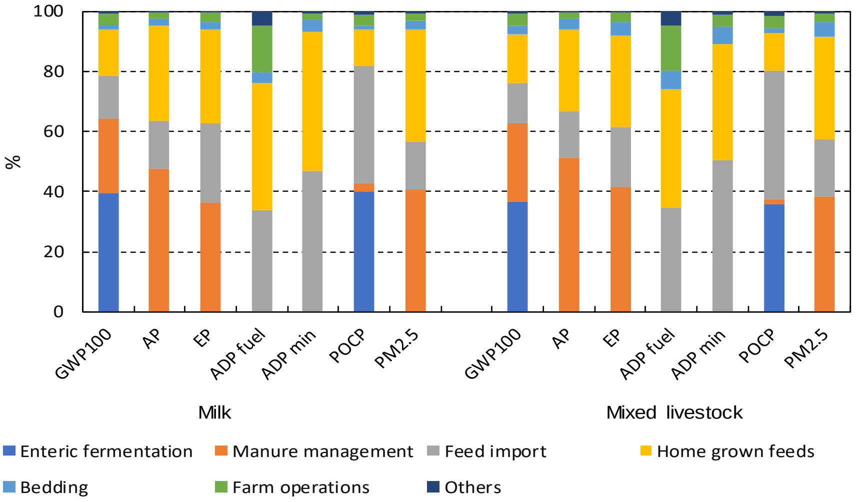
Impact category	Reference unit	Farming type	
		Dairying	Mixed livestock
Climate change (GWP100)	kg CO_2 eq.[1]	1.09×10^{0}	1.18×10^{0}
Acidification potential (AP)	kg SO_2 eq.[2]	1.27×10^{-2}	1.38×10^{-2}
Eutrophication potential (EP)	kg PO_4 eq.[3]	4.22×10^{-3}	4.24×10^{-3}
Abiotic resource depletion potential for fossil fuels (ADP fuel)	MJ[4]	3.00×10^{0}	3.57×10^{0}
Abiotic resource depletion potential for minerals (ADP min)	kg Sb eq.[5]	1.66×10^{-6}	1.98×10^{-6}
Photochemical ozone creation potential (POCP)	kg C_2H_4 eq.[6]	2.60×10^{-4}	2.90×10^{-4}
Particulate matter/respiratory inorganics (PM2.5)	kg PM2.5 eq.[7]	7.80×10^{-4}	8.90×10^{-4}

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.*

The impact indicators have been considered from the levels of the main milk production processes (Figure 2). The information obtained in this part of the study is of diagnostic importance, as it allows to determine processes of particular importance for the analyzed environmental issues. In milk production, biogenic emissions originating in intestinal fermentation and organic fertilizer management were most relevant for the impact categories GWP100, AP, EP and POCP in both types of farming. The processes which markedly also contributed to results of the indicators were home grown feed and imported feed. These processes were dominant in such categories as ADP fuel and ADP min, whereas feed imports - in POCP.

The remaining processes: bedding, farm operations and others were less important in creating ecological effects, regardless of the type of farming. Among these, farm operations had a more noticeable percentage share in the values of the indicators of the analyzed impacts, and ranged from 1.9% to 15.3%. In the specialized milk production type, an almost 2.2 - times smaller contribution to the ADP min was reported for farm operations compared to the mixed type, recognized as being less specialized in milk production. The environmental impact of the others group for most impact categories was negligible, except for ADP fuel and POCP.

Figure 2. *Contributing processes per 1 kg FPCM to different impact categories for farming types with milk production*

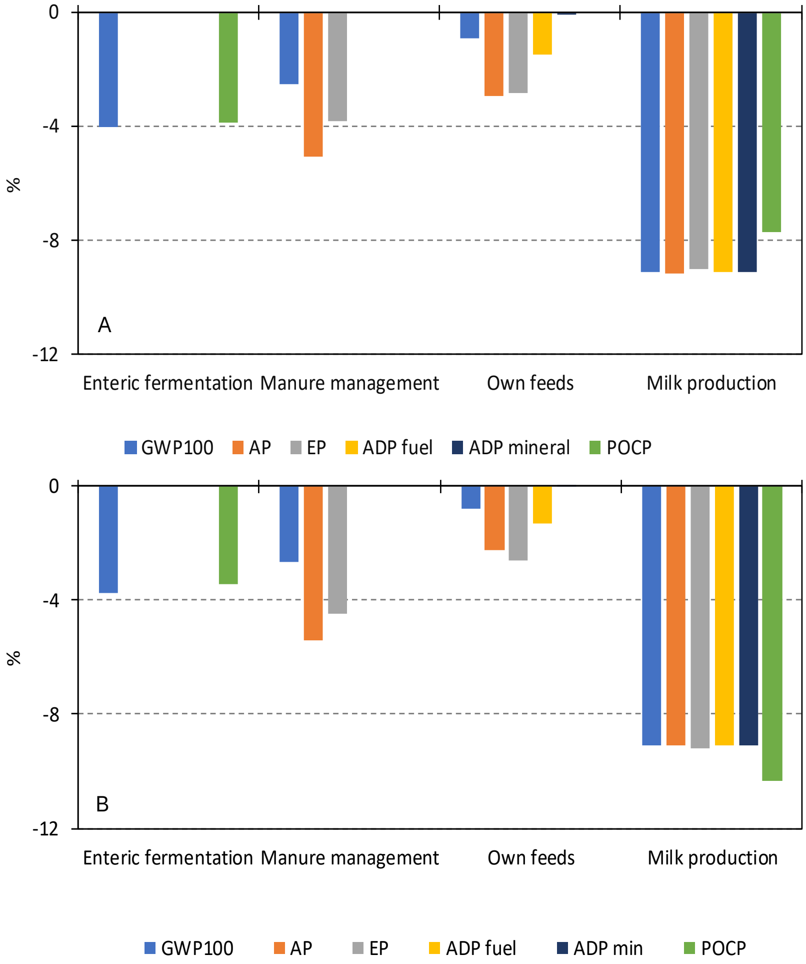


Source: *Own elaboration.*

Applying sensitivity analysis, the response of the indicator results to changes in some variables was examined (Figure 3). The processes with the greatest influence on the impact categories were determined. The results of this analysis point to the great impact of changes in the scale of milk production on the results of the examined impact categories. The reaction of the impact indicators to a 10% increase of milk production in milk farming and mixed livestock type was in the range of -7.7- -9.1% and -9.1- -10.3%, respectively.

Smaller changes in the results of the impact categories resulted in a 10% reduction in the levels of biogenic emissions, i.e. enteric fermentation and manure management. In both types of farms, the anaerobic fermentation factor affected only two categories of impact: POCP and GWP100, causing the indicators to drop from -3.5 to -4.0%. A rather strong reaction of the categories AP and EP on the reduction of emissions associated with the management of organic fertilizers was also observed. The size of these reactions was greater in the mixed livestock production type.

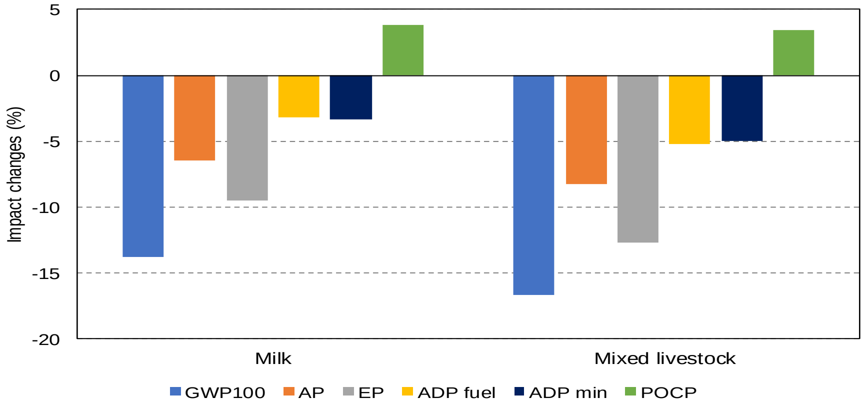
Figure 3. *Deviation in % from the impacts of the current milk production in milk (A) and mixed livestock (B) farming types in response to the decrease in direct sources of emissions and the increase in the milk production (by 10% individually)*



Source: *Own elaboration.*

Since animals are more commonly kept on bedding, it was important to assume a change of the existing system and a shift towards the slurry-based housing. Based on the scenario analysis, the environmental effects caused by the introduction of this system are presented in Figure 4. Transition to the slurry-based housing reduced the five impact category indicators. A greater reduction in indicators was reported for milk production in the mixed livestock type. The most favourable reaction to the introduction of liquid manure was in the GWP100, EP and AP impact categories. Only the POCP category presented an unfavorable direction of change, as its the indicator showed an increase in the emission potential of substances assigned to this category after straw bedding was replaced with liquid manure.

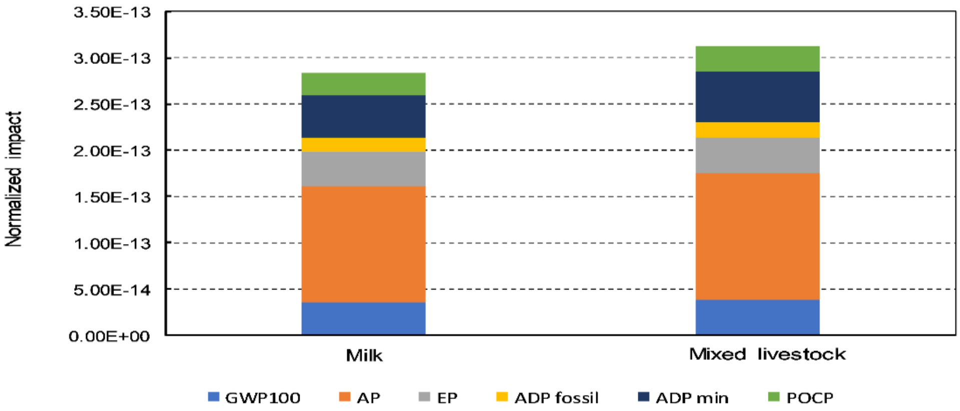
Figure 4. *Changes in the environmental impacts in the scenario where all animals are confined in slurry-based systems compared to the current manure management in the analyzed farming types*



Source: *Own elaboration.*

Figure 5 shows the total environmental indicators for the analyzed types of farming. It synthesizes the comprehensive environmental impact of milk production by grouping six impact categories. It can be observed that the total environmental impact of milk production in the mixed livestock type was about 10% higher than the dairy type. For both types, the main sources of environmental impact were AP, ADP min and EP categories. AP accounted for about 44% of the total indicator value. According to the structure of the share of the impact categories, the significance of the impact of climate change was lower and accounted for about 12% of the environmental indicator value in both types of farming.

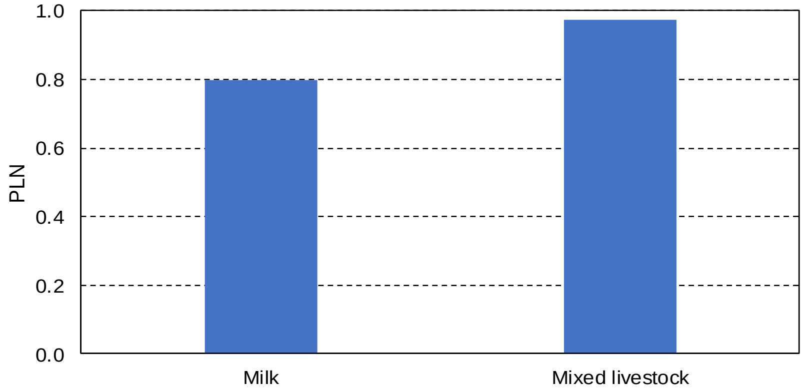
Figure 5. *Single figure score of total environmental impact of milk produced in different farming types (per 1 kg FPCM)*



Source: *Own elaboration.*

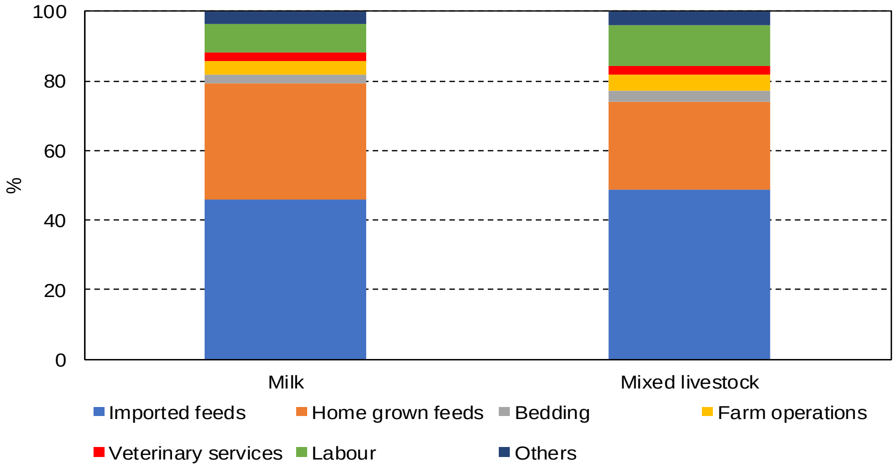
The economic dimension of milk production processes is characterized by the life cycle costing (LCC) (Figure 6). They show the total process costs per the functional unit of 1 kg FPCM. Higher LCC values occurred in the mixed livestock production type. Compared to the specialized milk farming type, they were almost 22% higher. The LCC cost structure is shown in Figure 7. The import of feed, home growing of feed crops and labour costs had the greatest impact on the costs. In terms of share, groups of costs arranged in the same order in both types of farming. The data indicates a higher relative share of all cost items except for home grown feed in the mixed farming type. Bedding and farm operations contributed least to LCC. Their highest share in the mixed farming type did not exceed 2.6% and 4.4%, respectively.

Figure 6. *Life cycle costs per 1 kg FPCM for the analyzed farming types with milk production*



Source: *Own elaboration.*

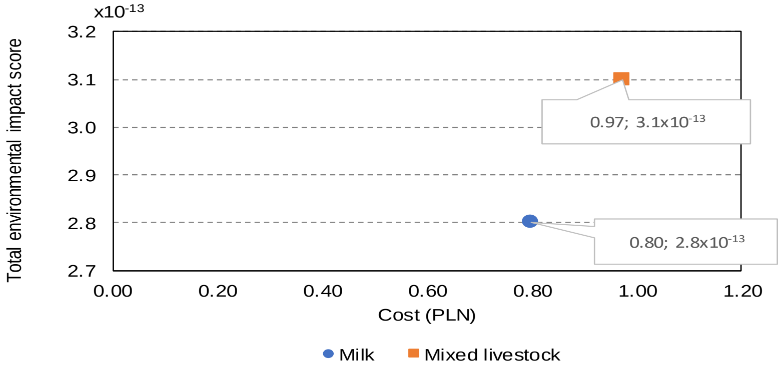
Figure 7. *Share of groups of costs contributing to the results of life cycle costs per 1 kg FPCM for the analyzed farming types with milk production*



Source: *Own elaboration.*

Figure 8 presents the eco-efficiency of milk production. The vertical axis marks the total environmental impact dimension, and the horizontal axis - LCC. This graphical interpretation clearly indicates that the eco-efficiency of milk production in the mixed type is markedly lower compared to the milk farming type. The measure of the differences in eco-efficiency is the distance between the points signifying farming types. The eco-efficiency calculated in the one-dimensional variant, defined here as environmental effect cost, was for milk and mixed livestock farming types respectively: 2.82×10^{12} and 3.10×10^{12} PLN per score of total impact. This means that the cost of the total environmental effect of producing milk in the mixed type was about 9.9% higher compared to the milk farming type.

Figure 8. *Eco-efficiency of milk production in XY coordinates of total environmental impact and costs*



Source: *Own elaboration.*

4. Discussion

The results of the environmental profile revealed the importance of the farming type in the environmental impact of milk production. These differences can be directly explained on the basis of the relationship between the input stream and the environmental effects obtained in the LCIA. Production and economic characteristics of the analyzed production types provide a more comprehensive background for the comparison of environmental impact. A more favorable environmental profile of the milk farming type corresponds to a number of features such as: degree of specialization in milk production, economic size of farms and higher average milk yield. In milk LCA studies, results for several impact categories simultaneously are less frequently published.

Publications focusing on the selective analysis of the impact of cattle farming on the category of climate change caused by agricultural activity are definitely more common. The concentration of research in this field can be generally attributed to the high levels of CH_4 emissions associated with cattle breeding in relation to total greenhouse gases (GHG) emissions from agriculture (Nguyen *et al.*, 2013). The LCA results for milk production in conventional dairy farms in the Bretagne region (France) can be used as suitable reference material for the results obtained as part of this study, due to a very similar functional unit and similarly outlined system boundaries (van der Werf *et al.*, 2009). The result of the GWP100 indicators for milk produced on conventional farms in France was about 5% lower compared to milk produced on the analyzed milk farming type, while this difference increased to over 12% compared to the mixed livestock type. Commenting on these differences, it should be noted that the average milk yields (kg FPCM/cow/year) in the group of conventional farms in Brittany and in the analyzed milk type were very similar.

According to the literature there is a negative correlation between the milk yield and GHG emissions per 1 kg FPCM (Gerber *et al.*, 2011). Foster *et al.* (2007) claim that the limit range for achieving the minimum warming potential values in a traditional milk production system is between 7000 and 9000 kg of milk per year. According to this relation, the value of the warming potential should be therefore considered close to the optimal one in the light of the average milk yield obtained in the milk farming type, as opposed to the mixed livestock farming where milk yield was much lower.

In the French studies, the results of EP category indicators for milk produced on conventional farms were much higher compared to milk produced in both analyzed types of farming. Similar indicators in this category were in turn obtained for milk from organic farms in Bretagne. With regards to AP, almost two times higher rates were recorded in milk production in the analyzed agricultural types in Poland, compared to the French results from Brittany. Such large differences in AP are most likely to result of different ways, in which animals are kept and manure is stored. In the agricultural types studied in Poland, cattle was almost exclusively kept on bedding. Literature data confirms that with this method of manure management, much larger amounts of NH_3 are emitted to the atmosphere than in the case of liquid manure. NH_3 has one of the greatest acidifying potentials of many substances with similar properties (Guinée *et al.*, 2002).

The sensitivity analysis allowed to determine which of the groups of processes have the strongest impact on particular impact categories when their input parameters are changed. Reduction of CH_4 emissions through anaerobic digestion is the most difficult to obtain. Attempts have been made to implement some dietary modifications to limit the production of CH_4 in cattle, with a moderate effect so far (Nguyen *et al.*, 2013; FAO, 2019). Environmental problems represented the greatest sensitivity relative to milk yield. From the point of view of process efficiency, this is the most direct way to reduce the environmental impact of milk production. The AP, EP and GWP100 milk production impact categories have also proved to be reactive to changes in manure management. In the analyzed types of agriculture, the traditional bedding system was still dominant. In this situation, it was interesting to learn the environmental effects in the scenario of a complete transition to a bedding-free, liquid-manure-based system. The analysis of this scenario showed that the environmental impact was significantly reduced, except for the POCP category. The increase in POCP is due to the fact that when manure is collected in liquid form, larger amounts of CH_4 are emitted, due to a higher conversion rate of organic fertilizer to CH_4 in the liquid manure system than in the bedding system (IPCC, 2019). Based on the results of the research, it can be expected that the combinations of changes in milk yield increase with the use of liquid manure system in the analyzed agricultural systems would be particularly beneficial in terms of the size of GWP100, AP and EP reduction.

The assessment of the impact of milk production was also presented by means of a total environmental indicator, which included the analyzed impact categories. In performing the analysis on the level of the overall environmental impact, the shares of the impact categories in the final environmental indicator were determined. It was shown that milk production in the mixed livestock type had a worse environmental performance. It was noted that the share of individual categories in the total environmental performance was very similar in both types of farming, with a clear domination of AP over GWP100 and EP. Due to the rather selective standardization procedure and subjectivity of weighing (procedure steps in summation of results of different impact categories), the total environmental impact indicator may be a source of uncertainty in the LCA study (Agarski *et al.*, 2016).

Life cycle costing (LCC) has been assumed to be the second dimension, adequate in assessing the eco-efficiency of the milk production system and, at the same time, complying with the LCA methodology. An important premise for this choice was the fact that the LCC analysis provides an opportunity to find out about the production inputs and costs of milk. Contrary to the total environmental indicator, the total cost according to LCC is not burdened with uncertainty because the aggregated costs are a direct measure of the financial impact (Swarr *et al.*, 2011). Applying this method, it was proven that in the milk production cost structure of the milk farming type, focused exclusively on milk, the costs of home grown feed constituted a greater percentage of total costs compared to the mixed livestock type. A higher share of home grown fodder costs in the cost of milk production in the milk type was compensated by a smaller contribution of imported feed costs. It can be assumed that, in the mixed type, the small share of home grown fodder in production costs was due to the lack of sufficient quantities of cattle fodder, which had to be imported from outside sources. This was one of the factors which apparently contributed to the increase in milk production costs.

A two-dimensional graphic presentation of the eco-efficiency of milk production (total environmental impact vs. LCC) showed the distribution of the examined agricultural types in relation to these two components. The data in the graph shows that milk production in the milk farming type was a benchmark for the mixed livestock one pointing to the necessary changes in eco-efficiency and determining the distance from the benchmark. The second measure of eco-efficiency was a one-dimensional indicator that determines the ratio of economic effects to total environmental impact of a product. Empirical values of indicators showed that milk production was more eco-efficient in the milk farming type. In calculating the indicator, costs were used as economic information. Depending on the priorities, the improvement of eco-efficiency is achieved by reducing the environmental loads or by reducing the amount of inputs and conserving natural resources (Burritt and Saka, 2006). It is assumed that calculated indicator expresses the cost of the environmental effect. This means that greater eco-efficiency is matched by a lower cost of the environmental effect.

5. Conclusions

Our results suggest that the production of milk by farms specializing in milk production had a lower environmental impact compared to the mixed livestock farms with two directions of production: milk and pig breeding. The main reason for the lower environmental pressure in the milk farming type was higher milk yield, which translated into a more favorable environmental profile of the functional unit. The continued specialization in milk production in Poland, which is expressed by the reduction of the number of farms with dairy cows, a systematic decrease in the number of dairy cows and an increase in milk yields, is generally conducive to reducing environmental pressure.

In the light of EU environmental policies requiring reductions in greenhouse gases (GHG) and NH_3 emission levels, the favorable direction of these changes may not be sufficient to achieve the EU environmental objectives in a relatively short-term perspective. Technological changes concerning the replacement of the still prevalent bedding system with liquid manure systems should be a necessary step in this direction. According to the scenario analysis based on the life cycle assessment (LCA), there are a number of environmental benefits associated with the introduction of liquid manure, especially in terms of reducing the climate change impact rate.

An important stage of the work was to combine different environmental issues into one total indicator, which in turn would be the basis for including it as one environmental dimension in the eco-efficiency analysis. For this purpose, a number of analytical operations were performed, consisting of standardization, weighing and then aggregation of impact category indicators into one, total environmental impact. Due to the way this total indicator is constructed, it can also be described as the cumulative environmental effect of milk production. A comparison of milk production between farming types in terms of the value of this effect was unfavorable in the type of mixed livestock production.

Milk production was more eco-efficient in the dairy than in the mixed livestock farming. The consideration of life cycle costing (LCC) as an economic factor places a preference on the directions of production solutions that harmonize with the principle of saving natural resources and reducing consumption of production inputs. So far, no uniform standards have been developed for evaluating the eco-efficiency of production processes. The paper presents eco-efficiency (LCC and total environmental impact) in two ways, firstly - in the graphic form, in a coordinate system, and secondly - in the form of an indicator. By presenting eco-efficiency in a graphic form, it is possible to interpret it more widely, which increases its informative value and creates the possibility of its practical use for diagnostic purposes. It also allows to establish benchmarks in terms of the values of eco-efficiency indicators of milk production.

The results of this study confirm the need to take into account local environmental conditions and the level of milk production technology in terms of differentiating environmental effects related to production processes. Territorial variability of conditions in production causes that any generalization of environmental effects cannot always be based on the assumptions of standard process parameters. The dairy cow population, significant export value of dairy production in Poland as compared to EU countries are the arguments justifying the need to confront the current environmental profile and eco-efficiency of milk production in the context of such research in the EU and worldwide.

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