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Article

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Farm Gate Energy Intensity of Food Production in Poland - Considering the Physical and Economic Aspects of Production

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ABSTRACT

Within food supply chains, attention is paid to the significant energy consumption at the farm gate level. In agricultural production, the energy intensity of animal production is much higher than that of plant production, but mainly if physical units are considered. This study examines the energy intensity of food production in Poland from 2010 to 2019, contrasting animal and plant production in both physical and monetary units. Utilizing the EXIOBASE database, it compares energy consumption across wheat, sugar beets, pig, and poultry farming sectors, addressing the gap in research on energy intensity within these individual sectors. The research reveals that, contrary to physical unit measurements, the energy intensity in monetary terms is lower for animal production than for plant production. Specifically, plant production showed higher energy intensity, averaging 28.02 MJ/€1 GDP for wheat and 30.15 MJ/€1 GDP for sugar beets. In contrast, animal production had higher energy intensity when measured by physical units, with pigs and poultry averaging 15.72 MJ/kg and 15.36 MJ/kg, respectively. These disparities arise primarily from the greater profitability of animal production, impacting the results per monetary unit. The findings underscore the importance of including economic aspects in energy intensity measurements, influencing agricultural producers' decisions.

Keywords: Food Production, Energy Intensity, Farm Gate, Animal Production, Plant Production
JEL Classifications: Q1, Q4, Q10

1. INTRODUCTION

Energy is used throughout the food supply chain, from production and application of agricultural inputs through processing, packaging, and distribution to the final consumer (Bajan et al., 2021). Estimates of the global food supply chain show that it accounts for 30% of the world's total energy consumption (IRENA and FAO, 2021). In the European Union (EU), the entire food supply chain is estimated to account for up to 17% of total energy use (Motola et al., 2015). Analyzing intra-supply chain energy consumption, Pelletier et al. (2011) indicate that in crop production, about 43% of energy inputs result from fertilizer production and 26% from direct energy consumption in the fields. 14% is from refrigeration, drying, and storage, 11% from manufacturing and repairing machinery, and 7% from producing pesticides.

Both the intensification of agricultural production and its globalization increase energy consumption. In this context, it is significant that the energy used in agriculture comes mainly from fossil fuels and threatens to improve energy and environmental efficiency (Parcerisas and Dupras, 2018). However, it substantially helps to improve the limiting factors in agriculture, particularly labor productivity, by increasing the use of mechanical power and land productivity by increasing the availability of nutrients (Giampietro, 2001). Through the use of fossil fuels, high-income countries have developed large-scale food production in complex industrial systems and increased labor productivity. However, such heavy reliance on energy throughout the food chain raises concerns about, for instance, the impact of energy prices on food prices, as well as national food security and the country's dependence on imported energy (Canning, 2010). The demand for energy throughout the supply chain also results in high intensity in food systems, and according to some estimates, collectively, as much as 10 kcaL of energy needs to be consumed at all stages of the food chain to produce 1 kcaL of food (Pimentel and Pimentel, 2007). However, the amount of energy consumed per unit of food produced is influenced by many factors, such as climate, growing conditions, cultivation practices, fertilization systems, yields, and other variables in food supply chains, such as the energy mix used in processing or transportation.

A significant portion of agricultural production undergoes processing, during which energy is needed, for instance, to preserve food and increase its physical availability over a longer period. Food processing activities range from post-harvest operations and the simplest preservation methods to modern processing methods (FAO, 2016). Pelletier et al., (2011) indicate that processing is responsible for up to 17% of energy consumption in food systems. However, differences in how food is processed make it quite challenging to identify energy consumption trends (Klemes et al., 2008), as energy consumption in the food industry varies from country to country and from product to product (Clairand et al., 2020). Moreover, inefficiencies and technological differences observed in food processing often result in high energy consumption in the food industry. This phenomenon is mainly observed in less developed countries and ultimately contributes to the high energy intensity of food products (Wang, 2014).

Due to the increasing demand for processed foods going hand in hand with the economic development of countries (Baker et al., 2020) and the fact that consumers need to have seasonal products available throughout the year, significant changes have been observed in food production and the intensification of transportation (Padfield et al., 2012). Some studies (Canning, 2010) indicate that energy flows associated with food transportation account for <5% of the total energy consumption of the entire food system. Such results are relatively small since transportation within a country is usually done by road and rail, while transportation outside a country is done by rail or ship, which are considered relatively energy efficient.

In recent years, due to the significant energy consumption in the entire food supply chain, much attention has been paid to the environmental problems associated with it. Producing enough food to feed a growing population seriously threatens the natural environment and may lead to a more significant depletion of energy resources and energy intensity of the food supply chain (Maysami and Berg, 2021). As various estimates indicate, animal production is more energy-intensive per physical unit than plant production (Pimentel and Pimentel, 2003). However, from the economic point of view, livestock production tends to generate higher unit value added. Thus, it can be seen as more profitable and cost-effective than plant production (Herrero et al., 2016). Many studies suggest that profitability or income generation possibilities are essential in production decisions made by farmers (Giller et al., 2021). Therefore, it is vital to examine energy intensity both in terms of physical units and in terms of monetary units. Such comparison allows considering both the environmental and economic aspects of food production energy intensity and sheds light on potential trade-offs between them.

The main goal of our study is to compare the energy intensity of food-producing sectors given in monetary units to the energy intensity given in physical units. The study area is Poland, where, to the best of our knowledge, there is a lack of studies on the energy intensity of individual food-producing branches (sectors). We analyzed four branches within crop and animal production, namely, the production of wheat, sugar beet, pig, and poultry farming. Energy intensity was calculated using monetary units (per global output and GDP) and physical units (per kg). Therefore, the novelty of our study lies in comparing energy intensity in both monetary and physical terms. Moreover, studies comparing the energy intensity of different food sectors in Poland are also lacking. We pose the hypothesis that unlike the energy intensity of food production in terms of physical units, energy intensity in terms of monetary units is lower for animal production than for plant production.

The remainder of the article is divided as follows: Section two contains theoretical background on the role of energy in the economy and methods for measuring energy efficiency and energy intensity of production, Section three describes the methods used in the study, Section four contains the results of the study showing the energy intensity of agricultural production in Poland and a discussion, while section five provides a summary and conclusions.

2. THEORETICAL BACKGROUND

As the importance of energy in economies increased, various resulting regularities began to be observed. Among others, W. S. Jevons, who studied issues related to coal mining and consumption in England, noted that increased efficiency in energy use results in increased demand for energy, which is defined as the Jevons paradox (Alcott, 2005). This paradox means that technological progress accelerates the consumption of resources and the environmental impacts of their extraction and use, resulting in the deterioration of ecosystems (Pieńkowski, 2012). In the case of the global economy, coal, oil, and natural gas have been the primary energy resources since the 1970s. In the context of economic development, it is significant that their resources are limited. In addition, it is worrisome that their consumption is increasing while resources are decreasing. In the case of Poland, after the transition to a market economy, the energy consumption structure is dominated by coal (Rokicki and Perkowska, 2020), which negatively affects the environment.

Currently, energy use studies in the economy focus more on energy intensity changes than absolute energy consumption (Cornillie and Fankhauser, 2004). Energy intensity is defined as the amount of energy consumed per unit of output (Martínez, 2010; Wang, 2013). In practice, energy intensity is often the ratio of energy consumption to GDP (Hang and Tu, 2007), and its changes are observed partly as a result of improvements in energy efficiency and partly as a result of changes in economic activity and structural changes in the economy (Metcalf, 2008). Energy intensity can also be affected by changes in the energy mix due to differences in economic efficiency between different types of energy (Ma and Stern, 2008). From the economic point of view of agricultural production, the use of the ratio between energy consumption and GDP is also justified since economic aspects and the desire to make a profit (income) are the main determinants in the decision-making process of agricultural producers (Wang et al., 2019).

Within energy analysis, there are two main techniques for assessing energy flows within a specific process or product: Process analysis and input-output analysis. Process analysis, also known as bottom-up analysis, considers the inputs and outputs of energy in a process by aggregating them into successive stages of production. Economic input-output analysis, or top-down analysis, on the other hand, combines input-output flow data with sector-specific energy intensity data by disaggregating them into production stages (Murphy et al., 2011). Although energy analysis methods are relatively well established, there are still inconsistencies in boundary setting, allocation choices, and other decision points. Therefore, greater standardization is desirable to improve the consistency and comparability of energy analyses (Pelletier et al., 2011). In the literature, one can find a variety of energy efficiency indicators (Mulder and Hagens, 2008), which are the inverse of energy intensity indicators (Martínez, 2010). One technique for evaluating the efficiency of energy systems is net energy analysis, which compares the amount of energy supplied to society by an energy system with the energy consumed directly and indirectly in that supply process (Cleveland et al., 2000). Such a technique is the energy return on investment (EROI), which is the ratio of energy delivered to energy consumed in the process (Cleveland et al., 1984; Kunz et al., 2014). The limitation of net energy analysis is the treatment of energy quality. In most net energy analyses, the inputs and outputs of different types of energy are aggregated according to their thermal equivalents (Cleveland et al., 2000). Additionally, due to the diverse interests and intentions of researchers, energy inputs and outputs are allocated differently (Hall et al., 2011), which often makes EROI results incomparable between countries, which is a significant drawback for indicators that measure energy efficiency (Murphy et al., 2011).

In turn, research in the field of food system energy mainly includes analyses specific to a given food product or branch, for instance, dairy products (Grönroos et al., 2006). Studies are also being conducted on food system energy productivity (Karkacier et al., 2006; Mushtaq et al., 2009; Cao et al., 2010) and energy distribution in food supply chains (Cuéllar and Webber, 2010). From a supply chain perspective, the most popular method for energy analysis of food production systems has become life cycle assessment (LCA), which uses standardized impact assessment methods to determine the potential environmental impact of a product. The most essential element of LCA is defining the scope of the study its objective, and establishing the boundaries of the system since all activities that contribute to a product's life cycle fall within these boundaries (Roy et al., 2009). Studies using the LCA focus mainly on agricultural production, industrial processing, and the quality of finished food products (Janulis, 2004; Berlin et al., 2007; Kim and Dale, 2002). Meanwhile, LCA can be used to compare products, processes, or services, compare alternative life cycles of specific products or services, and identify parts of the life cycle where improvements can be made (International Organization for Standardization, 2006).

It is possible in the LCA research to apply the from cradle to grave approach, which studies each impact of each phase of the food supply chain (farm inputs, agricultural stage, processing, distribution, use, waste management) (Hauschild et al., 2018). However, the phases involving indirect energy consumption at the agricultural supply stage and direct on-farm energy consumption have the most significant impacts (Bajan et al., 2020). Given the nature of our study, which is based on the data from the input-output tables, it is challenging to estimate energy consumption at the processing and distribution stages of food production. Therefore, the article uses input-output tables to account for the phases with the most significant impacts, stopping at the farm gate. Due to the inconsistency of boundaries between food-producing and food-processing sectors in input-output tables, the system boundaries had to be limited at the farm gate. Also, in the case of the consecutive phases of the food supply chain, matching given sectors to the energy consumption at distribution or sales stages could lead to significant errors in the estimates. Therefore, our approach is designed to mimic system boundaries of the so-called "from cradle to farm gate" concept in the LCA (Kokare et al., 2023), taking into account the supply stage and on-farm stage of production.

3. MATERIALS AND METHODS

Data from EXIOBASE input-output tables (Stadler et al., 2018) were used to calculate the energy consumption of individual food-producing branches in Poland, which is the numerator of energy intensity indicators. The EXIOBASE database is widely used in calculations of agri-food products due to the high level of disaggregation of sectors in this category (Owen et al., 2017). Through its environmental extension, it can determine the energy distribution among food-producing sectors (Merciai and Schmidt, 2018). Thus, we selected this database from among the available input-output databases because it is the best fit, resulting primarily from the level of sector disaggregation.

The study considers four directions of agricultural production, two branches each of animal and plant production: Poultry, pigs, wheat, and sugar beets. Such selection is made to compare results for animal and crop production. We selected production branches in which Poland is a significant producer in the EU. According to FAO data for 2019 (FAO, 2024), Poland was the largest producer of poultry in the EU, the third largest producer of wheat and sugar beets, and the fourth largest pork producer. A particular limitation in the choice of branches was the level of data aggregation in EXIOBASE. To adequately examine energy flows between branches, it is necessary to have a separate column and row for a specific branch in the input-output table. The study was conducted for the 10-year period 2010-2019, allowing us to observe variation patterns in the calculated indicators.

To calculate energy intensity indices at the gate farm level, we had to determine from the input-output table the indirect energy consumption for each food-producing branch, which is the result of all activities in each branch carried out prior to farm production. The value of direct energy consumption, resulting from activity at the farm level, is derived from EXIOBASE data. We specifically used the latest version of the data (3.8.2) that can be found on Zenodo (Stadler et al., 2021).

The first step in calculating intermediate energy consumption is determining Poland's cost structure matrix (A) from EXIOBASE multiregional input-output tables. Using the general properties of the input-output model, we determined an inverted Leontief matrix ($[I-A]^{-1}$) containing the full material intensity coefficients of all sectors of the economy. By multiplying the inverted Leontief matrix by the matrix of direct energy consumption coefficients (DIC_{EU}), which is the result of dividing the energy consumption of an economic branch by its output, the matrix of full energy consumption coefficients per unit of output (FIC_{EU}) was determined. Such an equation can be written as (Miller and Blair, 2009):

$$FIC_{\mathrm{EU}} = (I - A)^{-1} * DIC_{EU} \tag{1}$$

Where: FIC_{EU} = matrix of full impact coefficients of energy use; I = identity matrix; A = cost-structure matrix; DIC_{EU} = matrix of direct impact coefficients of energy use.

Due to the need to maintain comparability of results between the studied years, output values were deflated by using the relevant producer price indices from the organisation for economic co-operation and development database (OECD, 2024).

Indirect energy consumption was calculated by multiplying the full energy consumption coefficients for the analyzed sectors by their output and then subtracting the direct energy consumption given in the EXIOBASE. Energy consumption resulting from material and service flows between the analyzed branches was also deducted to avoid a double-counting error. The deduction results from the fact that the energy consumption values arising from these flows are included in the direct energy consumption of the branches under study. Indirect energy consumption for all four analyzed branches was determined in the same way, as illustrated by the example of poultry below:

$$\begin{aligned} IEU_p &= (FIC_{EUp} * GO_p) - DEU_p - \\ &(DEU_p * (I - A)^{-1}_{p,p} * GO_p) - (DEU_{a1} \\ &*(I - A)^{-1}_{p,a1} * GO_p) - (DEU_{a2} * (I - A) \\ &{}^{-1}_{p,a2} * GO_p) - (DEU_{a3} * (I - A)^{-1}_{p,a3} * GO_p) \end{aligned} \tag{2}$$

where: IEU_p = indirect Energy use in the sector p - poultry farming FIC_{EUp} = full impact coefficient for poultry farming; GO_p = global output of poultry farming; DEU_p = direct energy use in poultry farming; $(I-A)^{-1}_{p,p}$ = the element of Leontief inverse indicating the self-supply of poultry farming; $a1, a2, a3$ are consecutive analyzed agricultural sectors, i.e. pig farming, wheat production, and sugar beet production.

Calculated indirect energy consumption summed up with direct energy consumption gives the value of energy consumption at the farm gate level:

$$IEU_i + DEU_i = EU_{Fgi} \tag{3}$$

where: IEU_i = indirect energy use of sector i, DEU_i = direct energy use of sector i, EU_{FGi} = energy use at farm gate of sector i.

Using the determined energy consumption values at the farm gate, we calculated three different energy intensity indicators for each of the production branches analyzed. The first of the indicators is energy consumption per unit of GDP. For the results' full comparability, each sector's GDP was deflated using an appropriate implicit deflator from the EUROSTAT database (EUROSTAT, 2024). The formula for such energy intensity, in general form, can be presented as:

$$EI_{GDPi} = EU_{FGi}/GDP_i \tag{4}$$

where: EI_{GDPi} = energy intensity of sector i, EU_{FGi} = energy use at farm gate of sector i, GDP_i = GDP of sector i.

The second intensity indicator calculated is the rate of energy consumption per unit of output according to the formula:

$$EI_{GOi} = EU_{FGi}/GO_i \tag{5}$$

Where: EI_{GOi} = energy intensity of sector i, GO_i = global output of sector i.

The third indicator of energy intensity is the ratio of energy consumption per volume of food production in a given sector. Thus, this is an indicator in which there are physical units in both the numerator and denominator. This indicator can be determined according to the formula:

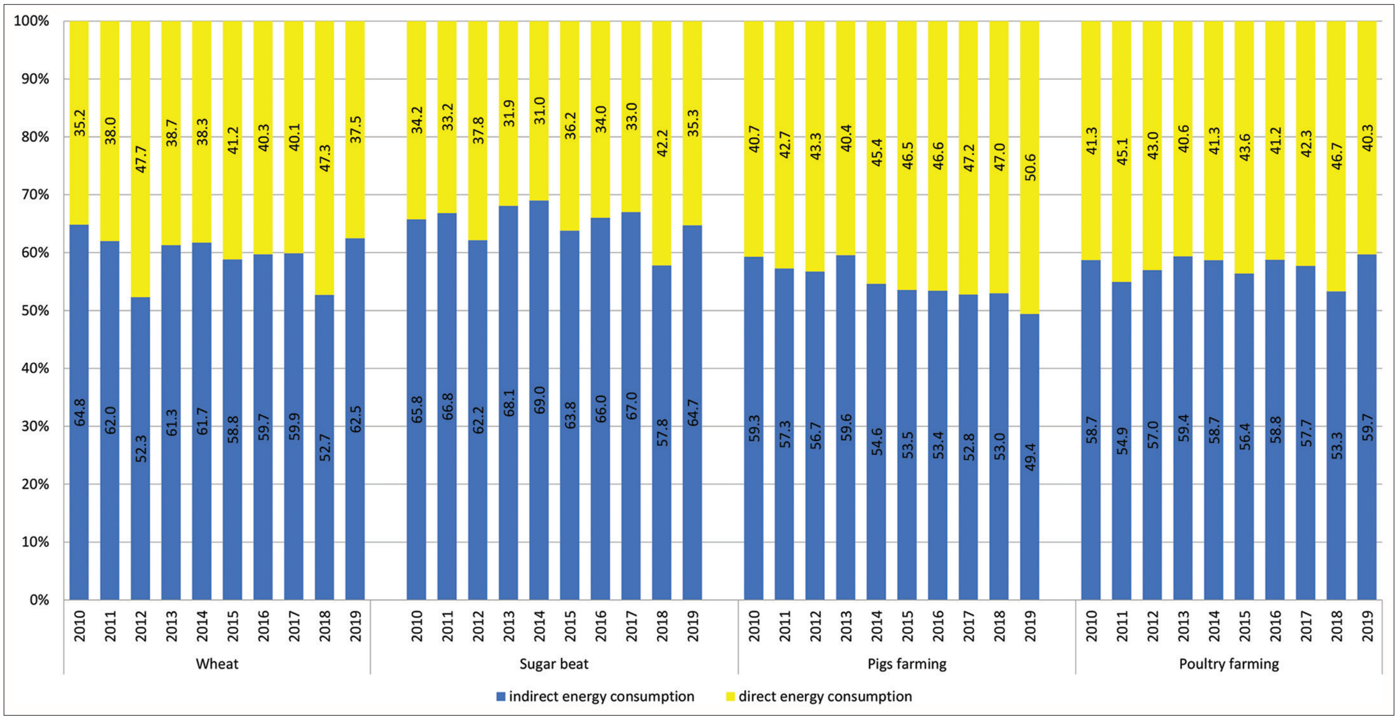
$$EI_{qi} = EU_{FGi}/P_{qi} \tag{6}$$

Where: EI_{qi} = energy intensity of sector i, P_{qi} = production quantity of food in sector i.

4. RESULTS AND DISCUSSION

For the analyzed food-producing branches in Poland, regardless of whether it was a branch within crop or animal production, indirect energy flows prevailed in the structure of energy consumption (Figure 1). In the case of wheat and sugar beets, the average annual share of the agricultural supply phase in the energy consumption structure in 2010-2019 was 60% and 65%, respectively. The predominance of indirect energy flows was mainly due to the supply of fertilizers and pesticides for production. In the case of pig and poultry farming, the significant share of indirect energy consumption was mainly due to animal feed supply, which was also partly linked to grain production in Poland. As the detailed data show, Poland's grain-producing branches also largely supplied

Figure 1: Energy consumption structure at the farm gate level (%)



Source: Own calculations based on the EXIOBASE data

animal feed, which was reflected in the significant share of indirect energy consumption at the farm gate level.

Often, discussion on energy consumption in agriculture is limited to direct energy consumption (Grönroos et al., 2006; Mousavi-Avval et al., 2011; Moitzi et al., 2014; Martinho, 2016), not including indirect flows, which typically account for more than 50% of total energy consumption in food-producing branches (Woods et al., 2010). Also, in the case of the study for Poland, the share of indirect energy consumption significantly exceeded 50% of total energy consumption at the farm gate. It is essential to keep in mind that the energy required to produce the final food product does not come only from direct consumption but also includes indirect energy flows. These include the accumulated value of energy used to produce inputs and services used in the various stages of food production (Pelletier et al., 2011), thereby significantly affecting food production's energy intensity.

Nevertheless, each branch within food production is characterized by a different energy intensity. Also, within a given group of products (plant or animal), energy intensity differs from one product to another. The literature usually indicates that animal production is more energy-intensive than crop production. According to Usubiaga-Liaño et al., (2020), up to 31% of energy consumption in food production systems in Europe, North America, as well as in high-income countries located in Asia, Australia, and Oceania, is related to animal products. In addition, global meat and milk production is projected to more than double by 2050 compared to 1999 production (Steinfeld et al., 2006), which could also adversely affect the share of energy consumption associated with animal production in the total energy consumption of food production systems and their energy intensity.

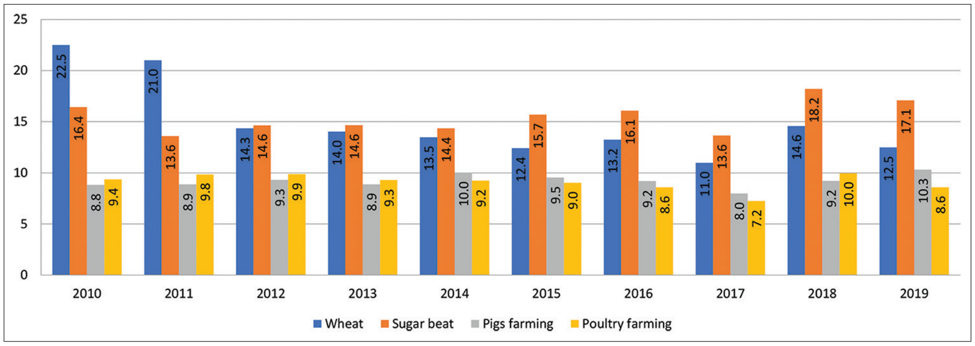
In the case of Poland, energy intensity in 2010-2019, for a total of 4 food-producing branches, was calculated both as energy consumption per €1 of global output (Figure 2) but also as energy consumption per €1 of GDP (Figure 3), which is value added at producer prices that excludes intermediate consumption. In both cases, despite slight fluctuations in the magnitude of the ratios throughout the analyzed period, it was possible to observe significantly higher values of energy intensity ratios in monetary terms for plant products (wheat and sugar beets) compared to animal production (pig farming and poultry farming).

In turn, the significant differences between the magnitude of the indicators per unit of output and per unit of GDP indicate the importance of the agricultural supply phase in food production. The farm supply phase tends to be characterized by higher energy intensity per monetary unit, as Bajan et al. (2020) confirmed. However, regardless of whether output or only value added is considered in the calculations, a reduction in energy intensity at the farm gate level could be observed in the last analyzed years, compared to 2010, which should be considered a positive development (The descriptive statistics of our results can be found in Table 1 in the appendix).

Due to fluctuations in agricultural profitability, especially in 2018, an apparent increase in the energy intensity of the analyzed branches could be observed. A decrease in the generated value added in agriculture by about 20% in 2018 compared to 2017 was observed, which increased the energy intensity of production per monetary unit. Such fluctuations are often observed due to imperfections in the market structure and differences in the bargaining power of participants in the marketing chain (Chlebicka et al., 2009). Most often, farmers have a weaker market position and less influence on setting the price than players in the sectors supplying agriculture. Such a vulnerable position is because agricultural producers operate in a highly fragmented way, similar to the perfect competition model, which results in low market power for a single farm. The consequence is that farmers tend to gain less in the long term than players in the agricultural supply sectors. More significant benefits accrue to those in the input supply sectors due to higher barriers to entering and exiting the market, resulting in a smaller number of such players, similar to an oligopolistic structure (LeVay, 1983). In addition, it is essential to keep in mind the dependence of agricultural production on weather conditions, which also, in the case of unfavorable conditions, results in lower yields and often more significant fluctuations in agricultural income.

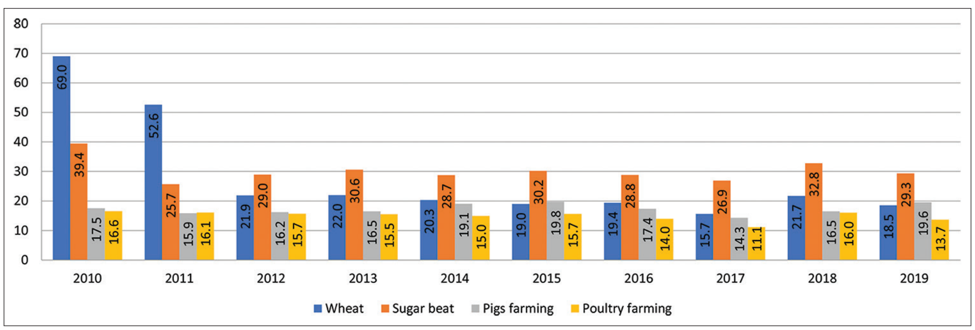
The energy intensity per monetary unit of selected sectors in Poland showed a significantly higher energy intensity in the case of crop production. However, energy consumption per physical unit usually indicates a higher energy intensity of livestock production. Therefore, for comparison, energy consumption per kilogram of final output of wheat, sugar beet, pig farming, and poultry farming was also calculated (Figure 4). In this case, poultry farming, as

Figure 2: Energy intensity of agricultural production in Poland at the farm gate level (MJ/1 EUR Global Output)



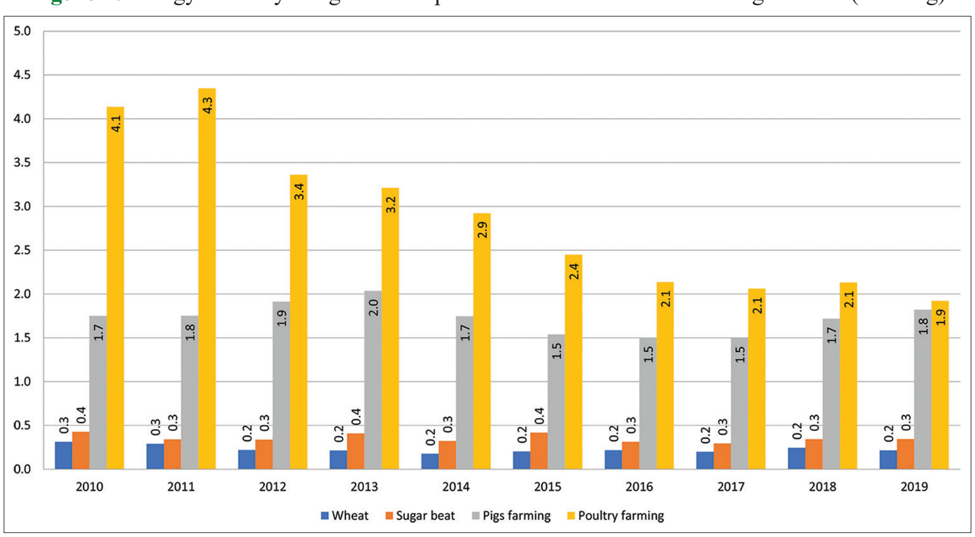
Source: Own calculations based on the EXIOBASE data

Figure 3: Energy intensity of agricultural production in Poland at the farm gate level (MJ/1 EUR GDP)



Source: Own calculations based on the EXIOBASE data

Figure 4: Energy intensity of agricultural production in Poland at the farm gate level (MJ/1 kg)



Source: Own calculations based on the EXIOBASE data well as pig farming, was the most energy-intensive throughout the study period. In contrast, sugar beet production proved to be the most energy-efficient.

Our results can be compared with studies from around the world. For instance, Erdal et al. (2007), examining the energy intensity of sugar beet production in Turkey in 2005, recorded an energy intensity of 0.65 MJ/kg. In the case of our study, the results are similar, ranging from 0.49 to 0.72 MJ/kg. In turn, Maysami and Berg (2021) found the energy intensity of wheat for grain in Iran to be 4.35 MJ/kg. In contrast, in our study, wheat production in Poland was characterized by an energy intensity of 3.89 MJ/kg in 2010, while in the last year studied, this result decreased to 2.65 MJ/kg due to the reduction of energy consumption.

In the case of the animal production branches, our results showed an average energy intensity of pig farming of 15.71 MJ/kg and poultry of 15.36 MJ/kg. Similar results on the energy intensity of pig farming were also obtained in other studies. Paris et al. (2022), studying the energy intensity of livestock in the EU, showed that in the case of pig farming, the energy intensity ranges from 14.2 MJ/kg (of which 11.6 MJ/kg is due to indirect energy consumption) to as much as 27.5 MJ/kg (16.4 MJ/kg resulting from indirect energy consumption). In contrast, in the case of poultry farming, they showed an energy intensity ranging from 7 MJ/kg to 21.4 MJ/kg. They also showed specific energy intensity results of Polish poultry farming at around 15 MJ/kg, similar to ours. By applying the LCA methodology, Benavides et al. (2020) observed much lower energy intensity results of poultry and pig farming in the United States. The energy intensity at the farm gate in the USA in the case of pig production was about 7 MJ/kg, of which about 5 MJ/kg was due to indirect energy consumption. In the case of poultry farming, the energy intensity was <6 MJ/kg, and the production supply stage was responsible for more than 4 MJ/kg. Also, Tallaksen et al. (2020), studying production in the USA and using the LCA method, found the energy intensity of pig farming in conventional production to be about 14 MJ/kg, a result similar to the results obtained in our study for Poland, while the result in the most prominent enterprises was about 9 MJ/kg. The results for the USA indicate a significant role of the scale effect in the energy intensity.

Compared to other countries, mainly in the case of pig farming, the results obtained for Poland tend to be higher. The high energy intensity of Polish agriculture is primarily attributed to the fragmented agrarian structure and the relatively slow technical progress in the countryside (Rokicki et al., 2021). Typically, large pig enterprises are not observed in Poland, consequently influencing less efficient energy management and, ultimately, significant energy intensity. However, in the case of poultry farming in Poland, in recent years, one can observe a considerable development of this branch, both in the technological aspect, which allows for reduced energy consumption, and in the production volume. Such progress is also reflected in our results, where for 2010, poultry farming was characterized by the highest energy intensity per physical unit, while in subsequent years, a gradual decrease in energy intensity could have been observed. The effect of these changes was that the energy intensity of poultry farming in 2019 was <11 MJ/kg.

5. CONCLUSION

Food production involves significant energy consumption and is considered relatively energy-intensive. In the case of our study conducted for Poland for 2010-2019 at the farm gate level, indirect energy flows were responsible for more than 50% of the energy consumption. This phase is related to the supply of materials and inputs to agriculture, which largely influences the energy intensity of agricultural production.

The energy intensity results per monetary unit and physical unit were significantly different. Regarding energy intensity, which is calculated as energy consumption per global output (MJ/1€) and value added (MJ/1€ of GDP), poultry farming and pig farming were the most energy efficient. In turn, in the case of energy intensity calculated as the ratio of energy consumption to production volume (MJ/kg), sugar beet and wheat production was characterized by significantly lower energy intensity. In recent years, great importance has been attached to the protection of the natural environment, and attention has been paid to the significant environmental footprint of animal production. However, we cannot forget about economic factors, which usually have a decisive influence on whether an agricultural producer decides to start or continue production.

The study achieved the goal of comparing energy intensities of different natures. The energy intensity results of wheat, sugar beet, pig farming, and poultry farming in Poland in 2010-2019 at the farm gate level confirm the research hypothesis that unlike the energy intensity of food production in terms of physical units, energy intensity in terms of monetary units is lower for the animal production than for the plant production. Such a conclusion has a number of consequences for policymakers.

When making production decisions, farmers primarily consider the financial aspect. Therefore, sufficient income must go hand in hand with developing production and increasing production efficiency. It is essential to focus not only on energy intensity in physical units but also on the economic aspect of production. Lower profitability of energy-efficient, and thus climate-efficient, sectors will result in reluctance on the part of farmers to change production directions, which lowers the chances of realizing sustainable development strategies for Polish agriculture. Therefore, based on our results, we recommend that decision-makers adjust these strategies considering energy intensity results in both aspects (physical and economic). In other words, in case of animal production, the policy instruments should focus on introducing advanced technologies and practices to reduce energy consumption, as the physical energy intensity is high. In the case of plant production, the main issue is low profitability. Therefore, policy instruments for plant production should focus more on the economic side while optimizing existing practices from the energy use perspective. Such an approach would allow searching for optimal solutions and production directions, sufficient in both resource and economic aspects. It may qualify for the effective development of production, increasing farm income. At the same time, it will be possible to reduce energy consumption in Polish agriculture further, which will adapt to environmental goals.

Future research should focus on expanding the analysis of energy intensity to include additional food production sectors and subsequent stages of the food supply chain, which would allow for a more accurate assessment of the energy intensity of food production in Poland. An interesting supplement to the research could also be extending it to include an analysis of other EU countries to compare the energy intensity level of food production within the same system boundaries.

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APPENDIX

Table 1: Descriptive statistics for energy intensity scores

Product	Unit	MIN	MAX	Average	Variation	Coefficient of variation (%)
Wheat	MJ/1 EUR GO	10.97	22.49	14.90	3.58	24.0
	MJ/1 EUR GDP	15.67	69.03	28.02	16.90	60.3
	MJ/1 KG	2.18	3.89	2.84	0.51	17.8
Sugar beat	MJ/1 EUR GO	13.59	18.20	15.44	1.45	9.4
	MJ/1 EUR GDP	25.68	39.41	30.15	3.60	11.9
	MJ/1 KG	0.49	0.72	0.59	0.07	12.3
Pigs farming	MJ/1 EUR GO	7.98	10.31	9.21	0.62	6.8
	MJ/1 EUR GDP	14.34	19.78	17.28	1.66	9.6
	MJ/1 KG	13.67	18.40	15.71	1.48	9.4
Poultry farming	MJ/1 EUR GO	7.24	9.95	9.10	0.77	8.5
	MJ/1 EUR GDP	11.12	16.59	14.94	1.54	10.3
	MJ/1 KG	10.64	23.20	15.36	4.41	28.7

GDP: Global durum wheat panel, Source: Own calculations based on the EXIOBASE data