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Factors Influencing the Productivity of Direct Energy Inputs in EU Agriculture

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Abstract: Agriculture is a major energy consumer and a significant contributor to global greenhouse gas emissions. As the world's population grows, increasing food production while reducing energy use presents a critical challenge. This study examined the trends in direct energy input productivity in agriculture across European Union (EU) countries from 2010 to 2021, focusing on the impact of structural factors, including production scale, mechanization, intensity, and output composition. The results showed a gradual decline in energy productivity, averaging a 1.04% annual decrease, reaching EUR 344,000 per terajoule (TJ) in 2021. Higher mechanization and production intensity improved energy productivity, while larger production scales and a greater share of animal farming had negative effects. Given the current trends of production expansion and extensification, further progress in energy productivity in agriculture appears limited. Policy measures should prioritize optimizing animal production's share and adopting a sustainable use of renewable energy to lower the dependency on non-renewable fossil fuel sources. Future strategies must balance high agricultural output with sustainable energy consumption per food unit.

Keywords: energy productivity; sustainable energy use; agriculture; intensification; mechanization; scale of production

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1. Introduction

The world's demand for food is increasing with the growth of the population. To meet this growing demand, the production of agricultural raw materials must also expand. This, in turn, requires with the use of limited land resources and production inputs to achieve the desired production levels. The aim of our research was to determine the direction of the changes in direct energy input productivity in agriculture across EU countries and to identify the influence of structural factors on this productivity level.

Agricultural production is associated with significant energy consumption, particularly fossil fuels, and substantially contributes to greenhouse gas (GHG) emissions. While food production must meet the growing demand driven by population growth, addressing climate change requires reducing non-renewable energy and GHG emissions [1,2]. Moreover, the scarcity of fossil fuels highlights the need to improve energy efficiency in agricultural processes.

There is increasing pressure to reduce energy consumption in agriculture. Still, any tools in this direction should not negatively affect farm productivity because this would limit the implementation of modern energy-saving agricultural technologies [3]. It should be emphasized, however, that the progress in agriculture across various fields has led to a reduction in GHG emissions per unit product of about 40% in recent decades [1]. This highlights the need for long-term approach in such studies. Higher and higher energy use in agriculture is essential for fulfilling the food demand, modernizing agricultural technology, and increasing labor productivity. However, the potential unintended consequences of this increasing energy usage must also be considered [4].

It is advisable to realize research and support solutions that will enable higher energy productivity in agriculture. These changes could include the use of more energy-efficient machines and buildings. They could also include changes in production structure and production technology, e.g., less tillage and the cultivation of plant varieties that are most efficient under the given conditions. Additionally, the diversification of energy sources towards renewable or low-emission ones could be considered. This will not lead to increased energy productivity but may reduce the negative impact on the environment. Suggestions for change must consider the various impacts beyond the country's borders. For example, research shows that reducing the production of ruminants in favor of non-ruminants increases energy efficiency but such a proposed change may reduce agricultural income and make utilizing local absolute feeds, e.g., grasses, much more challenging. An additional problem is that feed for non-ruminants may be easily imported in a significant share from countries with non-sustainable agriculture production [5]. As a result, energy consumption in that country is not considered, which distorts the comparison [6].

In the European Union and some other regions, agricultural policy aims to reduce energy consumption and greenhouse gas (GHG) emissions from agriculture through various actions limiting the size and extent of agrarian production. This includes setting aside part of agricultural land, promoting low-input organic farming, and providing subsidies for reducing livestock populations. However, such actions often result in a reduction in production and a decline in the productivity of energy inputs [7]. Various studies on EU countries have found a reduction in energy productivity of up to 10 or even 16%, depending on the period [4,8]. While decoupling an increase in energy consumption and increasing economic growth in the agricultural industry is a desirable goal, only a few countries have achieved this [9]. In less developed countries, the limited access to energy results in energy poverty, which has a strong negative impact on the level of production and the overall efficiency of agricultural outputs [10].

Energy used on farms can be divided into direct and indirect energy. Direct energy is energy processed on-site in connection with farm operations, particularly the energy needed for cultivating the field, harvesting, and transport. It is also the energy for driving machinery and heating and cooling buildings. Indirect energy consumption includes the energy needed to produce goods and services consumed on the farm. This consists of the energy used in producing and transporting fertilizers, pesticides, and agricultural equipment [11]. Direct energy inputs from various fuels constitute 25 to 50% of the total energy input in agriculture, with the remaining portion being indirect energy, primarily from nitrogen fertilizers, pesticides, and feed [2,12–14].

The efficient use of fossil fuels (which are nonrenewable resources), which are mainly consumed in on- and off-farm activities, is imperative. Even if the energy used on farms is produced more sustainably, e.g., a considerable part comes from renewable sources, better use of their resources is still beneficial.

Our study examined the direct energy inputs on agricultural farms and their productivity, considering factors such as production scale, structure, intensity, and the level of mechanization.

Given the importance of examining factors influencing energy productivity in agriculture, the primary aim of the research was to determine the direction of changes in the direct energy input productivity in agriculture across EU countries and to identify the impact of structural factors on the productivity of direct energy inputs in EU agriculture. We also want to emphasize that our research is related to energy productivity, not emission levels. Agriculture needs a certain amount of direct energy, whether from fossil fuels or renewable resources.

2. Literature Review

Efforts to increase food production are being made globally. This requires enhancing land productivity through the use of yield-generating inputs, which critically influence the scale of production. These inputs include direct energy from fuels as well as the energy embedded in fertilizers, pesticides, and feed.

Energy use is a vital component of modern farming, replacing human labor and performing tasks that would otherwise be impossible. Typical energy sources include electricity, natural gas, propane, fuel oil, and biomass. Energy Use Indices (EUIs) serve as a valuable tool for characterizing the efficiency with which a specific type of farming operation consumes energy. They are an essential benchmarking tool for assessing the overall energy efficiency of a farm.

2.1. Agricultural Development Level and Energy Use per Unit

Research has demonstrated the principle of diminishing returns in energy consumption. In countries with high-intensity agricultural production, the energy use per unit of output is higher [15]. However, this is partly due to differences in the price ratios of agricultural products to energy prices. For instance, in Bangladesh, energy input productivity declined by 24% as a result of agricultural modernization. The goal of such changes, however, was to achieve higher production rates per hectare and increase food production—objectives that are not achievable under low-intensity production systems [16].

Thus, achieving a balance between the need for food production and the drive for improved energy productivity is essential. The use of additional energy inputs in agriculture enables significantly better utilization of solar energy by crops and higher productivity per unit of land area [17,18]. This, in turn, increases the overall productivity of the agroecosystem.

At the high production level achieved in developed countries, it is possible to reduce energy consumption while maintaining the production level, but this requires the introduction of innovations in technique and technology. In some countries with highly developed agriculture, an upward trend in the productivity of energy inputs was observed [2]. This resulted partly from extensification and partly from technological progress. In most countries, however, there is a positive relationship between increasing agricultural production and increasing energy inputs, and energy productivity in agriculture decreases [9]. The demand that reducing energy consumption should be implemented without harming agricultural production, as it is closely related to food security, appears again. It is also worth emphasizing that when dealing with issues like climate neutrality and circularity, whose achievement involves complex trade-offs, e.g., closing loops and reducing waste when performing an activity, it could affect the use of more energy-intensive technologies, which, in the end, leads to an increase in energy use per unit of production [6].

2.2. Factors Influencing Energy Efficiency in Agriculture

2.2.1. Scale of Production

With an increase in the scale of production, better energy use is observed on farms. An upward trend is observed when moving from small to medium and large farms. Still, with a further increase in scale to very large, there is a gradual deterioration in energy productivity, which may result from higher mechanization of production processes [19,20] and a higher degree of use of machines instead of human labor [21]. With a high share of human labor in performing operations, energy productivity can be high, but the income per person and production per 1 hectare are low [22].

An important factor in reducing energy consumption per unit of production is achieving the scale effect related to the size of the farm and the size of the machines used. It is also very important that large farms can invest in machines and devices; thanks to this, the production technology is changed to a more sustainable and energy-efficient one [23–25]. The effect of progress (technological change) can be even more significant than the effect resulting from the increase in scale alone [26]. Many aspects of energy productivity in agriculture are related to both the scale of production and the level of technology and mechanization on farms. Additionally, it has been observed that with an increase in scale, a more sustainable energy input mix is used, as larger farms more often use renewable energy [27]. Biogas electricity production is quite common on large European farms [26]. Although this does not improve energy productivity per se, it can lead to lower GHG emissions.

Another issue regarding energy productivity improvement in large farms is their specialization and strong focus on increasing efficiency and reducing energy consumption and average costs, which may hinder their willingness to invest in Climate-Smart Agriculture measures [28]. This requires a balanced approach to assess such farms, considering both economic and environmental goals.

2.2.2. Mechanization

Machines and equipment in buildings used on farms significantly impact farm energy efficiency, which highlights the importance of considering the possibility of using new energy-saving solutions in this area to reduce energy consumption [29]. The introduction of new energy-saving technologies and machines leads to an increase in energy productivity [30]. Similarly, when ploughing was replaced with conservation agriculture technology, positive effects were obtained. Studies have shown an increase in energy productivity of up to several percent [31,32]. It was observed that with the rise in agricultural mechanization, energy consumption increases and the efficiency of using direct energy inputs, mainly from liquid fuels, deteriorates [16,33]. This results from changing traction to mechanical traction, and only then does it become possible to use more efficient machines and seek savings through simplifying processes or precise work techniques [34].

The most challenging thing is to reduce the consumption of the liquid fuels used to power machines [15,19,35]. In the case of increasing the mechanization of agricultural production and its intensity, it was observed that in Poland at the beginning of the 21st century, direct energy inputs in agriculture increased at a faster rate than production, which resulted from the increase in the share of mechanized processes on farms [36]. The improvement of energy efficiency indicators occurs in countries where a very high level of energy consumption was previously achieved, which usually results from improved technology. This is due to the fact that more machines and devices are used in modern production technologies than in traditional ones.

The most advanced stage in the mechanization and automation of production is currently the use of precision agriculture techniques (PATs). Although the introduction of PAT solutions requires higher energy inputs [37], savings are possible due to the faster execution of treatments, avoidance of double cultivation, lower expenditures on machine settings [38], and also due to only performing the treatments that are necessary for the given conditions [3]. As a result, the productivity of energy inputs increases. PATs in animal production, including the automation and optimization of energy-consuming processes like heating, cooling, or ventilation, also allow for a higher productivity for the direct energy inputs [39,40]. However, these technologies are expensive and only mainly available to large farms in wealthier countries [28]. Concerning improving energy productivity in connection with introducing new technologies, it was noted that the changes achieved were minor compared to those resulting from, for example, the weather during the vegetation period. Some results may have been inaccurate because the impact of weather on the results was not considered [41].

2.2.3. Production Intensity

An increased intensity of agricultural production leads to higher outputs per unit area or per animal head, which is usually the primary goal, but it leads to a lower efficiency of energy use [2]. Higher intensity requires more energy inputs for the mechanization of treatments, irrigation, etc. [11,42]. Energy consumption and its productivity in agriculture can also be influenced by the cropping system, which assumes a high share of plants with intensive soil cultivation [22]. There is general agreement that it is necessary to produce more intensively (more inputs), but this should be associated with a technology change that allows a proportionally higher production increase than an increase in inputs, including energy inputs [13,43].

In countries dominated by large-scale, relatively low-intensity agriculture, energy productivity is high, but this results from achieving economies of scale in production and extensive land use. For example, in Argentina, despite a several-fold increase in energy inputs in agriculture, the production volume per unit of energy input doubled in 1960–2000 [44]. It should be added, however, that this type of agriculture is only possible in countries with very large land resources per capita.

On the other hand, it is indicated that a high production intensity is necessary to obtain adequate production per 1 ha. Direct energy productivity may decrease, but when both direct and indirect energy inputs are considered, progress is noticeable, and a higher input efficiency can be achieved under high-intensity conditions in agriculture. The situation when high-input agriculture requires less land per unit of output is taken as a basis for using the opportunity cost principles of economics to evaluate energy performance. The calculations also consider the land area and labor inputs involved in the production process, not only energy use [18]. This approach also allows for achieving lower GHG emissions per unit of product [1,45]; unfortunately, usually, with an increasing intensity of animal production, the direct energy inputs per unit of production increase [46].

The energy input and productivity level also depend on the climate zone, the sum of temperatures, and the temperature during the vegetation period and the plants selected for production. The species cultivated should be well adapted to the climate zone [47]. It is also interesting that the desire to reduce the demand for energy from agriculture, e.g., by producing energy crops, leads to an increase in the intensity of production and usually to a deterioration in the productivity of energy inputs in agriculture and an increase in GHG emissions [34,48,49]. The energy yield from such crops is often lower than the energy inputs incurred. In such a situation, the economic profitability is determined by the price obtained for the product [12].

2.2.4. Production Technology

Closely tied to both the scale and mechanization of production are issues related to the technology used in agricultural production. Some aspects of technology are inherently dependent on the scale of production. One of the key factors concerning energy productivity in agriculture is the efficient use of fuel, fertilizers, and pesticides. Better agricultural management practices generally lead to improved efficiency of energy inputs [50]. As noted, the energy input for the same production process can vary by as much as double across different farms, depending on the production technology and equipment used [29,51]. In sectors with similar, standardized technologies, such as poultry farming, the differences are smaller, but still significant [33].

The introduction of the appropriate crop rotation combined with proper tillage and seeding practices can enhance the productivity of energy inputs by reducing fuel consumption [43]. Integrating crop and livestock production and using shared resources, such as grazing or fertilization, also facilitates energy savings and reduces GHG emissions per unit of production [45].

It is commonly highlighted that energy productivity can be improved by adopting conservation agriculture technologies, which minimize the number of interventions, including conventional tillage [31,32]. In cattle production, higher energy productivity has been observed in free-stall cattle barns compared to traditional barns [46].

2.2.5. Production Structure

A high share of animal production in agriculture is associated with lower energy use rates [2,45]. To reduce energy consumption in agriculture and increase energy productivity, some authors postulate a significant reduction in the size of animal production and a reduction in the share of animal products in consumption [52]. In addition, the production of a kilogram of pork or poultry meat is associated with twofold lower energy inputs than the production of a kilogram of beef. This means that changing the structure of meat production can also lead to higher energy input productivity [51]. On the other hand, animal production extensification is also considered. Expanding extensive livestock in the EU may bring positive effects only when countries ensure feed self-sufficiency and avoid additional feed import. In other cases, the energy inputs take place abroad [5,53].

3. Research Methodology

The study considered the consumption of direct energy from various fuels in agriculture and the amount of agricultural production obtained, divided by plant and animal production. The data used in the study cover agriculture in 27 EU countries in the years 2010–2021. The 27 countries were selected to ensure the continuity of data as the United Kingdom no longer reported results after leaving the EU, and complete statistics for newer member states have been available only since 2010. The Eurostat database served as the data source. From this database, data on energy consumption in the agricultural sector (NRG_BAL_S), agricultural production value at 2015 prices (AACT_EAA04), utilized agricultural area (APRO_CPSH1), number of employees (AACT_ALI01), fertilizer consumption (AEI_PR_GNB), livestock density index (TAI09), agricultural output (TAG00102; TAG00054, TAG00055, and TAG00123), and number of farms (EF_M_FARMLEG) were obtained. Data from the Farm Accountancy Data Network on the average value of fixed assets per farm and per 1 ha of UR were used as an aid. The following variables were used: (SE441) total fixed assets and (SE510) average farm capital. Based on the collected data, the energy productivity index for each country and year was calculated using the Formula (1):

$$EnergyProductivityIndex = \frac{P}{E} = \frac{Agricultural\ output}{Direct\ energy\ input} \tag{1}$$

where

P—agricultural output in 2015 prices,
E—direct energy input in agriculture in TJ.

Based on the literature review and previous research results, explanatory variables that may affect the energy productivity achieved in agriculture were selected. Two variables were adopted regarding the scale of production: average farm size and the level of production mechanization. Two variables were selected to reflect production intensity: the fertilization level and the intensity of animal production (measured in LAU per ha). Three variables were chosen to represent the structure of production: the share of animal production in agricultural output, the share of arable land in utilized agricultural area, and the share of cereals in sown area. All variables were defined at the country level for each year of the research period.

The following hypotheses were adopted:

H1. *As the scale of production (measured by the size of farms) increases, energy productivity in agriculture increases.*

H2. *As the importance of agricultural mechanization (measured by the level of labor input per unit area) increases, energy productivity in agriculture decreases.*

H3. *As production intensity increases, energy productivity decreases.*

H4. *As the share of animal production in total production decreases, energy productivity in agriculture decreases.*

In this study, we used static and dynamic panel regression models. We considered the following static panel regression model:

$$logy_{it} = \alpha + \boldsymbol{\beta' logx}_{it} + u_i + \varepsilon_{it} \tag{2}$$

where

$logy_{it}$—logarithm of the output level in i-th country in t-th year; $i = 1, 2, \ldots, N$; $t = 1, 2, \ldots, T$;
$\boldsymbol{logx}_{it}$—vector of log-transformed explanatory variables;
u_i—unobserved country-specific component; $i = 1, 2, \ldots, N$;
ε_{it}—error term; $i = 1, 2, \ldots, N$, $t = 1, 2, \ldots, T$;
α—scalar parameter and $\boldsymbol{\beta}$—vector of parameters to be estimated.

The component u_i is assumed to be time-invariant and homoscedastic across countries, while the error term ε_{it} is homoscedastic and uncorrelated over time.

We omitted a detailed description of the methods for analyzing the static panel models, as they are extensively covered in numerous econometric textbooks, e.g., refs. [54–56]. In addition to the static models, we considered the following dynamic panel model:

$$logy_{it} = \alpha + \gamma logy_{i,t-1} + \boldsymbol{\beta' logx}_{it} + u_i + \varepsilon_{it} \tag{3}$$

where

y_{it-1}—the lagged level of the output variable,
α, γ—scalar parameters, and $\boldsymbol{\beta}$—vector of parameters to be estimated.

The other symbols have the same meanings as those in Equation (2).

The dynamic nature of Model (3) renders the Ordinary Least Squares, the Fixed Effects, and the Random Effects estimators biased and inconsistent, as the lagged level of the output variable (y) is correlated with the error term (ε) [56]. To address the issue of endogeneity, an estimator based on the General Method of Moments (GMM) is commonly utilized [55]. In applied economics, the approach developed by Arellano and Bond [57], along with its refinement by Arellano and Bover [58] and Blundell and Bond [59], is widely adopted for dynamic panel estimation (see, i.e., refs. [60–62]).

This study applied the system GMM estimator introduced by Arellano and Bover [58] and refined by Blundell and Bond [59]. This method uses the lagged first differences as instruments for level equations and lagged levels as instruments for first differences equations. The system GMM estimator demonstrates favorable statistical characteristics, which was validated even with relatively smaller samples [59,63]. The dynamic panel estimates of the model parameters were obtained using Gretl 2024d econometric software.

The consistency of the system GMM estimator depends on the assumptions that there is no serial correlation in the error terms of the level Equation (3) and that the instruments are exogenous. To evaluate these assumptions, the autocorrelation test and the Sargan test for over-identifying restrictions were applied, following the procedure recommended by Arellano and Bond [57]. The autocorrelation test examines the null hypothesis of no second-order serial correlation in the first differenced residuals, ensuring that the errors in the level equations are free from serial correlation. The Sargan test assesses the appropriateness of the instruments, with its null hypothesis asserting that the instruments are uncorrelated with the error terms. Failure to reject both null hypotheses supports the validity of the model specification and the instruments used.

In our models, energy productivity was the dependent variable. In contrast, the independent variables included average farm size, average labor intensity, nitrogen input, share of animal output in total farm output, share of arable area in utilized agricultural area, and share of cereals in the sown area. A brief description of these variables is provided in Table 1. Furthermore, we considered including a binary time variable for each year in the period of 2010–2021.

Table 1. Descriptive characteristics of variables used in the study.

Item	Description	Average	Minimum	Maximum	Coefficient of Variation
Energy productivity (thousand EUR × TJ^{-1})	EP	324.6	115.3	664.2	0.40
Average farm area (hectares)	farm_size	37.2	2.9	154.1	0.85
Average labor intensity (AWU per 100 ha)	l_int	6.21	1.71	17.7	0.72
Nitrogen input (kg per ha)	N_int	64.8	26.7	136.6	0.41
Share of animal output in total farm output (percent)	animal_share	41.1	18.2	61.8	0.22
Share of arable land in utilized agricultural land (percent)	arable_share	66.1	24.3	98.9	0.25
Share of cereals in sown area (percent)	cereals_share	49.4	15.7	71.4	0.25

4. Study Results

4.1. General Characteristics

On average, the energy productivity in the EU countries changed over the period under study. In 2010–2011, it was slightly lower than in previous years. After 2010, there was a slight increase, followed by a decrease in energy efficiency. From 2012 to 2014, the index was around EUR 380,000 per TJ of energy inputs, but in subsequent years, it decreased to EUR 340,000 per TJ (Figure 1). Energy productivity decreased by 1.04% per year during this period. It can be stated that the expected increase in the efficiency of direct energy inputs in agriculture across the EU countries was not observed.

Table 1 presents the descriptive characteristics of the variables for the 27 EU countries. Energy productivity varied significantly, with the lowest levels observed in the new EU member states (Czechia, Estonia, Latvia, and Poland), Finland (where the natural conditions are unfavorable for agriculture), and the Netherlands (where the production intensity is exceptionally high).

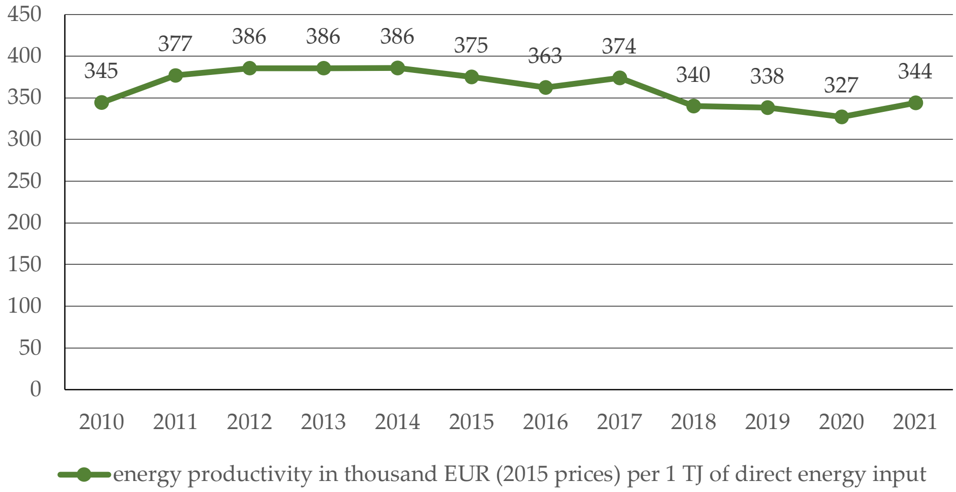

Figure 1. Changes in energy productivity in agriculture in the European Union countries (agricultural output in thousands of EUR [2015 prices] per 1 TJ). Note: The results were calculated as an average based on the total energy production and inputs across the EU countries. The results differ from the average obtained from the results for individual countries due to the different contributions of each country to the overall volume of agricultural production and their respective shares in energy consumption in agriculture.

The study revealed significant variations in each variable analyzed across the EU countries. Although some variability was observed over the years within individual countries, it was minor compared to the differences between nations. Energy productivity averaged 324.6 thousand EUR per terajoule (TJ), ranging from 115,000 EUR/TJ to 664,000 EUR/TJ. Generally, higher energy productivity was achieved in southern EU countries, while northern countries exhibited lower levels. Similarly, the explanatory variables showed a comparable degree of diversity. The average farm size was 37 ha, with the largest farms found in Czechia, where the average exceeded 150 ha per farm. The level of mechanization, measured by the necessary human labor per hectare, also displayed significant variability, correlating with farm size. Larger farms required much less human labor per hectare due to the predominant use of mechanized processes.

Production intensity could be assessed based on the input levels per hectare or the overall intensity of farming activities. Considering the differences among the EU countries, nitrogen fertilization levels were adopted as an indicator. The average nitrogen fertilization rate was 65 kg per hectare of agricultural land and ranged from 27 to 137 kg/ha, depending on the country.

The last group of variables are those related to the structure of production. The share of animal production in the total output is a basic one. It amounted to 41% on average and ranged from 18% to 62%, depending on the country. Similarly, the share of arable land in the total area of agricultural land can lead to a higher intensity of cultivation. This share amounted to 66% on average, ranging from 24 to over 90%. Such a significant range resulted from the fact that in some countries, grasslands are cultivated in the field. The last indicator is the share of cereals in the total crops. A higher share of cereals indicates a lower intensity of energy inputs than crops requiring, for example, more treatments. The share of cereals in the crops was around 50%, with the lowest share in countries where a large share of the land is allocated to produce feed and industrial plants.

4.2. Results of Statistical Analysis

Table 2 presents the results from the panel regression model applied in the study. Initially, the parameters of the static regression Model (1) were estimated. However, the

Durbin–Watson statistic of 0.855 indicated significant first-order autocorrelation of the error term (ε). Thus, we adopted the dynamic panel regression Model (3) to address this issue. The system GMM estimation results for Equation (3) are shown in Table 2.

Table 2. Results for the dynamic panel regression model.

Variable	Estimate	Standard Error	Z-Statistic	*p*-Value
const	0.524	0.160	3.272	1.07×10^{-3}
log EP(−1)	0.812	0.047	17.336	2.51×10^{-67}
log farm_size	−0.145	0.038	−3.762	1.68×10^{-4}
log l_int	−0.192	0.048	−4.001	6.31×10^{-5}
log N_int	0.083	0.026	3.198	1.38×10^{-3}
log animal_share	−0.155	0.034	−4.505	6.63×10^{-6}
log arable_share	−0.125	0.036	−3.424	6.17×10^{-4}
log cereals_share	0.034	0.016	2.132	3.30×10^{-2}
Dummy variables for years				
T3	−0.027	0.014	−1.905	5.67×10^{-2}
T4	−0.089	0.015	−5.825	5.70×10^{-9}
T5	−0.083	0.015	−5.628	1.82×10^{-8}
T6	−0.100	0.014	−7.220	5.18×10^{-13}
T7	−0.124	0.014	−8.952	3.48×10^{-19}
T8	−0.051	0.014	−3.748	1.78×10^{-4}
T9	−0.098	0.014	−7.114	1.13×10^{-12}
T10	−0.069	0.014	−4.989	6.06×10^{-7}
T11	−0.098	0.014	−7.166	7.71×10^{-13}
T12	−0.041	0.014	−2.985	2.84×10^{-3}
Overall model statistics				
Standard error of estimation	0.090			
R-squared	0.968			
Test AR(2) for error term	1.409, *p*-value = 0.159			
Sargan test	63.363, *p*-value = 0.499			

To validate the model, we used two tests—the Arellano–Bond autocorrelation test and the Sargan test. The result of the first test confirmed the absence of second-order autocorrelation in the error term, while the Sargan test supported the correctness of the over-identifying restrictions. Thus, these findings support the validity of our model specification. Additionally, we found a high R-squared value (0.968), calculated as the squared correlation coefficient between the output and predicted outputs. Furthermore, all parameters corresponding to the explanatory variables were significant at a level of 0.05. Specifically, the parameter for the lagged output variable was statistically significant, confirming the persistence of the output. Therefore, the dynamic panel regression model was the appropriate specification for our analysis.

Based on the obtained results, there were significant relationships between the characteristics of agriculture and energy productivity in agriculture. For the EU-27 and the years 2010–2021, it was found that an increase in the average farm area by 1% led to a decrease in EP by 0.0145%. Another relationship was that with an increase in agriculture mechanization, which resulted from a reduction in labor inputs per 1 ha, there was an increase in EP. When human labor inputs were reduced by 1%, there was an increase in PE of 0.192%. This means that an increase in the mechanization of production directly or indirectly promotes an increase in energy productivity indicators.

An increase in the level of production intensity led to higher energy productivity. With an increase in the level of N fertilization by 1%, energy productivity increased by 0.083%.

This is relatively small, but it means that in developed countries, with an appropriate level of production technology and adjustment of the level of inputs to the needs of the plants, it is possible to achieve higher input efficiency to a certain extent, even when increasing inputs.

The next relationship concerned the significance of the production structure for the direct energy productivity obtained in agriculture. It was found that with an increase in the share of animal production in total production of 1%, there was a decrease in EP by 0.155%; with an increase in the share of arable land in agricultural land of 1%, there was a decrease in energy productivity of 0.125%; and with an increase in the share of cereals in crops of 1%, there was an increase in direct energy productivity of 0.034%. The obtained results mean that a large share of extensively used land is not conducive to increasing the productivity of direct energy inputs, probably due to the low output level. On the other hand, an increase in the share of cereals on arable land leads to an increase in the direct energy productivity index, which means that both feed and industrial plants have worse efficiency indicators. Finally, in line with our expectations, it was found that a higher share of animal production was associated with a lower energy efficiency.

It is worth emphasizing that the time effects included in the model were statistically significant. The results suggest a decline in the energy productivity index over time.

Additionally, the model incorporated the lagged output variable, indicating that energy productivity remained relatively stable across the examined periods, closely mirroring the levels observed in previous years, demonstrating high persistence.

5. Discussion

In general, a decline in the direct energy productivity index was observed in the European Union countries in the years 2010–2021. This trend occurred despite a production increase of approximately 10%, as direct energy inputs rose by 11% during the same period. A similar increase in inputs accompanied the increase in production. Although the study focuses on developed countries, achieving an improvement in energy productivity proved to be unattainable. Similar conclusions were presented for Poland [36]. On average, the level of energy productivity in agriculture was similar in the period studied, which indicates stability in the field of technique and technology in agriculture. Similar results were obtained in [44], which compared countries with intensive and extensive agriculture. However, the conclusions from another study [2], which stated that in most European countries, there was an improvement in energy productivity in agriculture, were not fully confirmed. It should, therefore, be noted that without significant changes in the structure and intensity of agriculture in the EU, no changes in energy productivity in agriculture will be achieved. Some authors indicated that CAP measures may have effects on energy productivity. For example, support for organic or coal farming aims to reduce emissions from agriculture but leads to lower energy productivity [64]. Support for agricultural modernization leads to better equipment for farms with machines and a reduction in human labor inputs, but energy use increases. Energy productivity decreases when the scale is not large enough to effectively use the machines' power.

In ref. [21], it was stated that with an increase in scale, there is a decrease in input per unit due to technological progress. Perhaps the research period is too short to confirm such observations in the case of energy inputs. However, it should be emphasized that the obtained results are similar to those described in [34], which stated that although no increase in energy productivity indicators in agriculture, in general, could be observed, significant progress was achieved in some countries by introducing energy-saving techniques, including precision farming.

The modernization of agriculture and increasing the size of farms require greater mechanization of production. This increases labor productivity but requires greater energy inputs. Energy productivity decreased along with the reduction in human labor inputs and the increase in the size of farms. Similar results were presented in other studies [4], which indicated that actions aimed at increasing the productivity of energy inputs in the EU have not yet brought the expected effects. The attempt to decouple the growth of production from the growth of energy consumption was not achieved in the period studied. As indicated by Chen et al. [9], maintaining the level of output in agriculture while reducing the energy demand is only achieved in some countries with high agricultural productivity, where it is possible to slightly reduce energy consumption by improving production technology. In our research, a decrease in energy productivity was observed with the increase in the scale of production, as measured by the size of farms. This means that hypothesis H1 was not supported. However, it should be pointed out that the next hypothesis—H2, concerning the impact of the increase in the level of production mechanization and, thus, the decrease in human labor inputs on farms—was positively verified. The increase in the level of mechanization was associated with an increase in the productivity of energy inputs. It is worth noting that the obtained results are not unambiguous because a larger scale of production is usually associated with a higher level of mechanization. Explaining the reasons for this ambiguity would require accepting a more homogeneous group of farms for the study.

No increase in energy productivity attributable to improved production technologies was observed. Changes in agricultural production technologies contributed to higher energy productivity only in the context of rapidly modernizing agriculture [22,35]. The study's findings reflect the relatively high stability of production technologies in the examined countries. This stability may also be linked to the widespread use of machinery for tillage operations, which heavily depends on fossil fuels, particularly diesel [43]. The significant share of arable land requiring frequent tillage negatively impacts energy productivity indicators.

The limited production scale is another potential barrier to realizing the benefits of technological advancements. Smaller farms often cannot invest in modern, energy-efficient solutions [26].

The study found that the increase in production intensity in EU agriculture led to a slight improvement in energy productivity indicators. The increase in the level of fertilization was associated with an increase in energy productivity. This differs from the usual finding that a high production intensity is associated with a lower energy efficiency [15,16]. Therefore, hypothesis H3 stating that energy productivity indicators deteriorate with increasing production intensity (measured as N fertilization level per 1 ha) was negatively verified. The increase in production intensity improved the degree of use of direct energy inputs.

The results obtained in our study may have resulted from the fact that other factors were taken into account simultaneously, such as the scale of production or the level of mechanization, which also influenced the obtained results and allowed this relationship to emerge. The difference in the results may also result from the fact that in the period studied, there were no significant changes in the level of production intensity in EU agriculture. The possibility of increasing the productivity of energy inputs in conventional agriculture was also noticed in [29]. Reducing the number of treatments, including fertilization treatments, is such a possibility, and the precise determination of whether there is a need to perform treatments may contribute to reducing the consumption of fuels needed to drive machines [38]. Moreover, many researchers point to the correctness of agricultural technologies and practices as an important factor leading to a higher efficiency of energy inputs [50]. Studies of agriculture in the USA [65] and China [66] presented similar results to those obtained for EU countries. Similarly, an increase in agricultural output resulting from modernization, increased intensities, and technological progress was observed there. At the same time, direct energy inputs increased faster than agricultural outputs. It can be concluded that the decreasing productivity of direct energy inputs in agriculture occurs globally and results from the increasing intensity and growth of agricultural mechanization. The share of livestock production in the EU's agricultural structure significantly influenced the energy productivity levels. An increase in the share of livestock production by 1% resulted in a 0.155% decline in energy productivity. This indicates that livestock production in the EU is more energy-intensive than crop production, which is typically intensive. Similar assessments regarding the impact of livestock production on energy productivity have been reported in other studies [45,51]. Therefore, hypothesis H4 stating that a higher share of animal production in agricultural production leads to a deterioration in energy use indicators was confirmed for EU agriculture.

These studies also highlight that the energy intensity of livestock farming varies depending on the technologies employed. A transition to energy-efficient technologies is possible, but typically only in larger herds, where automation and precision farming solutions can be effectively implemented [39,46].

However, other authors, in agreement with this study's findings, note that increasing energy productivity can also be achieved by reducing the scale of livestock production [52]. It should be emphasized, however, that limiting animal production may lower food security in the EU. Moreover, less intensive production decreases the profitability of farms in the EU [64]. Similarly, it is not beneficial when low-intensive field crops are expanded and animal feed is imported. Maintaining the volume of animal production that meets at least the domestic demand is a reasonable proposal.

The research shows that a significant increase in energy productivity in agriculture would not have been possible without major changes in production volume and structure. Similarly, ref. [1] suggested that it is necessary instead to find a solution to reduce energy consumption in other links of the food supply chain, which will lead to lower emissions per unit of product delivered to the consumer.

6. Conclusions

The structure of farms, production scale, and the intensity of agricultural production in EU countries have remained relatively stable. With increased mechanization, energy consumption has risen, resulting in a slight decline in the energy productivity index at an annual rate of approximately 1% during 2010–2021. This trend persisted despite the EU's efforts to reduce energy consumption, including in agriculture. It should be clearly stated that modernizing agriculture, maintaining production, and reducing energy consumption in agriculture are not simultaneously possible. A pro-environmental action would be to increase the share of energy from low-emission sources, especially regarding electricity consumption. We should strive to achieve sustainable goals in energy consumption, limiting the impact of agriculture on the environment, reducing emissions, and producing food for the population.

Factors such as an increased farm production scale, share of animal production, and mechanization at the expense of human labor negatively impacted the energy productivity indicators. Conversely, changes like optimizing fertilization and increasing the share of cereals in crop rotations at the expense of industrial or fodder crops positively influenced these indicators. A notable finding is that measures introduced under the EU's Common Agricultural Policy to improve energy efficiency and reduce agriculture's environmental impact did not produce observable effects during the study period. This may be attributed to conflicting forces: on the one hand, the rising mechanization and production scale lowered the energy efficiency indicators; on the other, measures to enhance these indicators were implemented. As a result, energy productivity in EU agriculture remained relatively constant. This resulted from support for the modernization and competitiveness of agriculture on the one hand and the extensification of production on the other (e.g., support for organic agriculture and crop rotation). These actions may have been implemented by different groups of farmers and in various regions. However, the effects on energy productivity may cancel each other out in the context of EU agriculture as a whole.

In the long term, reducing energy inputs per output unit seems possible only with a significant reduction in animal production and relatively extensive large-scale farming development. Large farms may appear in those production specializations where economies of scale improve energy productivity. In the European agricultural context, this would require a substantial decrease in the number of farms and potentially a reduction in intra-EU food production. This does not align with the idea of sustainable development of agriculture in EU countries. The EU within CAP influences the remaining rural social viability and maintaining family farms as core food producers. In countries where several to a dozen percent of the population works in agriculture, such solutions are not socially acceptable. It would also be challenging to gain acceptance due to both job losses and the disappearance of agricultural functions in regions dominated by small farms. Also, the scenario of reducing food production in EU countries and even a partial loss of food security is unacceptable. Hence, it should be recognized that limiting energy consumption in agriculture should not be supported if it leads to decreased agricultural output.

The adoption of efficient and precise production technologies, which enable higher yields without additional energy inputs, is a promising avenue for reducing energy intensity in agriculture. However, it is essential to understand that the changes will be relatively small. Developing sustainable low-carbon energy sources is a good idea rather than limiting energy use.

Several potential research directions can be identified. First, examining energy productivity in agriculture in individual countries is justified, given the significant disparities in agriculture structures and natural conditions. Second, focused studies on farms within particular specializations are suggested to identify best practices, including those associated with precision and sustainable agriculture. Third, exploring the relationship between direct and indirect energy inputs across various agricultural systems should be expanded to enhance understanding of the dependencies in this issue. Fourth, studies should consider the national emission level related to direct energy inputs since, in some countries, energy production is more low-carbon, especially electricity.

7. Research Limitations

The presented study was subject to certain limitations, primarily stemming from the accuracy of the source data. The reported values for direct energy inputs and production varied significantly for some countries in certain years, likely due to differences in research methodologies across countries. Another limitation lies in representing the agriculture of individual countries with a single figure, despite possible internal diversity. The impact of these limitations was mitigated by using a relatively long time series and applying panel regression. This approach allowed for the observation of the dominant trend in energy productivity.

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