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Greenhouse Gas Emissions Efficiency in Polish Agriculture

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Abstract: Analysis of the efficiency of greenhouse gas emissions in agriculture is an important part of agricultural and environmental economics research. The theme is extremely important due to the deepening problem of climate change and the simultaneous need to ensure food security. However, counteracting climate change cannot be achieved at the expense of reducing agricultural productivity. Due to the need to study the economic-environmental relationship in agriculture, the main purpose of this study was to assess the changes in the level and structure of agricultural greenhouse gas emissions and to examine the changes in efficiency of agricultural greenhouse gas emissions. The authors also estimated the relative efficiency of emissions, which allowed for comparing the efficiency of emissions between agriculture and other sectors of the national economy. Analyzing the changes in agricultural emissions efficiency, as well as changes in relative efficiency of emissions, is an indirect way of assessing whether the ongoing trends are consistent with the sustainable development concept and if the country is effective enough in mitigating climate change in relation to its economic performance. The research conducted showed that agriculture has a significant share of greenhouse gas emissions among all sectors of the Polish economy. However, greenhouse gas emissions from agriculture decreased by a total of 23.5% in the years studied. The most significant changes occurred in the context of greenhouse gas emissions from intestinal fermentation. The research also shows that the efficiency of emissions from agriculture more than doubled in the years examined. However, it decreased compared to other sectors of the economy in the country. This study was based on emissions data retrieved from National Inventory Reports prepared by the National Center for Emissions Management and on the Agricultural Statistical Yearbooks of the Central Statistical Office. This paper also proposes some examples of measures that could be taken to reduce agricultural emissions. Some of them include reducing food losses, sustainable use of fertilizers, increasing energy efficiency, and greater use of renewable energy.

Keywords: greenhouse gas emissions (GHG); agriculture; agricultural production; value added in agricultural production; sustainable development

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1. Introduction

The 21st century is an era of rapid development in technological, economic, and social terms. Because of anthropocentrism, most previous discoveries and research efforts were focused on humans without caring for the environment, which is largely reflected in its degradation [1]. Therefore, the environmental crisis is one of the biggest challenges of this millennium [2], and the analysis of environmental protection has become increasingly complex. The adoption of national environmental policies and the involvement of international bodies in environmental matters are factors that strongly contribute to debates and political discussions [3,4]. Also, environmental research is one of the key measures taken in response to the ecological crisis [5,6].

It seems worrying that agriculture—the part of the economy that is essential for humans to survive on Earth—is among the sectors with the most detrimental environmental impacts [7–9]. Of all agricultural subsectors, meat production carries the heaviest environmental burden [10]. Organic production is believed to be one of the ways to improve the

quality of agricultural produce while protecting the environment. However, Maleksaeidi and Memarbashi [11] list a series of obstacles to the development of organic farming that make it impossible to push out conventional agriculture, primarily including economic, technical, managerial, and infrastructural barriers.

Agricultural development is of key importance for food security [12], while also contributing to sustainable development goals set out by the United Nations [13,14]. The concept of sustainable agriculture is increasingly addressed in research projects and politics [15]. It is essential to make sure that the intensification of agricultural production does not become more and more harmful to the environment. There is a growing number of studies on how to reduce carbon emissions in the agricultural sector [16–18]. Indeed, in the 2010s, agricultural greenhouse gas emissions—one of the reasons behind environmental degradation—accounted for 10–12% of all emissions of greenhouse gases caused by human activities [19]. According to more recent studies, farms are accountable for ca. 16–27% of total anthropogenic emissions [20], which mostly include methane [21] and nitrous oxide [22,23]. The dominant source of methane emissions is enteric fermentation, whereas nitrous oxide is primarily generated by fertilizers and intensive soil cultivation [13]. According to a study by Tubiello et al. [24], agricultural GHG emissions grew globally at an annual rate of 1.1% between 2000 and 2010. The growing population, together with increased demand for food [25], are factors that may drive consistent growth in greenhouse gas emissions from agricultural production [26]. Some forecasts suggest that population growth coupled with increased wealth will boost the demand for meat and dairy products by 50% to 80% [27,28]. This requires increasing agricultural productivity through greater investments, which are not necessarily environmentally friendly [29]. The intensification of agricultural production largely contributes to environmental degradation [30,31]. Furthermore, the increased adoption of agricultural mechanization also adds to the environmental burden [32,33]. After World War II, Europe was not food secure. However, interventionism rapidly led to overproduction of food, which was not consistent with sustainable development principles [34]. Also, the lack of adequate control measures contributed to the irrational development of the agricultural sector.

Unfortunately, the ongoing changes carry disastrous consequences for the whole planet. Global processes such as glacier melting or rising global mean sea levels are largely caused by growing greenhouse gas emissions and resulting climate change and have become a common problem for the international community [35]. Therefore, the analysis of GHG emissions needs to be continuously extended, and a per-sector approach must be adopted. This is especially true for agriculture, which does not only impact the environment but also heavily depends on its condition [36–38].

In Poland, the agricultural sector contributes 2.5% to GDP [39]. Over the barely 30-year study period, it has undergone a major transformation, including the dismantling of state-owned agricultural holdings, the modernization of farm machinery, and becoming focused on production growth [40]. This led to a great intensification of agricultural production (even on the smallest farms, to a certain degree), which translated into higher energy consumption. Also, there is no control over how farmers manage fertilizers [41] and production waste, which leads to private economic trade-offs that do not take the economic impacts into account [42]. Socioeconomic development is supportive of sustainable agricultural development, and the demand for organic agricultural produce keeps growing. However, the conflict between social needs, the economic development of agriculture, and the environment becomes increasingly pronounced [43]. One possible answer is circular (closed-circuit) agriculture, which minimizes waste generation while implementing the recycling policy [44,45].

One of the greatest challenges of tomorrow's agriculture is to reduce greenhouse gas emissions per unit of agricultural production [46]. As regards GHGs, agriculture is the biggest source of some kinds of anthropogenic nitrogen pollution [47]. Technological changes driven by investments are viewed as an important factor in improving agricultural productivity, which should also contribute to savings in production inputs [48] and thus

minimize the negative environmental footprint. Agricultural modernization is an important step in ensuring sustainable food security [16]. While the agricultural sector consumes great amounts of energy, it can also be a source of renewables [49,50], such as biomass or biofuels [51]. Hence, the development of sustainable agriculture can promote the use of renewable energies and, as a consequence, drive a reduction in greenhouse gas emissions [50]. In order for this to happen, research efforts must be focused on analyzing historical GHG emissions, and an attempt must be made to evaluate the possible scenarios for reducing them. Monitoring the indicators of emissions efficiency could considerably contribute to finding the reasons behind excessive emission levels and to classifying the measures that should be taken in the future with a view to reducing emissions from agricultural production.

The main purpose of this study was to analyze and assess the changes in the levels of greenhouse gas emissions in Poland, with a particular focus on agriculture, and to analyze the changes in economic efficiency of greenhouse gas emissions from the agricultural sector. The changes in greenhouse gas emissions were analyzed between 1990 and 2019, which allowed us to briefly present the background of the environmental transformation in Poland. In turn, the analysis of changes in the economic efficiency of greenhouse gas emissions spanned from 2000 to 2019, which was conditioned by data availability. Based on this study, it was possible to compare the changes in economic efficiency of agricultural emissions against the national economy and to indicate some opportunities for reducing them. The topic discussed is important in research on the economics of agriculture and the environment due to the deepening development differences between agriculture and other sectors of the economy. At the same time, emphasizes the great importance of agriculture in greenhouse gas emissions. The undertaken research fills the gap in the analysis of the economic effectiveness of greenhouse gas emissions from the agricultural sector. Moreover, research on the efficiency of greenhouse gas emissions at the level of one of the larger European Union countries, in the context of the application of climate neutrality, is of great importance for expanding knowledge in this field. In the future, the method may be implemented in other countries. This study took into account greenhouse gases such as CO_2, CH_4, and N_2O, which account for more than 99% of all greenhouse gas emissions in Poland.

2. Materials and Methods

As climate change is a global process, the reduction of greenhouse gas emissions from anthropogenic sources is among the main political goals at national and international levels [52]. The key international agreements that require Poland to restrict greenhouse gas emissions include the 1994 United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol (from 2002). Under these arrangements, signatory states are committed to restricting greenhouse gas emissions and reducing them to 80% of the levels recorded in the base years (for Poland, the base year for CO_2, CH_4, and N_2O is 1989). The general assumption behind the Convention is to restrict and stabilize greenhouse gas emissions at a level that does not pose a real threat to the climate [53].

The progress in attaining the reduction goals is accounted for and monitored based on yearly inventory reports prepared as part of Poland's obligations under the UNFCCC and commitments towards the European Union (Regulation (EU) No. 525/2013 of the European Parliament and of the Council of 21 May 2013 on a mechanism for monitoring and reporting greenhouse gas emissions and for reporting other information at the national and Union level relevant to climate change) [54]. The reports provided in the national inventory framework for greenhouse gases are prepared at the national level by the National Center for Emissions Management (KOBiZE) at the Environmental Protection Institute of the National Research Institute. The documentation complies with the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, a methodology proposed by the Intergovernmental Panel on Climate Change. In accordance with the Guidelines, the yearly reports follow the Common Reporting Format in five main categories: 1. Energy,

2. Industrial processes and product use, 3. Agriculture, 4. Land use, land-use change, and forestry (LULUCF), and 5. Waste (a total of ca. 90 categories and subcategories).

However, the assessment of progress in attaining the reduction goals does not take account of the balance of emissions and removals from category 4. Land use, land-use change, and forestry (LULUCF). In addition to the main categories listed above, the report also includes subcategories that enable a detailed analysis of greenhouse gas emissions from each sector. The unification of the inventory and reporting system makes it possible to compare the countries and analyze the changes in emissions from one year to the next.

In order to attain its goal, this study used emission data at the countrywide level together with data on agricultural emissions retrieved from the KOBiZE National Inventory Reports and the UNFCCC database, which provides a comparison of data between available inventory reports. The analysis took account of selected categories from the KOBiZE reports so as to properly discuss the amount and structure of agricultural greenhouse gas emissions: 3. Agriculture, which in the case of Poland includes 3.A Enteric fermentation; 3.B Manure management; 3.D Agricultural soils 3.F Field burning of agricultural residues; 3.G Liming; 3.H Urea application; and 3.I Other carbon-containing fertilizers as well as subcategory 1.A.4.c. Emissions from energy use in agriculture under category 1. Energy. The data on Gross Value Added of agricultural production—which reflects economic outcomes—was retrieved from the Statistical Yearbooks of Agriculture of the Central Statistical Office (the base year is 2019; adjusted values were used in this study).

Measuring the efficiency of greenhouse gas emissions is a way to gauge how successful a country is in maintaining emissions at a low level relative to economic performance or production volumes, for instance [55]. The relationships between the economic effects of Polish agriculture and greenhouse gas emissions, referred to as the economic efficiency of greenhouse gas emissions, were calculated as per the following formula [56–58]:

$$EEr = \frac{GVA_a}{E_a} \quad (1)$$

where:

GVA_a: gross value added of agriculture;

E_a: greenhouse gas emission from agriculture.

The next step consisted in estimating the relative emissions efficiency based on the following formula [56–58]:

$$WEE = \frac{GVA_a}{E_a} / \frac{GVA}{E} \quad (2)$$

where:

GVA_a: gross value added of agriculture;

GVA: gross value added at national level;

E_a: greenhouse gas emissions from agriculture in the country concerned.

E: greenhouse gas emissions at the national level.

Estimating the relative efficiency of emissions laid the groundwork for a discussion on emissions efficiency in agriculture compared to other sectors of the national economy.

The discussed method clearly illustrates changes in emissions efficiency and is suitable for illustrating changes in a selected country in a relatively short period of time. Thanks to the use of the method, it was possible to show changes in gross value added in PLN million per kt CO_2e. The literature also examines the impact of various factors on changes in emission efficiency. For this purpose, more advanced methods suitable for panel data and longer time series are used; these include stochastic frontier analysis (SFA), data envelopment analysis (DEA), or autoregressive distributed lag (ARDL) [59–61].

In turn, a discussion on changes in agricultural greenhouse gas emissions in the context of evolving economic circumstances allows us to tell whether the trends are consistent with the sustainable development concept, i.e., if the environmental and economic changes are not contradictory to one another.

3. Results and Discussion

The analysis of inventory reports provides grounds for concluding that Poland witnessed changes in greenhouse gas emissions between 1990 and 2019 (Table 1). Socialism treated the exploitation of the environment as a necessary cost of development [62], hence there were real changes in this area after its collapse. Total gaseous emissions dropped from 475,000 kt CO_2e to nearly 387,000 kt CO_2e, i.e., by 18.67%. The same results of changes in greenhouse gas emissions were shown by [63], proving that they decreased in several EU countries, including Poland. The biggest positive changes took place right after the 1989 Polish economic transformation and after the introduction of the first climate regulations in the 1990s. A decline in emissions was recorded in all main categories, i.e., 1. Energy, 2. Industrial processes (. . .), 3. Agriculture, and 5. Waste. The latter experienced the greatest transformation, with an over 44% reduction in emissions, mostly driven by the tightening of regulations for waste management [64]. Another significant drop (by nearly 34%) was witnessed in category 3. Agriculture. The most important period for reducing agricultural emissions is 1990–2000, i.e., the years that directly followed the economic transformation. It was primarily marked by the dismantling of large state-owned farms, the increase in economic activity, the liberalization of trade, and new investments—all of which made agriculture much less important. In category 1. Energy, emissions dropped by almost 16%. The smallest change took place in category 2, with a reduction of less than 9.5%. The energy sector is still an emitter of a significant portion of the total amount of greenhouse gases [65].

Table 1. Emissions of selected greenhouse gases in Poland by category in 1990, 2000, and 2019 [kt CO_2e].

Category	1990	2000	2019	Change [%] (2019/1990)	Change [%] (2019/2000)
Total (except for Cat. 4)	475,721.1	395,328.4	386,898.5	−18.7%	−2.1%
1. Energy	373,832.7	307,815.3	310,285.9	−17.0%	0.8%
2. Industrial processes (. . .)	22,403.9	21,809.6	20,283.0	−9.5%	−7.0%
3. Agriculture	49,424.9	33,491.4	32,735.4	−33.8%	−2.3%
5. Waste	21,498.4	18,317.7	11,992.5	−44.2%	−34.5%
1.A.4.c. Emissions from energy use in agriculture	8561.1	13,894.3	11601.7	35.5%	−16.5%

Source: my own compilation based on Poland's National Inventory Report 2021 [54].

Interestingly, despite the emissions in the main categories becoming increasingly smaller over that period, growth was recorded in category 1.A.4.c: Emissions from energy use in agriculture (from 8500 kt CO_2e to more than 11,500 kt CO_2e, i.e., by over 35%. This was mostly due to agricultural mechanization, which involves the consumption of fossil fuels [66]. However, energy is the key factor in making agriculture more efficient [67], and therefore an increased share of energy use in greenhouse gas emissions is the consequence of improvements in agricultural efficiency. Because of these changes, agricultural emissions grow despite agriculture having a declining share in the economy (as also reflected in emission changes in category 3. Agriculture). Moreover, as the agricultural sector is now both a supplier of raw energy materials and a consumer of energy, the relationship between agriculture and the energy sector becomes more complicated and also more important to the analysis [68]. Imran and Ozcatalbas (2021) [69] showed that efficient use of energy in agriculture and reduction of greenhouse gas emissions will lead to efficient use of resources and sustainable production.

Changes are also evident in the structure of greenhouse gas emissions in Poland (Figures 1 and 2). In the first and last year covered by the study (1990 and 2019), category 1. Energy contributed the most to total emissions (78.6% in 1990 and 80.2% in 2019). While high levels of energy consumption stimulate economic growth, they also drive an increase in environmental costs [70], especially in Poland, where most energy is derived from non-renewable sources [71]. The second-largest share of greenhouse gas emissions was that of category 3. Agriculture. However, it dropped by nearly 2 percentage points over the study period because of the reduction in agricultural production volumes, including smaller animal

numbers. A decline was also recorded in categories 2 and 5. However, just like in subcategory 1.A.4.c related to agricultural energy use, there was growth compared to 1990. Its share in the emissions structure went up from 1.8% to 3%. Based on the analysis of the structure of greenhouse gas emissions in Poland, it has to be noted that agriculture accounted for ca. 12.2% of total emissions in 1990 and ca. 11.5% in 2019, which represents a considerable contribution to anthropogenic emissions. However, this also has to do with the fact that Poland's agricultural sector is one of the largest among European Union member states [72].

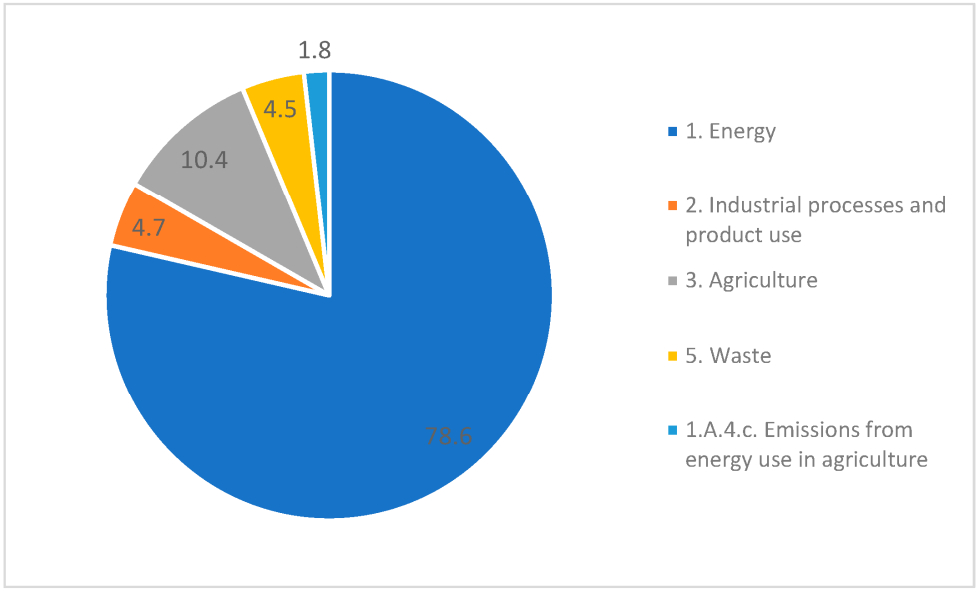


Figure 1. Share of categories of greenhouse gas emissions in Poland in 1990 [%] (without category 4). Source: my own compilation based on Poland's National Inventory Report 2021 [54].

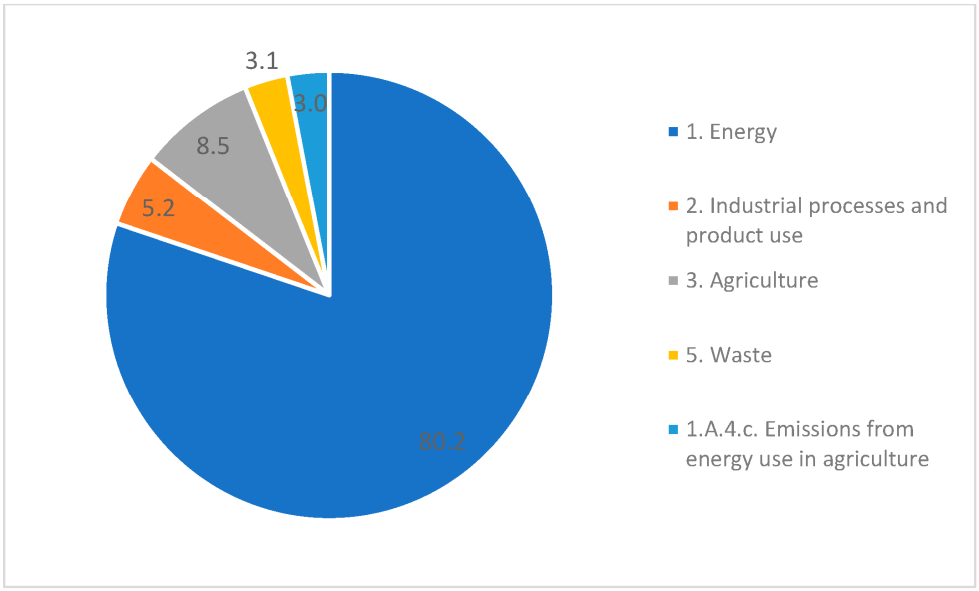


Figure 2. Share of categories of greenhouse gas emissions in Poland in 2019 (without category 4). Source: my own compilation based on Poland's National Inventory Report 2021 [54].

The volume of agricultural emissions fluctuates due to changes in animal numbers, in the mix of agricultural production, and in the use of plant protection products and fertilizers [73,74]. In Poland, greenhouse gas emissions from agriculture dropped by a total of 23.5% over the study period (Table 2). Subcategories of category 3: Agriculture also demonstrate a reduction in emissions from all sources covered by the inventory,

which is consistent with the countrywide trend and with changes taking place in their parent category. As mentioned before, this is primarily due to the declining importance of agriculture in the country's economic structure and the related decrease in animal numbers, reduced use of fertilizers, and a change in agricultural practices [75]. The biggest changes took place in subcategory 3.A, Enteric fermentation, with a nearly 7000 kt CO_2e drop in emissions between 1990 and 2019. The reduction in subcategories 3.D Agricultural soils and 3.G Liming was ca. 6000 kt CO_2e and 1500 kt CO_2e, respectively. In other cases, emissions were not that high or the drops were not that important (the largest emissions in the agricultural sector come from enteric fermentation [76]). In turn, emissions related to agricultural energy use went up by ca. 3000 kt CO_2e, which—as explained above—is due to agricultural mechanization. Detailed changes in the structure of greenhouse gas emissions from agriculture and descriptive statistics are presented in the Table attached to the Appendix A (Tables A1 and A2).

Table 2. Emissions of selected greenhouse gases from agriculture in Poland, grouped by source, in 1990 and 2019 [kt CO_2e].

Category	1990	2000	2019	Change, 2019/1990 [%]	Change, 2019/2000 [%]
Total	57,986.0	47,385.72	44,337.1	−23.5%	−6.4%
3.A Enteric fermentation	19,649.9	12,293.3	12,699.2	−35.4%	3.3%
3.B Manure management	2087.6	1637.6	1186.0	−43.2%	−27.6%
3.G Liming	2099.4	1095.0	541.4	−74.2%	−50.6%
3.H Urea application	571.1	457.1	411.4	−28.0%	−10.0%
3.I Other carbon-containing fertilizers	236.1	296.9	169.9	−28.0%	−42.8%
3.B Manure management	4075.3	2898.7	2798.8	−31.3%	−3.4%
3.D Agricultural soils	20,674.8	14,785.6	14,895.2	−28.0%	0.7%
3.F Burning of agricultural residues	30.6	27.1	33.4	9.1%	23.2%
1.A.4.c. Emissions from energy use in agriculture	8561.1	13,894.3	11,601.7	35.5%	−16.5%

Source: my own compilation based on Poland's National Inventory Report 2021 [54].

Due to access to economic data, the changes in the efficiency of greenhouse gas emissions in agriculture were calculated for the period 2000–2019 (Table 3). The years between 1990 and 2000, which directly followed the economic transformation, were marked by unprecedented rapid transformations. Economic transformation has significantly contributed to changes in greenhouse gas emissions in Poland [77]. This makes the post-2000 interval a good study period where above-average economic changes stopped and the economic situation became stable.

Table 3. Efficiency of agricultural emissions in Poland: emissions volume in relation to gross value added of agricultural production and total volume in 2000–2019.

Year	EER [PLN Million/kt CO_2e]	WEE Ratio	Year	EER [PLN Million/kt CO_2e]	WEE Ratio
2000	0.56	0.22	2010	0.82	0.17
2001	0.56	0.21	2011	0.90	0.18
2002	0.52	0.19	2012	0.99	0.18
2003	0.53	0.19	2013	1.10	0.20
2004	0.76	0.25	2014	1.00	0.17
2005	0.63	0.20	2015	0.86	0.14
2006	0.66	0.19	2016	0.96	0.15
2007	0.84	0.22	2017	1.14	0.18
2008	0.73	0.18	2018	1.01	0.15
2009	0.74	0.16	2019	1.22	0.16

Source: my own compilation based on KOBiZE and Central Statistical Office data.

This study reveals that the absolute efficiency of agricultural emissions grew from ca. 560,000 PLN/kt CO_2e to 1.22 million PLN/kt CO_2e (i.e., more than doubled) over the study period (descriptive statistics are presented in the table attached to Table A3). It means that agricultural production, which involved emitting 1 kt CO_2e generated more and more gross value added from agriculture. The increase in efficiency was recorded almost every year (Figure 3). The first major growth was witnessed in 2004, which could be related to Poland's accession to the European Union and the ability to expand into intra-community markets. In the years after the accession, there was fluctuation in efficiency, but the growth trend continued. A slight decline was recorded between 2007 and 2008–2009, which could be explained by the global crisis. In the next few years, efficiency grew at a relatively fast rate until 2013, when it exceeded 1 million PLN/kt CO_2e. Then, it went down again in 2014 and 2015, probably because of the shift in power and the changes to the trade policy. In summary, the efficiency of agricultural emissions in Poland more than doubled over the study period. Although no major changes in greenhouse gas emissions were recorded during these years, there was growth in efficiency, mostly because of production intensification (including higher yields), which is a beneficial trend. However, greater efficiency could be attained by reducing emissions. This is the goal that Poland should attain in the years to come. The transformation of agriculture towards low-emission practices is associated with balancing production and consumption processes while reducing greenhouse gas emissions [78].

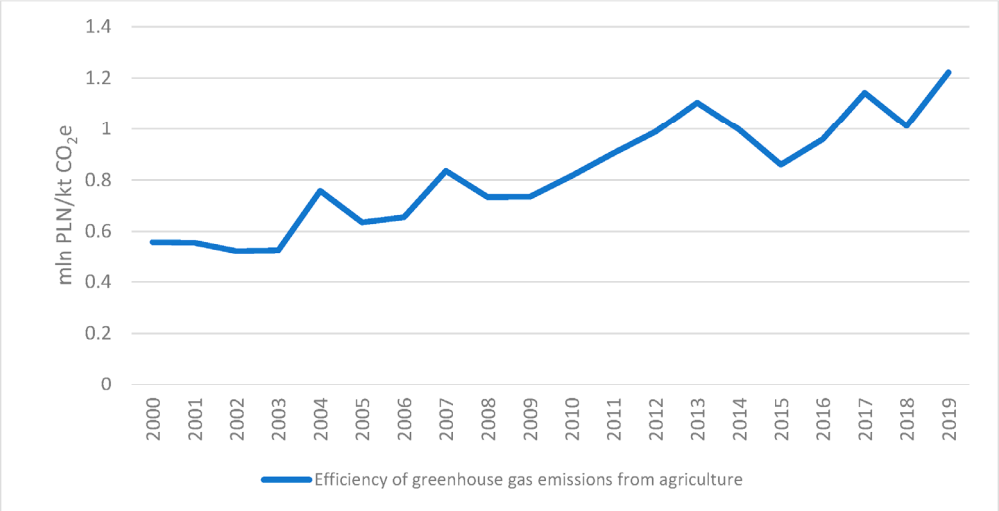


Figure 3. Efficiency of greenhouse gas emissions from agriculture in Poland. Source: my own compilation based on KOBiZE and Central Statistical Office data.

The analysis of relative efficiency figures suggests that, compared to other sectors, agriculture experienced a drop in efficiency (Figure 4). The ratio fell from 0.22 in the initial year to 0.16 in the last sub-period of this study. It means that the economic efficiency of emissions in agriculture grows slower and in a less effective way than in other sectors of the national economy. It also suggests that emitting 1 kt CO_2e in other industries can add more economic value.

In the study period, positive changes in greenhouse gas emissions from agriculture were more significant than in other sources of emissions. It can therefore be concluded that agriculture attained a higher level of environmental performance than other areas accountable for greenhouse gas emissions. In the environmental context, this is a satisfactory result. However, the changes in economic efficiency of emissions suggest that despite the growth in economic efficiency of its greenhouse gas emissions, agriculture lags behind the national economy. In the light of sustainable development principles—which assert equality between economic and environmental aspects—it can be noticed that the economic transformation accompanied by positive environmental transformation is not as positive/effective in agriculture as in other sectors. This prompts action in the area

of management practices and the implementation of new technologies in agriculture so that economic decisions are environmentally friendly [79]. The analysis of environmental efficiency in Poland is important in connection with activities towards climate neutrality in the European Union. In this sense, the research conducted is also of a nature that allows for its extension to other European Union countries.

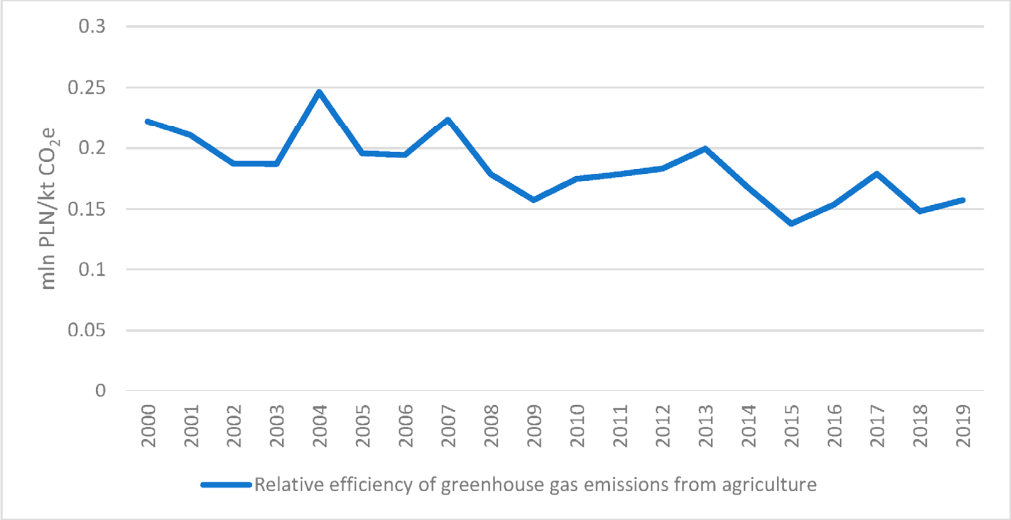


Figure 4. Relative efficiency of greenhouse gas emissions from agriculture compared to the national economy. Source: my own compilation based on KOBiZE and Central Statistical Office data.

4. Discussion

As agriculture continues to greatly contribute to greenhouse gas emissions, it is essential to find and identify the areas where changes can be implemented and pollutant emissions can be reduced [80]. The reduction of greenhouse gas emissions has a real impact on mitigating climate change [66,81]. Any measures put in place become more effective when aligned with regional conditions. The Polish case study reveals that the main sources of gaseous pollution can be ranked as follows: agricultural soils, enteric fermentation, emissions from energy use, and manure management. Table 4 presents a summary of examples of how to reduce greenhouse gas emissions from agriculture.

Table 4. Examples of how to reduce greenhouse gas emissions from agriculture in Polish realities.

Source	Result	Reduction Method
Enteric fermentation	Accounts for ca. 30% of total agricultural emissions, including CH_4 in particular.	- changes in human diet; reducing the consumption of meat; changes in the structure of meat consumption (e.g., a higher share of poultry whose production generates less methane); - reducing food waste; - changes in animal diet, e.g., specialized feedingstuffs that reduce/bind methane
Liming/urea application/other fertilizers	GHG emissions from the use of nitrogenous fertilizers	- reducing the use of mineral fertilizers; - choosing appropriate forms of nitrogenous fertilizers; - using inhibitors; - proper fertilizer management (applying fertilizers at a rate not in excess of what the plants can use within a given period); - reducing nutrient losses, e.g., by restricting surface run-offs;

Table 4. *Cont.*

Source	Result	Reduction Method
Manure management	Atmospheric emissions (N_2O in particular)	- proper manure management; - use of animal excrement in biogas production;
Emissions from energy use (. . .)	CO_2 emissions caused by energy use in agriculture	- increasing energy efficiency; - use of renewable energies; - use of enhanced sources of nuclear energies;
Agricultural soils	N_2O emissions	- soil carbon sequestration, e.g., by sowing appropriate seeds (e.g., clover) between harvests;

Source: own elaboration based on Gołasa et al. [36], Smith et al. [82], Johnson et al. [83].

The key method for reducing emissions from enteric fermentation consists of changing consumption patterns and reducing the consumption of beef, pork (though to a lesser degree), and milk, i.e., products originating from farmed animals, which are accountable for the greatest emissions of methane. However, it may be difficult to meet that goal because of increased wealth in society and unified nutrition trends [84], which at the global level, include growing levels of meat consumption [85]. Also, this is somehow contradictory to sustainable development assumptions, according to which environmental growth should not pose a barrier to social growth [86,87]. Indeed, addressing the need for food and seeking optimum ways of feeding the human body, i.e., qualitative aspects of human life, are, in a way, the goal of economic development and cannot be neglected. These products demonstrate high nutritional qualities and are difficult to replace by an equivalent with similar quantities of easily digestible protein and fat. Hence, reducing the consumption of meat and milk is not a perfect solution. However, a good practice for reducing methane emissions from enteric fermentation could be, for instance, to use appropriate animal feedingstuffs, farm appropriate animal species [88,89], and—perhaps as the first thing to do—reduce food waste [90]. As regards other sources, the problem of excessive emissions can be solved with such tools as targeted agricultural techniques, e.g., sowing clover; proper fertilization, which takes the physical and chemical properties of soil and local conditions into account; and the use of green energy [91,92].

Therefore, the reduction of agricultural emissions is a feasible goal that can also be attained in Poland. Indeed, it is possible to increase the efficiency of greenhouse gas emissions in agriculture while maintaining, if not increasing, the economic efficiency of agriculture and reducing emissions.

5. Conclusions

Anthropogenic greenhouse gas emissions cause climate change, which, in turn, pose a threat to human health and life and can become a barrier to continued economic growth (e.g., in the form of payments for emission allowances). There is a particularly strong relationship between climate change and agriculture. Greenhouse gas emissions from agriculture cause climate change, which, in turn, is of major importance to agricultural productivity. Thus, it is essential to understand the scale of greenhouse gas emissions from agriculture, identify their main sources, and pinpoint the potential areas where they may be reduced while maintaining high levels of economic efficiency and agricultural productivity.

It follows from this study that in Poland, agriculture accounted for ca. 12% of anthropogenic emissions in 2019. Over the years, there was a decline in agricultural emissions (by 23.5% compared to 1990 and ca. 6.5% compared to 2000). The greatest changes were witnessed in emissions caused by agricultural energy use, which increased by 35.5% compared to 1990. After 2000, they dropped a bit, probably due to the climate policy. However, in the

context of economic efficiency, these changes come as no surprise because energy is the key factor in making agriculture more efficient [67]. Therefore, an increased share of energy use in greenhouse gas emissions is a condition for increasing agricultural efficiency. The above can also explain the relatively positive changes in the relationship between greenhouse gas emissions from agriculture and the economic performance of the agricultural sector. The efficiency of agricultural emissions grew from ca. 560,000 PLN/kt CO_2e to 1.22 million PLN/kt CO_2e (i.e., more than doubled) over the study period. It means that Poland is increasingly successful in maintaining emissions at a low level relative to economic performance. However, relative agricultural emissions reveal that this is where agriculture lags behind other sectors. That ratio went down over the study period, which means that the gap between agriculture and other industries keeps growing and that agriculture could improve its environmental competitiveness. In the future, it would be necessary to identify the factors determining changes in emission efficiency and improve the emission efficiency ratio of agriculture compared to other sectors.

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Appendix A

Table A1. Shares of individual sources in GHG emissions from agriculture in Poland in 1990–2019.

Category	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
3.A Enteric fermentation	33.9	33.6	32.4	29.4	28.7	27.4	26.8	26.9	27.1	26.4	25.9	25.4	25.6	25.9	25.0	25.1	26.6	27.3	26.9	27.1	27.2	27.3	27.4	27.3	27.8	29.0	27.8	27.2	27.4	28.6
3.B Manure management	3.6	4.0	4.1	3.6	3.5	3.6	3.3	3.3	3.4	3.5	3.5	3.5	3.9	4.0	3.8	4.0	4.1	4.0	3.6	3.4	3.4	3.2	3.0	2.9	3.0	3.1	2.9	2.7	2.7	2.7
3.G Liming	3.6	3.0	2.7	2.6	2.3	2.9	2.8	3.0	2.9	2.4	2.3	2.3	2.3	2.2	2.2	2.1	1.3	0.9	0.9	0.8	0.9	0.9	0.8	1.0	1.1	0.9	1.5	1.1	1.1	1.2
3.H Urea application	1.0	0.4	0.5	0.4	0.5	0.5	0.6	0.5	0.6	0.8	1.0	0.7	0.7	0.7	0.8	0.9	0.9	1.0	1.0	1.1	1.1	1.1	1.2	1.3	1.2	1.1	1.1	1.1	1.1	0.9
3.I Other carbon-containing fertilizers	0.4	0.3	0.2	0.3	0.4	0.5	0.5	0.5	0.6	0.7	0.6	0.5	0.6	0.6	0.6	0.5	0.6	0.6	0.6	0.6	0.6	0.7	0.7	0.7	0.7	0.6	0.6	0.7	0.7	0.4
3.B Manure management	7.0	7.3	7.3	6.6	6.6	6.4	6.2	6.1	6.3	6.2	6.1	6.1	6.2	6.0	5.6	5.8	6.1	6.3	6.0	5.9	6.0	5.9	5.7	5.7	5.8	6.1	6.0	5.9	6.1	6.3
3.D Agricultural soils	35.7	31.5	29.7	29.9	29.2	30.5	30.0	29.6	30.8	30.3	31.2	32.0	31.9	31.1	32.0	31.2	33.3	35.2	35.5	35.7	34.3	35.3	35.3	36.1	36.0	35.2	35.2	35.3	34.8	33.6
3.F Burning of agricultural residues	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
1.A.4.c. Emissions from energy use in agriculture	14.8	19.7	23.0	27.1	28.8	28.2	29.8	30.1	28.1	29.6	29.3	29.4	28.7	29.4	29.8	30.5	26.9	24.6	25.3	25.3	26.5	25.5	25.9	25.0	24.3	23.9	24.7	25.9	25.9	26.2

Source: my own compilation based on Poland's National Inventory Report 2021 [54].

Table A2. The statistical description of the variables (1990–2019) [kt CO_2e].

Variable	Min	Median	Mean	Max.	Std. Dev.
1. Energy	302,641.5	326,101.4	330,552.3	373,832.7	20,878.1
2. Industrial processes (. . .)	16,685.4	20,171.6	20,318.2	24,365.1	1700.1
3. Agriculture	31,412.4	33,074.5	34,594.1	49,424.9	3721.2
5. Waste	11,992.5	16,996.5	16,871.8	21,498.4	2673.9
1.A.4.c. Emissions from energy use in agriculture	8561.1	11,846.1	12,380.9	15,844.7	1786.5
3.A Enteric fermentation	11,259.7	12,093.4	13,053.2	19,649.9	1941.2
3.B Manure management	1186.0	1700.2	1620.3	2124.9	266.4
3.G Liming	336.7	968.4	906.4	2099.4	479.4
3.H Urea application	218.3	410.0	396.4	571.1	103.4
3.I Other carbon-containing fertilizers	122.8	263.2	259.2	368.2	52.3
3.B Manure management	2483.4	2770.8	2919.9	4075.3	418.1
3.D Agricultural soils	13,826.6	15,297.9	15,407.5	20,674.8	1141.1
3.F Burning of agricultural residues	26.0	30.9	31.2	38.4	3.4

Source: my own compilation based on Poland's National Inventory Report 2021 [54].

Table A3. The statistical description of the variables (2000–2019) [mln PLN].

Variable	Min	Median	Mean	Max.	Std. Dev.
gross value added of agriculture	23,381.3	35,824.3	36,615.6	54,195.9	8974.6
gross value added at national level	993,153.4	1,861,906.0	1,850,794.0	3,006,953.2	609,028.1

Source: my own compilation based on Central Statistical Office data.

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