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Economic and Energy Assessment of Emissions from European Agriculture: A Comparative Analysis of Regional Sustainability and Resilience

Lilia Șargu [1], Gabriela Ignat [2,*], Angela Timuș [1], Ioan Prigoreanu [2,*] and Nicu Șargu [3]

[1] National Institute for Economic Research, Academy of Economic Studies of Moldova, 45 Ion Creanga Street, MD-2064 Chisinau, Moldova; sargu.lilia@ase.md (L.Ș.); timus.angela@ase.md (A.T.)
[2] Faculty of Agriculture, "Ion Ionescu de la Brad" Iasi University of Life Sciences, Mihail Sadoveanu Alley, 700489 Iasi, Romania
[3] Faculty of Finance, Academy of Economic Studies of Moldova, 61 Banulescu-Bodoni Street, MD-2005 Chisinau, Moldova; nicu.sargu@mail.ru
* Correspondence: gabriela.ignat@iuls.ro (G.I.); ioan.prigoreanu@iuls.ro (I.P.)

Abstract: This study analyzes the economic and energy dimensions of greenhouse gas (GHG) emissions from agriculture at the European level, making a regional comparison for the period 2000–2022. The research assesses the sustainability and resilience of agricultural systems through regional comparisons, analyzing emissions at the farm and agricultural land level using indicators such as emissions per capita, emissions relative to economic value and emissions per hectare of agricultural land, providing insights into the disparities between Eastern, Northern, Southern and Western European regions. The results reveal significant variations in emissions intensity and sustainability practices between regions, with Northern Europe showing the highest emissions per unit due to intensive agriculture, Southern and Eastern Europe showing lower emissions influenced by climatic conditions and economic transitions, and Western Europe showing a balance between agricultural intensification and sustainability due to early adoption of advanced technologies. The study underlines the importance of adapting regional strategies to increase sustainability and energy resilience in agriculture, providing valuable insights for integrating renewable energy sources, optimizing resource use and implementing targeted policies to reduce emissions.

Keywords: agricultural sustainability; greenhouse gas emissions; energy resilience; regional disparities; sustainable agricultural practices

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1. Introduction

Agriculture plays a key role in the European Union (EU) economy, contributing to food security and economic development, yet agricultural activities are a major source of greenhouse gas (GHG) emissions, negatively impacting the environment and accelerating climate change. GHG emissions from agriculture are influenced by a number of factors, such as land use, intensification of agricultural activities, livestock farming and the use of fertilizers and pesticides [1], so in the context of European climate policies such as the European Green Pact [2] and the "Farm to Fork" strategy [3], reducing emissions from agriculture is becoming a key priority. However, EU countries differ significantly in their farming systems and emission levels, and a deeper understanding of the trends of convergence or divergence between countries is needed; thus, in 2022, agriculture accounted for about 12% of total EU greenhouse gas (GHG) emissions, equivalent to 380 million tons of CO_2 [4], of which almost two-thirds came from meat and dairy farming [5]. Over the

period 2005–2022, emissions from the agricultural sector fell by about 1 million tons of CO_2 annually [6], equivalent to a total reduction of only 5%; this decrease underlines the effectiveness of EU-wide programs and policies to make agriculture one of the least polluting sectors after 2030.

Direct emissions from EU agriculture are projected to fall significantly, especially from the livestock sector [7], as livestock numbers are reduced and the shift to more extensive production systems. According to data from the European Environment Agency (EEA) [8] and the FAO [9], agriculture is a significant contributor to greenhouse gas (GHG) emissions in Europe; thus, in 2017, agriculture contributed about 20% of global GHG emissions, including 11% from direct agricultural activities and 9% from associated land use.

In 2023, the EU experienced its warmest year on record, with increased average temperatures and a northward shift of agroclimatic zones, and due to severe droughts and extreme heat waves, large areas in regions such as the Mediterranean and Eastern Europe were severely affected, contributing to significant losses in productivity [10]. Demand for biofuels is declining as advanced production increases, with biofuels derived from municipal waste projected to become the main source of biofuel by 2035, replacing much of the use of vegetable oils for energy [11].

Methane, nitrous oxide and carbon dioxide from agriculture have different characteristics and require specific approaches [12]; in addition, the lack of standardized reporting tools at the farm level and the difficulties related to ongoing land management complicate the implementation of an effective accountability system [13]. A standard for reporting greenhouse gas (GHG) emissions in agriculture is to collect, measure and report emissions from agricultural activities in order to ensure transparency, comparability and efficiency in managing environmental impacts. Thus methane (CH_4), mainly from enteric fermentation [14], contributes 49% of total agricultural GHG emissions [15], followed by nitrous oxide (N_2O) emitted from soils, which accounts for 30% [16], and manure management is the third major source, with a contribution of 17% [4], while other agricultural sources, although present, have a low impact, accounting for less than 5% of the total [17].

Industry and agriculture play a key role in ensuring food security, technological development, job creation and maintaining economic competitiveness, yet these sectors are among the largest contributors to GHG emissions, with negative effects on air quality, biodiversity and human health [18]. While progress has been made in reducing emissions in some Member States, differences between EU countries remain significant, and mitigation strategies need to be tailored to the specific economic and structural context of each region [19].

Carbon emissions from agriculture have become a major global concern in the context of intensifying climate change and international efforts to meet emission reduction targets. Thus, agriculture is recognized as one of the main contributors to greenhouse gas (GHG) emissions, being responsible in particular for methane (CH_4) and nitrous oxide (N_2O) emissions, which contribute significantly to global warming [20]. Within this framework, a comprehensive review of research on carbon emissions from agriculture can support the development of effective policies to protect the environment without compromising economic progrowth.

Over the last decades, research on agricultural carbon emissions has evolved from simple estimates of emissions [21] to complex studies on drivers [22,23], abatement methods [24] and sustainable management strategies [25,26]. In the context of the EU's commitments under the European Green Pact and the emission reduction targets set for 2030 and 2050, it is essential to analyze the structure and dynamics of agricultural emissions in order to identify the most effective abatement measures. Agriculture contributes to GHG emissions through several main sources, including enteric fermentation of ruminants [27],

manure management [28], fertilizer use on agricultural soils [29], burning of agricultural residues [30] and application of lime and urea [31]. Despite some progress in reducing emissions, the decrease to date is below the EU's targets, which requires further action to accelerate the transition towards more sustainable agriculture.

The research aims to analyze the sustainability and energy resilience of greenhouse gas emissions (CO_2, CH_4, N_2O) from agriculture at the European level, with a focusalization on the regional comparison between Eastern, Northern, Southern and Western Europe. Thus, the study aims to identify trends in emissions at the farm gate and on agricultural land, to correlate emission indicators with agricultural intensity (per capita, per economic value and per hectare) and to highlight the main regional differences in agricultural resource management to support the transition towards more sustainable agricultural practices.

The main research objectives are:

O1: To analyze regional trends in greenhouse gas emissions (CO_2, CH_4, N_2O) from agriculture at the European and regional level between 2000 and 2022 according to European regions (East, North, South and West) with a focus on identifying the main trends and variations.

O2: Assessment of regional disparities in emission contributions, highlighting how agricultural intensity, resource use and environmental practices influence emission levels and sustainability outcomes.

O3: Assessing sustainability and resilience in agriculture through correlations between regional emissions (per capita, per economic value and per hectare) and total EU-wide emissions, using linear regression and other relevant statistical methods to understand the impact of regional agricultural practices on sustainability.

The research will provide a detailed analysis of trends in greenhouse gas (CO_2, CH_4, N_2O) emissions from agriculture at both European and regional (Eastern, Northern, Southern and Western Europe) levels, highlight disparities in agricultural emissions between European regions, taking into account factors such as agricultural intensity, resource use and environmental management practices, and by exploring the relationships between emissions and key indicators (e.g., emissions per capita, emissions per value of agricultural output and emissions per hectare of agricultural land), the research aims to identify the regional drivers of emissions and their impact on the overall sustainability of European agriculture. The results will establish a framework for ongoing analysis of emissions from agriculture, providing a basis for future research on innovative solutions for achieving low-emission and climate-resilient agriculture in Europe.

2. Materials and Methods

2.1. Data Sources and Materials for Analyzing Energy Sustainability and Resilience

For the analysis of the sustainability and energy resilience of emissions from agriculture in Europe, relevant data and resources were used from the FAO database, Emissions Indicators section [32], available at FAOSTAT, which provided data on greenhouse gas emissions (CO_2, CH_4, N_2O) from agriculture for the period 2000–2022, and the geographical regions included in the analysis were: Eastern Europe, Northern Europe, Southern Europe and Western Europe [33].

The indicators analyzed in the study include both total greenhouse gas (GHG) emissions and normalized indicators, which allow a more accurate comparative assessment between regions. Thus, total GHG emissions are represented by the three main gases: carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), which have a significant contribution to climate change and are analyzed for each European region for the period 2000–2022.

In addition to total values, normalized indicators were used to compare the efficiency and sustainability of emissions between different regions:

- Emissions per capita (t/capita): measures average emissions relative to the population in each region, reflecting the individual environmental impact [34];
- Emissions per economic value (kg/Int$): measures emissions relative to the value of agricultural output, reflecting the economic efficiency of agricultural activities [35];
- Emissions per hectare of agricultural land (t/ha): indicates the intensity of emissions in relation to the agricultural area used, providing information on pressure on natural resources [36].

These indicators allow a more detailed understanding of regional sustainability and help to identify differences in agricultural practices and resource use efficiency.

Emissions per capita in agriculture have decreased significantly in recent years due to the implementation of effective measures aimed at sustainability and resilience [37,38]. An important factor in this reduction has been the transition to renewable energy sources in the agricultural sector [39]: the use of solar panels [40], biogas from organic waste [41] and wind energy has contributed to reducing dependence on fossil fuels, thereby reducing CO_2 emissions per capita. In parallel, the adoption of energy-efficient agricultural technologies has played a key role: the use of modern equipment, such as electric or hybrid tractors and machinery, together with smart irrigation systems and digital crop monitoring, has optimized resource consumption and reduced energy losses [42]. These measures are part of broader strategies supported by EU policies such as the European Green Pact [43] and the LULUCF Regulation [44], which aim to reduce emissions and make agriculture more resilient to climate change.

Innovative and sustainable measures in the agricultural sector have played a key role in reducing emissions relative to economic value by adopting the principles of the circular economy, which promotes the efficient reuse and use of resources. By reducing waste and optimizing production flows, farms have been able to reduce emissions per unit of economic value produced [45]. The introduction of low-carbon farming practices has also contributed considerably to this decrease: the use of organic fertilizers instead of chemical fertilizers [46], the reduction of soil inputs to conserve soil carbon and the implementation of precision farming technologies for efficient resource management [47].

Emissions per hectare of agricultural land have been significantly reduced through the adoption of sustainable agricultural practices aimed at optimizing the use of resources and contributing to soil carbon sequestration. An effective strategy in this regard is crop rotation, which prevents soil depletion and maintains soil fertility, thus reducing the need for intensive use of chemical fertilizers with negative environmental impacts [48,49], and the integration of leguminous crops in crop rotation plays a key role, due to the ability of these crops to fix atmospheric nitrogen in the soil.

Auxiliary sources used to determine the sustainability and energy resilience of agricultural emissions have been European agricultural policies [50–53], such as the implementation of sustainability measures (GAEC—Good Agricultural and Environmental Conditions) [54–59], socio-economic data for analyzing the impact of emissions [60–62], such as the value of agricultural production and available agricultural land [63–65].

For data analysis and visualization of the results, statistical analysis software (IBM-SPSS—Statistics, versions 26) was used to perform statistical analyses, including calculating Pearson correlations and performing linear regressions. This software facilitated the identification of the relationships between the studied variables, such as GHG emissions and norm-measured indicators, and allowed obtaining the relevant coefficients for the observed trends and data visualization tools (Microsoft Excel) for initial data pro-

cessing, tabular organization and generation of descriptive graphs, such as the percentage change in emissions by region.

According to the FAO database (FAOSTAT) [33], Europe is divided into four major regions: Eastern Europe, Northern Europe, Southern Europe and Western Europe. Each European region contributes differently to total emissions from agriculture, reflecting their geographical and economic specificities; thus, while Western Europe and Northern Europe focus on reducing emissions through advanced technologies and stringent policies [66], Southern Europe and Eastern Europe [67] face challenges in transitioning to more sustainable agricultural practices, and the comparative analysis carried out between these regions provides a thorough understanding of the energy resilience and sustainability of European agriculture (Figure 1).

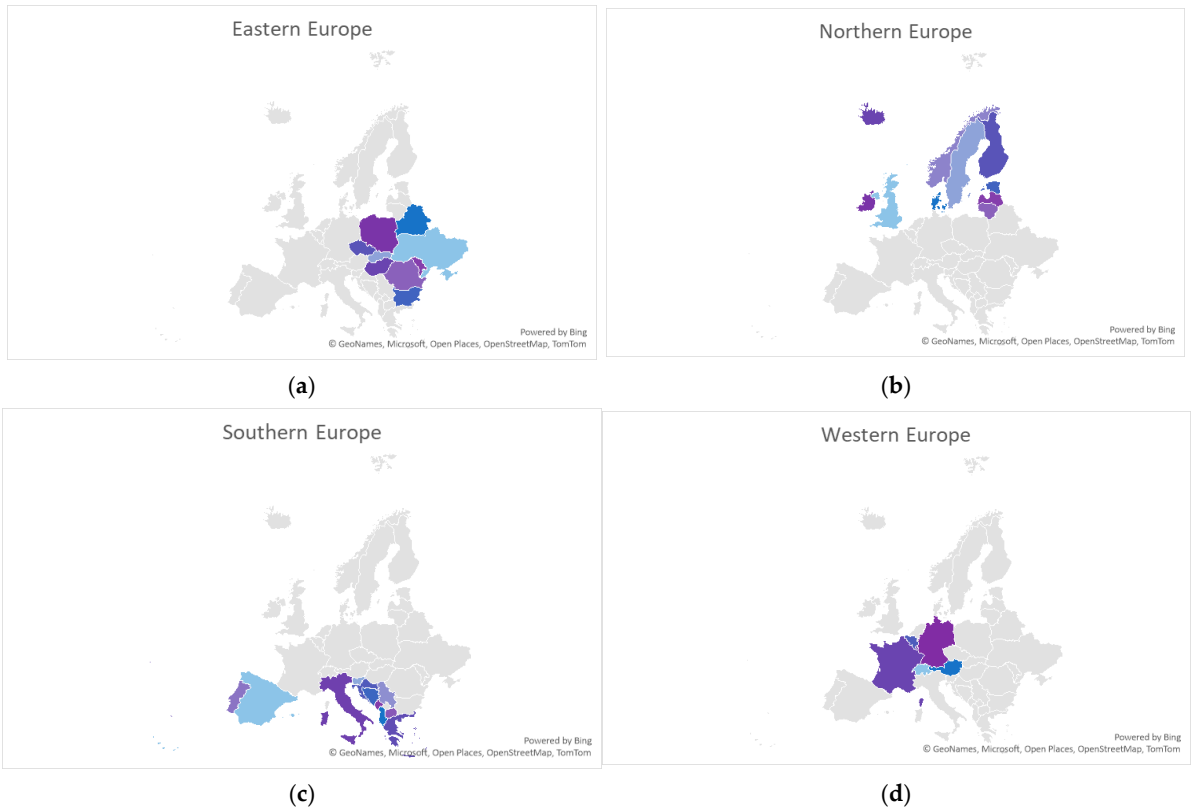


Figure 1. Map of analyzed regions: (**a**) Eastern Europe, (**b**) Northern Europe, (**c**) Southern Europe, (**d**) Western Europe. Source: authors' contribution based on FAO data [33].

Eastern Europe (Belarus, Bulgaria, Czech Republic, Hungary, Poland, Republic of Moldova, Romania, Russian Federation, Slovakia, and Ukraine) is characterized by mixed agriculture, combining subsistence farms with large-scale industrial farms [68]. Thus, in this region, agriculture is an important part of the economy, and intensive land use for cereal production and livestock farming contributes significantly to greenhouse gas (GHG) emissions, with the majority of emissions coming from fertilizer use, manure management and enteric fermentation processes [69]. At the same time, the post-socialist economic transition has influenced resource management strategies, making energy sustainability a major challenge for countries in this region (Figure 1a).

Northern Europe (Denmark, Estonia, Finland, Iceland, Ireland, Latvia, Lithuania, Latvia, Norway, Sweden, United Kingdom of Great Britain and Northern Ireland) is characterized by a cold climate and modern agricultural practices [70], oriented towards sustainability; thus agriculture in this region is dominated by technologized farms and resource

efficiency [71], and most emissions come from livestock and organic waste management processes (Figure 1b).

Southern Europe (Albania, Bosnia and Herzegovina, Croatia, Greece, Italy, Malta, Montenegro, Portugal, Serbia, Slovenia, Spain, Serbia, and Northern Macedonia) is marked by a Mediterranean climate, which favors diversified agriculture [72], with a focus on olive, citrus and vine cultivation, but faces significant water stress, making water resource management essential for energy resilience (Figure 1c). Thus, emissions are mainly generated by intensive irrigation, pesticide use and agrifood processing.

Western Europe (Austria, Belgium, France, Germany, Luxembourg, The Netherlands, and Switzerland) the region is considered a model of efficient agriculture [73], characterized by large-scale industrial farms and extensive use of modern agricultural technologies, and emissions in this region are mainly generated by livestock farms and the use of chemical fertilizers (Figure 1d).

2.2. Regional Comparative Analysis Methodology

This paper uses a quantitative methodological approach to analyze the evolution of agricultural emissions in European regions (total Europe, Eastern, Northern, Southern and Western Europe) over the period 2000–2022, with a focus on energy sustainability and resilience. The comparative analysis focuses on "Farm gate" and "Agricultural land" emissions, using indicators such as total CO_2, CH_4 and N_2O emissions alongside normalized indicators (emissions per capita, per economic value and per hectare) from the FAO database [32].

The percentage evolution of "Farm gate" and "Agricultural land" emissions for different European regions (Europe, Eastern, Northern, Southern and Western Europe) between 2000 and 2022 was calculated based on the following formulas:

1. Percentage calculation for each region (normalized values to percentage): allowed the identification of the relative contribution of each region to total European emissions, highlighting the differences in sustainability between the regions analyzed; thus, for each year and each region, the percentage of emission is calculated as follows:

$$\mathrm{E_R}\ (\%) = \frac{\mathrm{E_R}}{\mathrm{Te_E}} \times 100 \tag{1}$$

where: $\mathrm{E_R}$: emissions from a region (Eastern, Northern, Southern, Western Europe); $\mathrm{Te_E}$: total emissions Europe: the sum of all emissions in Europe.

2. Analysis of percentage variations between two consecutive periods to highlight changes in emissions over time, providing insight into trends in increasing or decreasing emissions in each region, being essential for assessing sustainability. Using the formula:

$$\text{Variation}\ (\%) = \frac{\mathrm{E_t} - \mathrm{E_{t-1}}}{\mathrm{E_{t-1}}} \times 100 \tag{2}$$

where: $\mathrm{E_t}$: Emissions in the current period; $\mathrm{E_{t-1}}$: Emissions in the previous period.

3. Statistical analysis (covariance and variance) to analyze the relationship between regional emissions and other variables, such as years and total European emissions:

(a) The covariance Cov(x,y) was calculated to measure the relationship between year (x) and percentage of emissions (y), according to the following formula:

$$\mathrm{Cov(x,y)}\ \frac{\sum_{i=1}^{n}(x_i - \overline{x})(y_i - \overline{y})}{n} \tag{3}$$

where: x_i: year for observation i; y_i: emission value for observation; $\overline{x}$: mean of x values (years); $\overline{y}$: mean of y values (percentage of emissions).

(b) Variance (Var(x)) was used to assess the dispersion of emission values over time according to the following formula:

$$\mathrm{Var}(x) = \frac{\sum_{i=1}^{n}(x_i - \overline{x})^2}{n} \tag{4}$$

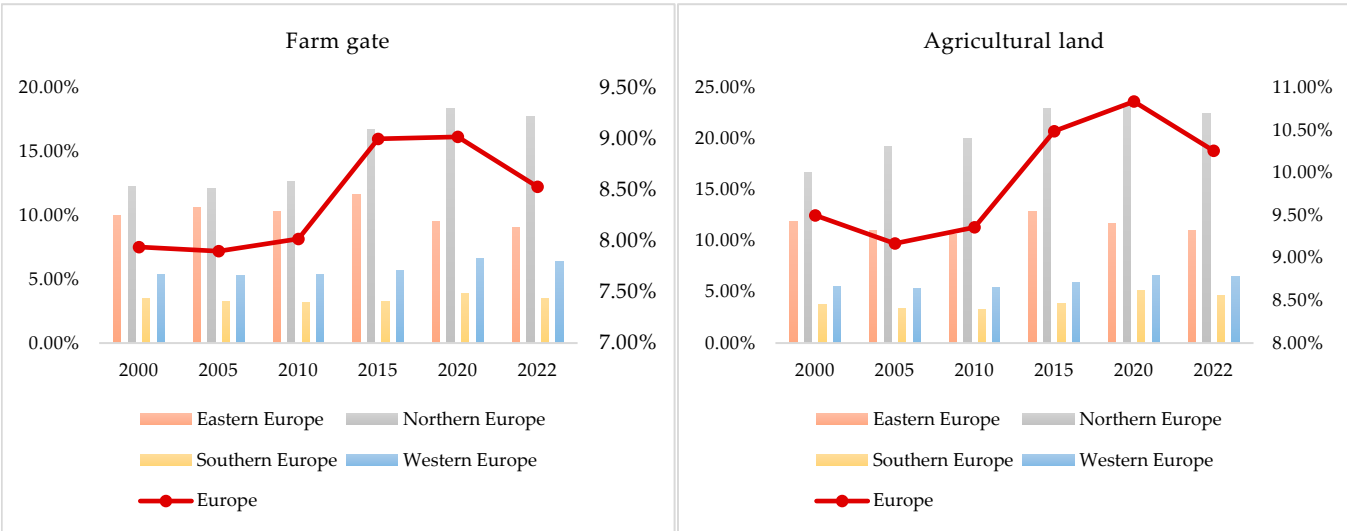
The results were illustrated through line graphs to represent the percentage evolution of emissions and the relationships between variables and boxplots that highlight both regional distributions and long-term trends.

3. Results

3.1. Regional Trends in Agricultural Emissions: Insights on Resilience and Sustainability

3.1.1. Regional Dynamics of CO_2 Emissions: Practices and Intensity

Trends in carbon dioxide (CO_2) emissions from agriculture at the regional level are influenced by several factors, including land use practices [74], the intensity of agricultural activities [9], environmental policies and economic and climatic conditions [75,76], thus these influences differ according to the specificities of each European region, leading to significant variations in CO_2 emissions [77]. The evolution of CO_2 emissions from agriculture in Europe, with a focus on regional contributions and differences between "Farm gate" and "Agricultural land", provides a detailed perspective on temporal trends, highlighting both increases associated with the intensification of agriculture and recent progress in reducing emissions due to the implementation of sustainable practices, and from a regional perspective, the analysis highlights significant variations between Eastern, Northern, Southern and Western Europe, reflecting the diverse adaptation of agricultural practices to the requirements of sustainability and energy resilience (Figure 2).



(**a**) (**b**)

Figure 2. Emissions Share (CO_2) (%): (**a**) Farm gate; (**b**) Agricultural land. Source: authors' contribution based on data from the FAO database [32].

Figure 2 shows "Farm gate" and "Agricultural Land" values of emissions share (CO_2) for the different European regions (left Y-axis) and for Europe as a whole (right Y-axis). The right axis represents average values at the European level, which vary within a narrower range, while the left axis illustrates the more pronounced regional variations.

In Europe, the values increased from 7.94% in 2000 to a peak of 9.02% in 2020, indicating an intensification of agriculture and more intensive use of resources; however, between 2020 and 2022, a decrease to 8.53% was observed, suggesting progress in the more

efficient management of agricultural inputs and adoption of more sustainable technologies. Thus, the overall increase by 2020 can be explained by the increase in food demand and the expansion of intensive agriculture.

Emissions from agricultural land: this indicator reflects CO_2 emissions directly associated with the use of agricultural land, including soil tillage, fertilizer application, irrigation and other agricultural practices. Thus, in Europe, emissions on agricultural land have steadily increased from 9.5% in 2000 to a peak of 10.84% in 2020, indicating the intensification of agriculture to meet increased food demand. After 2020, there was a slight decrease to 10.26% in 2022, suggesting the implementation of measures aimed at reducing agricultural impacts, and the general trend reflects a balance between increasing agricultural production and the adoption of more sustainable practices in recent years. The decrease in 2022 can be attributed to both the impact of the COVID-19 pandemic, which reduced agricultural and trade activities through logistical restrictions and bottlenecks and the progressive adoption of sustainability measures in agriculture.

In some regions, the conversion of natural land to agricultural land leads to significant CO_2 emissions, e.g., Eastern Europe experienced an intensification of agricultural land use in the first decades after 2000, and intensive fertilizer use, frequent plowing and other practices that affect soil carbon stocks contribute to increased CO_2 emissions, particularly in agriculturally intensive regions such as Northern Europe [78]. Reliance on fossil fuels for farm machinery, irrigation and other intensive processes contributes to CO_2 emissions; thus, Western Europe, with more intensive agriculture, faces these challenges, but the use of more energy-efficient farm equipment, such as modern fuel-efficient tractors and GPS systems for optimizing farm work, together with the transition to renewable energy sources such as solar panels and bioenergy, have contributed to CO_2 emission reductions in regions such as Western Europe and the Nordic countries, where environmental policies and investments in sustainable agricultural technology have been more intense [79].

Northern and Western Europe have seen a significant intensification of agriculture to meet domestic and international demand for food, leading to increases in CO_2 emissions, and in warmer regions such as Southern Europe [80], the use of intensive irrigation systems contributes to the CO_2 emissions associated with the energy needed to power them [81]. In regions with strict environmental policies, such as Western Europe, CO_2 emissions have gradually decreased due to the promotion of organic farming and sustainable land management systems [82], and the implementation of the European Green Pact has encouraged investment in low-emission technologies, reducing the environmental impact of agriculture in several European regions [2]. In Eastern Europe, economic restructuring and modernization of farms have contributed to lower CO_2 emissions per unit of production, although increasing land use intensity remains a risk factor, and in Southern Europe, natural limitations such as water scarcity influence emissions by reducing input use intensity, leading to relatively lower emissions compared to other regions.

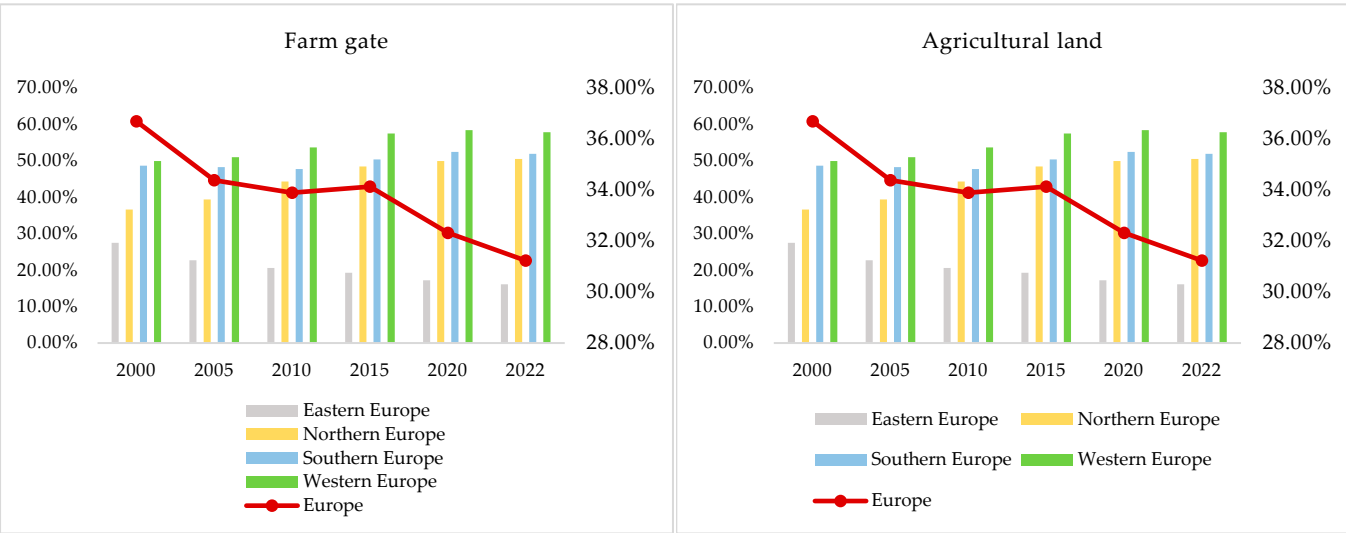
The reduction in agricultural emissions in Western Europe has been more pronounced, reflecting the effectiveness of strict environmental policies and continued investment in sustainable agricultural technologies. The use of modern equipment, such as fuel-efficient tractors and GPS systems, to optimize farm work has contributed significantly to lower emissions. At the same time, the shift towards renewable energy sources such as solar panels and biogas has reinforced this downward trend. By contrast, in Eastern Europe, the rise in emissions in the early decades of the 2000s was associated with the intensification of agriculture; however, economic restructuring and modernization of farms have subsequently allowed more efficient farming practices to be adopted, leading to a gradual decline in emissions. In Northern Europe, high demand for food has maintained high emission levels despite the implementation of modern technologies, while in Southern

Europe, arid climatic conditions and limited water resources have contributed to relatively low emissions.

3.1.2. Methane (CH_4) Emissions and the Role of Animal Management

The analysis highlights significant fluctuations over time and space, reflecting the economic and social dynamics of European agriculture, the intensification of animal husbandry practices and technological advances [83]. In particular, it highlights both the reduction in emissions due to the adoption of advanced technologies and the challenges faced in regions with intensive agriculture, where demand for animal products maintains pressure on resources and the environment.

The evolution of methane (CH_4) emissions from agriculture in European regions highlights regional variations and differences between emissions reported to 'Farm gate' and those associated with 'Agricultural land'. Methane, emitted predominantly from enteric fermentation processes and manure management, is a critical factor in assessing the sustainability of the agricultural sector (Figure 3).



(**a**) (**b**)

Figure 3. Emissions Share (CH_4) (%): (**a**) Farm gate, (**b**) Agricultural land. Source: authors' contribution based on data from the FAO database [32].

Trends in methane (CH_4) emissions from agriculture at the regional level are influenced by a combination of factors related to agricultural practices, socio-economic changes, technological advances and environmental policies [84]. These factors vary significantly between regions, reflecting differences in farming systems, resource availability and policy priorities; thus, methane (CH_4) emitted at the farm gate comes mainly from ruminant digestion, a natural process in the stomachs of livestock, and manure management [85]. In Europe, methane emissions at the farm gate decreased from 36.69% in 2000 to 31.23% in 2022; this significant reduction reflects important advances in emissions management in the livestock sector, such as the adoption of modern technologies for manure management and feed optimization, and is also a result of reduced livestock numbers in some regions and the implementation of stricter environmental policies; however, the sector remains a major source of methane in Europe, indicating the need for continued investment in emission reduction technologies.

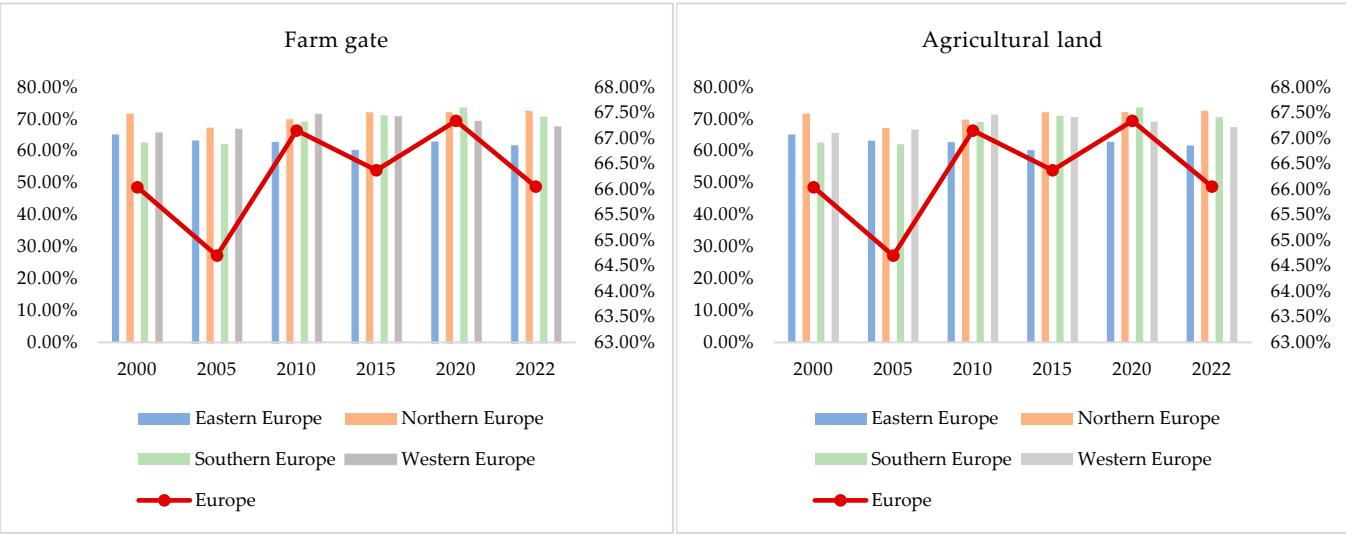
Methane emissions from agricultural land in Europe have decreased from 36.69% in 2000 to 31.23% in 2022, suggesting important progress in reducing agricultural environmental impacts, including optimizing manure management and adopting modern

farming practices. Regions with intensive livestock farming, such as Northern and Western Europe, have high CH_4 emissions due to the concentration of dairy and meat production systems [86], and enteric fermentation in ruminants is the main source of emissions compared to those with mixed farming or a focus on crops, and in Eastern Europe, the significant reduction in livestock numbers after 2000, driven by economic restructuring and low demand, has led to lower CH_4 emissions [87]. Warmer regions (such as Southern Europe) have lower livestock densities, which limits CH_4 emissions; however, these regions face challenges related to resource availability [88], such as water scarcity, and increasing environmental awareness has led to a slow transition to plant-based diets in some regions, contributing to lower livestock numbers and thus CH_4 emissions [89].

The reduction of methane (CH_4) emissions from agriculture in Europe between 2000 and 2022 reflects important progress in the sustainable management of livestock activities and in the implementation of environmental policies. The decrease from 36.69% to 31.23% highlights the positive impact of the adoption of modern technologies for manure management and feed optimization. These measures have made a significant contribution to reducing emissions, particularly in intensive livestock farming regions such as Northern and Western Europe, where dairy and meat production systems are dominant. In Eastern Europe, economic restructuring and reductions in livestock numbers after 2000 have also led to lower emissions, while Southern Europe, characterized by lower livestock densities, has seen lower emissions, although facing challenges related to resource availability.

3.1.3. Nitrous Oxide (N_2O) Emissions: Fertilizer and Soil Management Challenges

Nitrous oxide (N_2O) is one of the most potential global warming agents in the agricultural sector [90], mainly generated from fertilizer use and agricultural soil management [91]. Analysis of N_2O emissions at the regional level reveals significant variations driven by the intensity of agricultural practices, environmental policies and adaptation to sustainable technologies (Figure 4).



(**a**) (**b**)

Figure 4. Emissions Share (N_2O) (%): (**a**) Farm gate, (**b**) Agricultural land. Source: authors' contribution based on data from the FAO database [32].

At the European level, N_2O emissions have been relatively constant between 2000 and 2022, reflecting the balance between agricultural intensification and advances in agricultural resource management; however, regional differences highlight the area-specific

challenges, from intensive agriculture in Northern Europe to more restrictive conditions in Southern Europe.

Nitrous oxide (N_2O) is emitted at the farm gate mainly from fertilizer use and manure management. Thus, N_2O emission values at the European level have been relatively constant, ranging from 64.7% in 2005 to 67.34% in 2020, before decreasing slightly to 66.05% in 2022. This stability indicates balanced management of agricultural inputs but also continued challenges to reduce emissions, with the increase to 2020 attributed to the intensification of agriculture to meet increased demand for agricultural products and the recent decrease suggesting progress in the adoption of sustainable practices.

Emissions from agricultural land are mainly generated by the use of nitrogen fertilizers on agricultural land; they are a significant component of agricultural greenhouse gas emissions, having a direct impact on climate change; thus, at the European level, nitrogen oxide (N_2O) emissions from agricultural land have remained relatively constant, ranging from 64.7% in 2005 to 67.34% in 2020, before decreasing slightly to 66.05% in 2022. This stability reflects consistent agricultural practices in fertilizer use, and the increase up to 2020 suggests an intensification of agriculture, while the subsequent decline indicates the gradual adoption of input efficiency measures and stricter emission policies.

Regional trends in nitrous oxide (N_2O) emissions from agriculture are determined by agriculture-specific factors such as the use of chemical fertilizers, soil management practices, intensity of agricultural activities and the implementation of advanced technologies. N_2O, a highly potent greenhouse gas, is mainly released from microbiological processes in the soil, and regions with intensive agriculture, such as Northern and Western Europe, have high N_2O emissions due to the heavy use of chemical and organic fertilizers, while regions that intensify production to meet food demand (e.g., Northern Europe) have higher N_2O emissions because the use of agricultural inputs is directly proportional to the increase in productivity.

European policies, such as the Common Agricultural Policy, encourage sustainable agricultural practices that reduce N_2O use and optimize soil management; thus, in Eastern Europe, the modernization of agricultural infrastructure and the transition towards more efficient agriculture have led to a decrease in N_2O emissions per unit of production, although intensification of land use in some areas remains a risk factor.

The evolution of nitrous oxide (N_2O) emissions in Europe between 2000 and 2022 reflects a balance between agricultural intensification and improved agricultural resource management. The stability of values, with fluctuations between 64.7% in 2005 and 67.34% in 2020, followed by a slight decrease to 66.05% in 2022, suggests that although emission reduction measures are starting to have an effect, challenges persist. The increase up to 2020 is attributed to the intensification of agriculture to meet the growing demand for agrifood products, while the subsequent decline indicates the gradual adoption of sustainable agricultural practices and fertilizer efficiency measures.

At the regional level, N_2O emissions are influenced by the specificity of agricultural activities: In Northern and Western Europe, the intensive use of chemical and organic fertilizers has contributed to high emissions. In contrast, in Eastern Europe, the modernization of agricultural infrastructure and the shift towards more efficient practices have led to a reduction in emissions per unit of output, while in Southern Europe, drier climatic conditions and lower input use have kept emissions low.

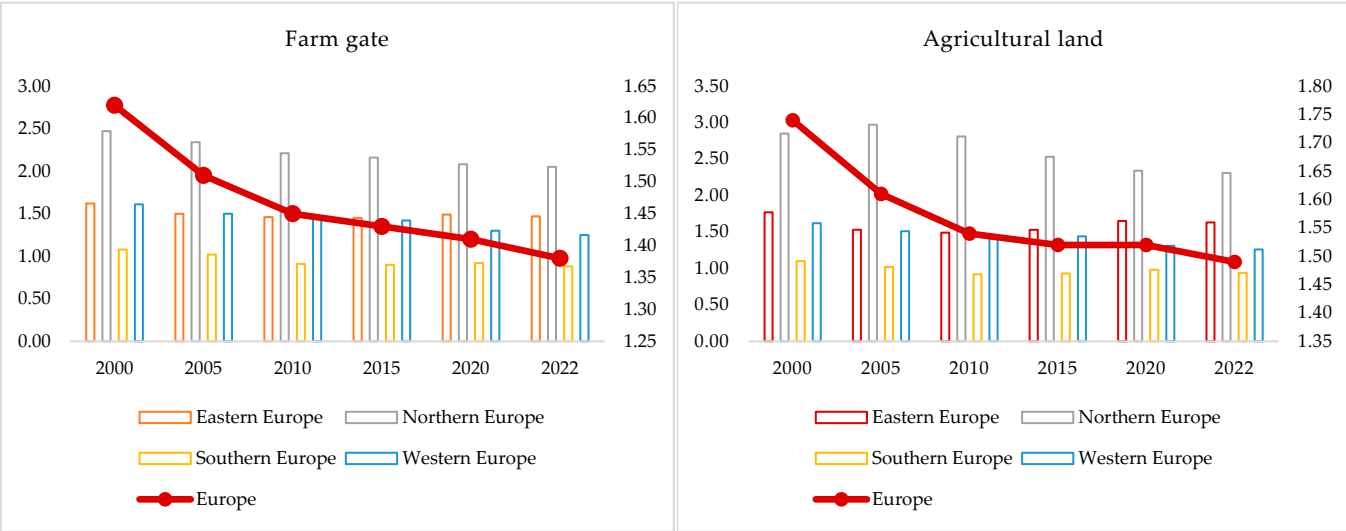
3.2. Regional Economic Perspectives on Agricultural Emissions: Efficiency, Sustainability and Resilience

3.2.1. Regional Trends and Their Contribution to Agricultural Resilience

The analysis explores the correlates of per capita emissions from agriculture from two key perspectives: emissions at the farm gate, which include all on-farm processes and

activities (such as fertilizer use, manure management or energy use) [92] and emissions on agricultural land, which reflect the direct impact of agricultural practices on soil and ecosystems (e.g., emissions from the decomposition of plant residues or pesticide use) [93]. The indicators used are defined according to the FAO [55], which integrates greenhouse gas calculation methods in the context of agricultural activities and land use change, thus providing a standardized basis for measuring environmental impacts.

Figure 5 plots the relationship between regional and European per capita emissions (at the farm gate and on agricultural land). The analysis is based on emission indicators structured into two main categories: farm gate and agricultural land, reflecting the evolution of per capita emissions in the EU regions (Eastern Europe, Northern Europe, Southern Europe and Western Europe) over a 22-year period.



(**a**) (**b**)

Figure 5. Relationship between regional per capita emissions and European per capita emissions (t/capita): (**a**) Farm gate, (**b**) Agricultural land. Source: authors' contribution based on data from the FAO database [32].

Eastern Europe has per capita agricultural emissions of between 1.45 and 1.60 t/cap, indicating relatively low variability in this region, and at the European level, emissions fluctuate in a close range between 1.40 and 1.65 t/cap; thus, the closeness of these values suggests that Eastern Europe closely reflects the general trends in European agricultural emissions and that this region is characterized by a combination of traditional farming methods and gradual modernization of the agricultural sector, which contributes to the stability of emissions over time.

In Northern Europe, agricultural emissions are significantly higher, ranging between 2.00 and 2.50 t/cap at the farm gate, with a regional median of 2.25 t/cap, compared to 1.50 t/cap at the European level. The considerable difference between these values suggests that Northern Europe exerts a strong influence on the overall trends, which can be explained by the specificity of Nordic agriculture, dominated by intensive livestock farming and the use of technologies with a high impact on greenhouse gas emissions, in addition to the harsher climatic conditions requiring higher energy consumption in agricultural production, which contributes to the high emissions.

Southern Europe has the lowest agricultural emissions per capita, ranging between 0.85 and 1.10 t/capita, reflecting a less intensive agricultural sector adapted to the region's specific climatic conditions. However, the positive relationship between regional and European emissions remains significant. The averages calculated for this region of 1.00 t/cap

compared to 1.50 t/cap at the European level confirm that Southern Europe maintains a direct correlation with the general trends but with a lower contribution to total emissions, which is determined by an agricultural mix oriented towards extensive cropping and lower dependence on inputs with high environmental impact.

Western Europe has agricultural emissions per capita in a range between 1.20 and 1.60 t/capita, suggesting a relatively moderate variability, showing a close correlation with overall European trends, with similar averages to those at the continental level. However, the level of emissions in Western Europe is influenced by local factors such as agricultural policy, the degree of adoption of sustainable technologies and the diversity of farming practices, and the transition towards more sustainable agriculture, promoted by environmental policies and technological innovation, contributes to reducing emissions and aligning the region with European environmental objectives.

The study of the relationship between regional agricultural emissions per capita and total Europene emissions shows significant positive correlations. These relationships indicate that regional trends play a key role in the dynamics of total emissions from the European agricultural sector and that each region contributes differently to this development, depending on its agricultural specificity, the technologies used, and the environmental policies implemented.

In Eastern Europe, agricultural emissions per capita vary between 1.50 and 1.80 t/cap, reflecting a relatively wide range of farming practices and efficiency levels, while total European emissions range between 1.45 and 1.75 t/cap, indicating a similarity between this region and the European average. The close averages of 1.60 t/cap for Eastern Europe and 1.65 t/cap for Europe as a whole suggest that this region contributes to the stability of emissions at the continental level, which can be explained by a combination of traditional and modern technologies and a gradual process of agricultural modernization. In contrast, Northern Europe shows significantly higher values of agricultural emissions, ranging between 2.40 and 3.00 t/cap, and highlights the specificity of Nordic agriculture, characterized by a higher intensity of production and a developed livestock sector. The regional median of 2.70 t/cap contrasts sharply with the European median of 1.65 t/cap, suggesting that this region makes a major contribution to total agricultural emissions. This can be attributed both to the predominantly livestock-oriented agricultural structure and to resource-intensive climatic conditions.

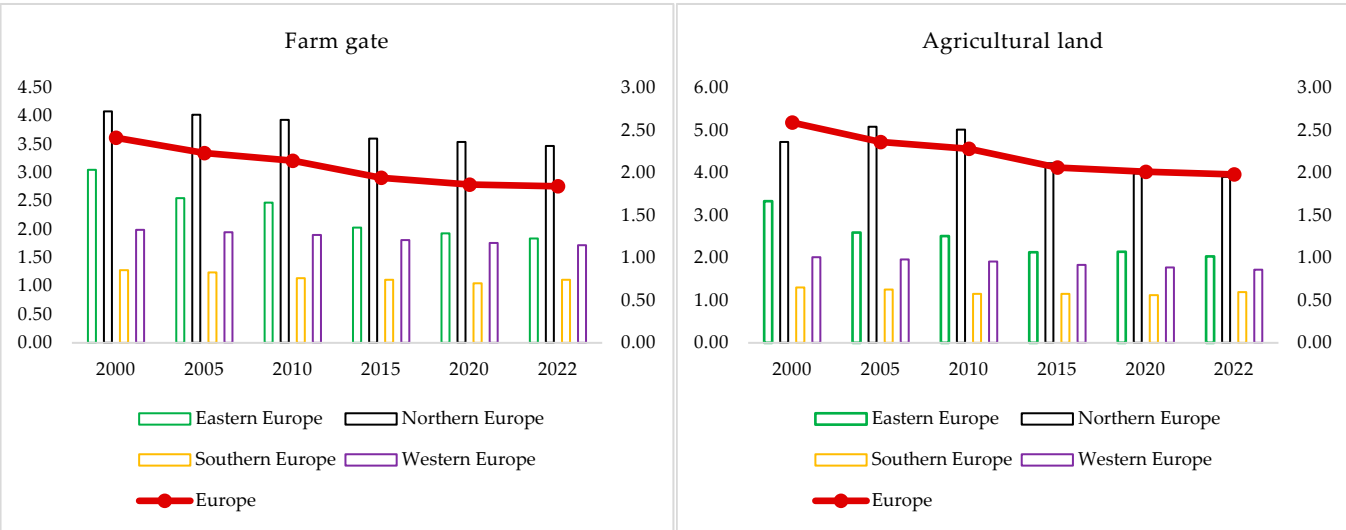
Southern Europe is characterized by the lowest agricultural emissions per capita, ranging between 0.90 and 1.10 t/cap, reflecting a less intensive agricultural sector better adapted to arid climatic conditions, where sustainable practices are more common. Even in this context, the statistical analysis confirms a positive relationship between regional and European emissions; thus, the respective medians of 1.00 t/cap for Southern Europe and 1.65 t/cap for Europe as a whole suggest that, although the contribution of this region to total emissions is lower, its dynamics follow the general trends of the continent. In Western Europe, agricultural emissions per capita range between 1.20 and 1.60 t/cap, indicating a moderate level compared to the other regions, reflecting the transition towards more sustainable agricultural practices and increased efficiency in managing emissions. The median of 1.40 t/cap for this region is slightly below the European average of 1.65 t/cap, indicating that Western Europe contributes in a balanced way to total European emissions, a trend that can be correlated with the adoption of strict emission reduction policies and the implementation of advanced technologies in agriculture.

The analysis of agricultural emissions per capita in Europe shows significant differences between regions, influenced by the intensity of agricultural activities and the degree of modernization. Eastern Europe shows stable emissions between 1.45 and 1.60 t/capita, close to the European average, reflecting a combination of traditional farming methods and

gradual modernization. In contrast, Northern Europe has the highest emissions, between 2.00 and 2.50 t/cap, due to intensive agriculture and energy-intensive climatic conditions. Southern Europe has the lowest emissions (between 0.85 and 1.10 t/cap) due to less intensive agriculture and resource efficiency. In Western Europe, moderate values between 1.20 and 1.60 t/cap reflect the application of advanced agricultural technologies and strict environmental policies. These differences underline the need for tailored regional strategies to reduce agricultural emissions.

3.2.2. Assessing the Economic and Energy Efficiency of Agricultural Emissions in European Regions

Comparative analysis of agricultural emissions in kilograms of CO_2 equivalent (kg/Int$) at the farm gate in European regions reveals distinct contributions and significant positive correlations with total European emissions. Thus, this statistical relationship suggests that regional variations directly influence continental emission trends, and differences between regions are driven by factors such as the economic structure of agriculture, the degree of technologization and resource management practices (Figure 6).



(**a**) (**b**)

Figure 6. Relationship between emissions per regional economic value and emissions per economic value at the European level (kg/Int$): (**a**) Farm gate, (**b**) Agricultural land. Source: authors' contribution based on data from the FAO database [32].

In Eastern Europe, agricultural emissions on a production value basis range from 1.80 to 3.00 kg/Int$, indicating significant differences in agricultural practices in the region, from intensive farming to traditional systems with lower emissions. In comparison, the European emissions range is narrower (2.00–2.50 kg/Int$), reflecting greater uniformity in farming methods in other regions. Due to this wide range, Eastern Europe contributes significantly to the total variation in European emissions, emphasizing the role of the diversity of farming systems in the region. Although Eastern Europe shows significant variability in agricultural emissions relative to the value of output, this is not the only driver of the variation in emissions across Europe. Northern Europe, with a higher median value (3.7 kg/Int$), and Southern Europe, with lower values (1.15 kg/Int$), also contribute significantly to the European average (around 2.2–2.5 kg/Int$). The influence of Eastern Europe, although relevant, needs to be interpreted in the broader context of the diversity of farming systems across Europe. Northern Europe is characterized by the highest emissions per value of agricultural output, ranging between 3.40 and 4.00 kg/Int$,

which significantly exceed the European average and suggest a major contribution of the region to total emissions, while the median emissions in Northern Europe are 3.70 kg/Int$, well above the European median of 2.20 kg/Int$. This discrepancy underlines the high impact of agricultural activities in this area on total European emissions, and factors such as intensive farming systems, the predominance of livestock and specific climatic conditions, which require higher resource consumption, explain this high level of emissions relative to production.

In Southern Europe, emissions are significantly lower, varying between 1.05 and 1.25 kg/Int$, and thus have a more modest influence on total European emissions, reflecting a less intensive agricultural sector better adapted to local climatic conditions. The regional median of 1.15 kg/Int$ is considerably lower than the European median of 2.20 kg/Int$, and the moderate variations in emissions in this region indicate a relatively stable agricultural system characterized by more efficient use of resources and low environmental impact. Western Europe has emissions per unit value of output between 1.70 and 2.00 kg/Int$, which contributes significantly to European emissions but with wider variations depending on the specificity of each country (median emissions in Western Europe is 1.85 kg/Int$), so the adoption of policies to reduce agricultural impacts, together with the modernization of technologies and the promotion of precision agriculture, contribute to lower emissions per unit of output in this region. The results emphasize the importance of regions in the overall trends and the need for regional strategies to reduce agricultural emissions, adapted to the intensity of agricultural activities and the particularities of each area.

The statistical analysis of emissions by the value of agricultural production in European regions on agricultural land shows significant variations between areas, as well as positive correlations with total European emissions. Thus, these differences reflect the intensity of agricultural activities, farm typology and degree of technologization, directly influencing the level of emissions per economic unit produced. In Eastern Europe, regional emissions vary between 2.00 and 3.25 kg/Int$, and EU-wide emissions between 2.10 and 2.60 kg/Int$, with similar medians (2.40 kg/Int$ and 2.35 kg/Int$), indicating a strong influence and moderate variability of emissions in this region. Northern Europe, with higher values (3.90–5.10 kg/Int$) and a median of 4.40 kg/Int$, contributes significantly to European emissions, although the dispersion of the data suggests important regional differences in agricultural intensity. Southern Europe shows lower emissions, between 1.10 and 1.30 kg/Int$, with a median of 1.20 kg/Int$, indicating a more stable and less intensive agriculture compared to the European level, where the median is 2.35 kg/Int$. Western Europe, with emissions between 1.70 and 2.00 kg/Int$ and a median of 1.85 kg/Int$, reflects a moderate and well-balanced use of agricultural resources, contributing to the wider European variations.

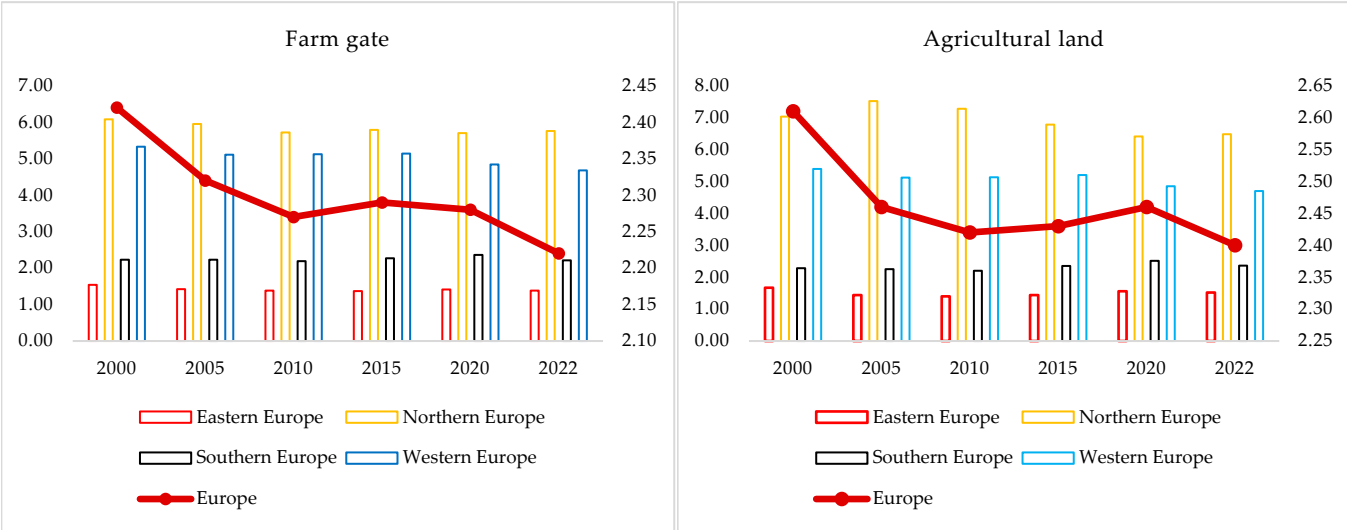
The analysis of agricultural emissions relative to production value shows significant differences between European regions. Eastern Europe shows emissions ranging from 1.80 to 3.00 kg/Int$, with an average of 2.40 kg/Int$, similar to the European average of 2.35 kg/Int$, indicating a stable contribution to continental emissions, driven by the diversity of agricultural practices. In contrast, Northern Europe has the highest emissions, between 3.40 and 4.00 kg/Int$, with a regional average of 3.70 kg/Int$. These high values reflect the region's specific intensive agriculture, dominated by livestock farming and intensive resource use. Southern Europe has the lowest emissions, between 1.05 and 1.25 kg/Int$, reflecting a less intensive agricultural sector adapted to arid climatic conditions. In Western Europe, moderate values (between 1.70 and 2.00 kg/Int$) indicate a balance between agricultural productivity and the adoption of strict environmental policies, helping to reduce the environmental impact of agriculture.

The results of the analysis highlight the need to tailor mitigation strategies to regional specificities. Thus, Northern Europe requires more sustainable agricultural technologies to

control high intensity, while Southern Europe could benefit from optimizing traditional practices, and Western Europe serves as a model for balancing agricultural productivity with reduced environmental impact.

3.2.3. Regional Resilience in Relation to Agricultural Land Use and Emissions Intensity

This analysis details the evolution of emissions per hectare of agricultural land in Europe and its regions (East, North, South and West) for the period 2000–2022. The indicators provide insight into the intensity of emissions relative to land use, highlighting the efficiency of agricultural land management and environmental impacts (Figure 7).



(**a**) (**b**)

Figure 7. Relationship between emissions per regional agricultural area and European emissions per agricultural area (t/ha): (**a**) Farm gate, (**b**) Agricultural land. Source: authors' contribution based on data from the FAO database [32].

The analysis of the relationship between emissions per area of agricultural land at the farm gate and emissions at the European level highlights significant differences between European regions, marked by the intensity of agricultural activities and resource use. Thus, Eastern Europe shows relatively low emissions, between 1.35 and 1.55 t/ha, with a median of 1.45 t/ha, in contrast to the European level, where emissions range between 2.30 and 2.45 t/ha, and the uniform distribution reflects traditional farming practices and moderate intensification, but the upward trend suggests a possible convergence with higher European levels.

Northern Europe has the highest emissions, between 5.70 and 6.10 t/ha, with an average of 5.90 t/ha, significantly higher than the European average (2.35 t/ha). This reflects intensive agriculture and massive resource use, highlighting the need to adopt more sustainable technologies to limit environmental impacts. Southern Europe shows constant emissions, between 2.20 and 2.35 t/ha, with a median of 2.30 t/ha, almost perfectly in line with the European level (2.35 t/ha). Less intensive but stable, agriculture indicates a moderate positive trend and low variations reflect the gradual adoption of sustainable practices. Western Europe has moderate emissions, between 4.60 and 5.40 t/ha, with a median of 5.00 t/ha, contributing significantly to European emissions. The increasing trend suggests more intensive agriculture compared to other regions, underlining its role in the average European emissions and the need to optimize practices to reduce impacts.

These results highlight the specificity of each region and emphasize the importance of tailoring emission reduction strategies to local particularities to support European sustainability objectives.

Analysis of the relationship between emissions per hectare of agricultural land and emissions at the European level highlights regional differences in agricultural intensity: in Eastern Europe, emissions per hectare range between 1.40 and 1.65 t/ha, with a median of 1.50 t/ha, reflecting low agricultural intensity. At the European level, emissions are higher (2.40–2.65 t/ha, median 2.50 t/ha), indicating a moderate contribution of the region. The upward trend suggests a gradual increasing alignment with higher agricultural intensities in other regions.

Northern Europe shows the highest emissions, between 6.50 and 7.50 t/ha, with a median of 7.00 t/ha, significantly above the European level. The extreme agricultural intensity requires the urgent adoption of sustainable technologies to reduce the impact. The almost flat relationship with European emissions indicates a steady contribution of the region. Emissions in Southern Europe range between 2.20 and 2.50 t/ha, with a median of 2.35 t/ha, very close to the European average (2.50 t/ha); thus, the slight decreasing trend and the use of sustainable agricultural practices indicate progress in reducing environmental impacts. In Western Europe, emissions range between 4.80 and 5.40 t/ha, with a median of 5.20 t/ha, indicating intensive agriculture. Its significant contribution to the European total reflects the intensification of agricultural practices, underlining the need for further implementation of efficient technologies and sustainability measures.

Analysis of agricultural emissions per unit area shows significant regional differences across Europe. Eastern Europe has the lowest emissions, between 1.35 and 1.65 t/ha, with a median of 1.50 t/ha, reflecting traditional farming practices and moderate intensification. However, a slight upward trend suggests a possible alignment with higher values in other regions. In contrast, Northern Europe shows the highest emissions, between 6.50 and 7.50 t/ha, indicating intensive agriculture and high energy consumption, highlighting the urgent need for sustainable technologies. Southern Europe has moderate emissions, between 2.20 and 2.50 t/ha, with a decreasing trend due to the adoption of sustainable methods. In Western Europe, values between 4.80 and 5.40 t/ha reflect a balance between agricultural productivity and the adoption of efficient technologies. These results underline the importance of tailored regional strategies to reduce emissions.

4. Discussion

Comparative analysis of greenhouse gas emissions from agriculture at the regional level in Europe reveals significant differences, driven by the specific economic development strategies and the degree of adoption of sustainable technologies. While Northern and Western Europe continue to record the highest emissions, driven by intensive agriculture and high farm density, the implementation of stringent policies and advanced technologies is starting to generate positive effects, reflected in recent emission reductions. Thus, Eastern Europe shows a clear downward trend in emissions due to the modernization of farms, reduction in livestock numbers and optimization of chemical inputs, indicating significant progress in the transition towards more efficient and cleaner agriculture; in contrast, Southern Europe maintains lower emission levels, but the slow pace of adoption of advanced technologies suggests that there is still considerable potential for improvement through strategic investments and sustainability-oriented policies [2,7,9].

Trends in methane (CH_4) and nitrous oxide (N_2O) emissions confirm the importance of the transition to modern agricultural practices and the balance between increasing production intensification and reducing environmental impacts. The significant reductions in CH_4 emissions in Eastern Europe demonstrate the effects of agricultural modernization,

while the high values in Northern and Southern Europe underline the dependence on intensive farming systems and the use of chemical inputs, and Western Europe adopts an equilateral model, combining agricultural intensification with effective emission reduction measures [10].

Overall, the analysis emphasizes that differentiated regional strategies are key to reducing emissions and promoting sustainable agriculture and that tailoring measures to the specificities of each region, investing in advanced technologies and implementing effective policies will play an important role in achieving the EU-wide emission reduction targets. Thus, a balanced transition that maintains agricultural productivity and protects the environment is fundamental to the sustainable future of European agriculture.

The analysis of agricultural emissions in Europe shows a steady reduction in environmental impacts due to the adoption of modern technologies and the transition towards sustainable practices; both on-farm and on-farm emissions have shown significant decreases over the period 2000–2022, reflecting the improved efficiency of the European agricultural sector. However, there are significant regional differences that underline the need for specific policies and strategies in specific areas. Northern Europe continues to have the highest per capita emissions due to agricultural intensification, particularly in the livestock sector; although values have decreased over the last two decades, they remain above the European average, indicating the need for stricter policies and accelerated modernization. In Eastern Europe, emission trends are more fluctuating, highlighting difficulties in standardizing the implementation of technologies and modernizing agricultural infrastructure. While significant percentage reductions have been achieved, recent challenges suggest that maintaining progress requires continued support and additional investment. Southern and Western Europe have performed better in reducing emissions, thanks to a less intensive agricultural sector and effective policies, while Southern Europe maintains the lowest emissions, demonstrating efficient use of resources, albeit influenced by climate constraints, and Western Europe reflects a successful transition to a sustainable agricultural model, supported by advanced technologies and well-implemented strategies.

The analysis of emissions relative to the value of agricultural output confirms the improvement in eco-efficiency across Europe, with an overall decrease in emissions per economic unit produced, with Eastern Europe showing the largest percentage reduction, but recent challenges highlight difficulties in maintaining progress, while Northern Europe continues to have the highest emissions, while Southern and Western Europe maintain a balance between sustainability and productivity.

These results underline the need for continued investment in advanced technologies and tailored policies, especially in the northern and eastern regions, to reduce disparities and accelerate the transition towards sustainability, and a differentiated approach based on the specificities of each region will be essential to achieve the emission reduction targets [24] and to ensure sustainable agriculture in Europe [29].

The regional analysis of agricultural emissions in Europe confirms that the implementation of sustainable technologies [59,64] and the adaptation of policies to local specificities [23,28] are key factors for the transition to more environmentally friendly agriculture [91]. Thus, the southern and western regions provide positive examples of emission reductions, while in the north and east, progress is slower, requiring additional investment [5,7], stricter policies [2] and the adoption of more efficient farming practices [14]. The decrease in emissions per hectare of agricultural land at the EU level from 2.42 t/ha in 2000 to 2.22 t/ha in 2022 reflects clear progress in the environmental efficiency of the agricultural sector, while the adjusted emissions reduction from 2.61 t/ha to 2.4 t/ha indicates an improvement in sustainability, but also the need for tailor-made strategies for each region. Thus, Western Europe stands out with the most significant reduction in

emissions (from 5.33 t/ha to 4.68 t/ha), which demonstrates the success of sustainability policies and the integration of modern technologies. This transition pattern could serve as a benchmark for other regions; in contrast, Northern Europe, although showing a reduction in emissions (from 6.08 t/ha to 5.76 t/ha), remains the region with the highest values, due to the high intensity of agriculture, dominated by livestock and the use of chemical fertilizers. Southern Europe maintains low emissions (2.23 t/ha in 2000, compared to 2.21 t/ha in 2022), but recent variations (increase to 2.51 t/ha in adjusted emissions) underline the region's vulnerability to climate change and the need for further adaptation, this trend indicates that although southern agriculture is less intensive, climate change may affect the region's environmental performance, requiring adaptation and innovation measures, and Eastern Europe has the lowest emissions per hectare (1.54 t/ha in 2000 to 1.38 t/ha in 2022), but recent fluctuations suggest an intensification of agricultural activities, which requires modernization of infrastructure and use of advanced technologies to maintain emission reductions without compromising agricultural productivity.

The results of the analysis show that European agriculture has the potential to improve its environmental performance, but intensive farming regions, especially Northern and Western Europe, require stricter policies and additional investment to balance the need for production with sustainability objectives, while Southern and Eastern regions need to adapt to climate change and accelerate the transition to more efficient agricultural technologies. In the long term, differentiated regional strategies, investments in sustainable technologies and the implementation of regio-specific policies will be key to achieving Europe's emission reduction targets and strengthening resilient and sustainable agriculture.

5. Conclusions

Regional analysis of agricultural emissions in Europe underlines the need for differentiated and customized strategies tailored to the specificities of each region to ensure a balance between productivity and sustainability. While Western Europe demonstrates a balanced model based on advanced technologies and efficient policies, the Nordic regions, with an intensive and highly input-dependent agricultural sector, require stricter measures and innovative solutions to reduce emissions. At the same time, Eastern and Southern Europe present distinct opportunities for optimization, either by upgrading infrastructure and implementing sustainable technologies or by increasing efficiency in the use of natural resources.

Reductions in emissions per hectare and per value of agricultural output indicate that transition efforts are underway, but progress is uneven and recent fluctuations highlight structural vulnerabilities in certain regions. Thus, the development of integrated policies to support the transition towards circular and energy-efficient agriculture is essential to achieve the EU-wide agricultural emission reduction targets, while investments in digitalization, precision agriculture and optimizing supply chains can accelerate the decarbonization process, reducing environmental impacts without compromising the sector's competitiveness. Digitization, precision agriculture and the use of renewable energy sources can significantly reduce emissions from the agricultural sector; in particular, the use of advanced technologies for manure management, optimized fertilization, and the use of drones for precise pesticide application can contribute to lower CH_4 and N_2O emissions. Thus, integrating agriculture into Emissions Trading Schemes (ETS) could provide economic incentives for farmers to reduce emissions, and the creation of regulated carbon markets for agriculture could help promote sustainable practices and increase investment in green solutions.

To complement and deepen this analysis, future research should focus on assessing the costs of implementing green technologies in agriculture, identifying the most effective

support policies for farmers and comparing different funding schemes in EU countries to identify the most efficient support models for the transition towards sustainable agriculture.

Aligning intensification with sustainability will be key to a resilient agricultural model that is able to respond to both economic demands and climate challenges in a fair framework for all regions of Europe.

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References

1. Murawska, A.; Goryńska-Goldmann, E. Greenhouse Gas Emissions in the Agricultural and Industrial Sectors—Change Trends, Economic Conditions, and Country Classification: Evidence from the European Union. *Agriculture* **2023**, *13*, 1354. [CrossRef]
2. Prigoreanu, I.; Ungureanu, B.A.; Ungureanu, G.; Ignat, G. Analysis of Sustainable Energy and Environmental Policies in Agriculture in the EU Regarding the European Green Deal. *Energies* **2024**, *17*, 6428. [CrossRef]
3. Georgescu, P.-L.; Barbuta-Misu, N.; Zlati, M.L.; Fortea, C.; Antohi, V.M. Quantifying the Performance of European Agriculture Through the New European Sustainability Model. *Agriculture* **2025**, *15*, 210. [CrossRef]
4. European Environment Agency. *Greenhouse Gas Emissions from Agriculture*; European Environment Agency: Copenhagen, Denmark, 2024; Available online: https://www.eea.europa.eu/en/analysis/indicators/greenhouse-gas-emissions-from-agriculture (accessed on 4 September 2024).
5. Eurostat. *EU Economy Emissions in 2022: Down 22% Since 2008*; Eurostat: Luxembourg, 2023; Available online: https://ec.europa.eu/eurostat/web/products-eurostat-news/w/ddn-20231221-3 (accessed on 5 September 2024).
6. IFOAM Organics Europe. Understanding agriculture's share of greenhouse gas emissions and where they come from. In *Organic Farming, Climate Change Mitigation and Beyond*; IFOAM Organics Europe: Brussels, Belgium, 2024; Available online: https://read.organicseurope.bio/publication/organic-farming-climate-change-mitigation-and-beyond/understanding-agricultures-share-of-greenhouse-gas-emissions-and-where-they-come-from/ (accessed on 3 September 2024).
7. European Parliament. *Reducing Pollution from Industry and Large Livestock Farms*; European Parliament: Strasbourg, France, 2024; Available online: https://www.europarl.europa.eu/news/en/press-room/20240308IPR19007/reducing-pollution-from-industry-and-large-livestock-farms (accessed on 7 September 2024).
8. European Environment Agency (EEA). *Total Greenhouse Gas Emission Trends and Projections in Europe*; European Environment Agency (EEA): Copenhagen, Denmark, 2024; Available online: https://www.eea.europa.eu/en/analysis/indicators/total-greenhouse-gas-emission-trends (accessed on 4 September 2024).
9. FAO. Emissions due to agriculture. In *Global, Regional and Country Trends 2000–2018*; FAOSTAT Analytical Brief Series No. 18; FAO: Rome, Italy, 2020; Available online: https://openknowledge.fao.org/server/api/core/bitstreams/cc09fbbc-eb1d-436b-a88a-bed42a1f12f3/content (accessed on 5 September 2024).
10. Benalcázar-Murillo, D.; Vilcekova, S.; Pardo, M.Á. Analysis of Equivalent CO2 Emissions of the Irrigation System—A Case Study. *Sustainability* **2023**, *15*, 16240. [CrossRef]

11. Nuţă, F.M.; Sharafat, A.; Abban, O.J.; Khan, I.; Irfan, M.; Nuţă, A.C.; Dankyi, A.B.; Asghar, M. The relationship among urbanization, economic growth, renewable energy consumption, and environmental degradation: A comparative view of European and Asian emerging economies. *Gondwana Res.* **2024**, *128*, 325–339. [CrossRef]
12. Nuta, A.C. The Significance of Economic Complexity and Renewable Energy for Decarbonization in Eastern European Countries. *Energies* **2024**, *17*, 5271. [CrossRef]
13. Lynch, J.; Cain, M.; Frame, D.; Pierrehumbert, R. Agriculture's Contribution to Climate Change and Role in Mitigation Is Distinct From Predominantly Fossil CO_2-Emitting Sectors. *Front. Sustain. Food Syst.* **2021**, *4*, 518039. [CrossRef]
14. Jun, P.; Gibbs, M.; Gaffney, K. CH_4 and N_2O Emissions from Livestock Manure. In *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*; IPCC/OECD/IEA: Hayama, Japan, 2000.
15. Rivera, J.E.; Chará, J. CH_4 and N_2O Emissions From Cattle Excreta: A Review of Main Drivers and Mitigation Strategies in Grazing Systems. *Front. Sustain. Food Syst.* **2021**, *5*, 657936. [CrossRef]
16. Forabosco, F.; Chitchyan, Z.; Mantovani, R. Methane, nitrous oxide emissions and mitigation strategies for livestock in developing countries: A review. *S. Afr. J. Anim. Sci.* **2017**, *47*, 268. [CrossRef]
17. Petersen, S.O.; Blanchard, M.; Chadwick, D.; Del Prado, A.; Edouard, N.; Mosquera, J.; Sommer, S.G. Manure Management for Greenhouse Gas Mitigation. *Animal* **2013**, *7* (Suppl. S2), 266–282. [CrossRef]
18. Fanelli, R.M. Assessing the Convergence of Farming Systems towards a Reduction of Greenhouse Gas Emissions in European Union Countries. *Agronomy* **2023**, *13*, 1263. [CrossRef]
19. Vărzaru, A.A. Assessing Agricultural Impact on Greenhouse Gases in the European Union: A Climate-Smart Agriculture Perspective. *Agronomy* **2024**, *14*, 821. [CrossRef]
20. Hu, J.; Dong, J.; Xu, D.; Yang, Q.; Liang, J.; Li, N.; Wang, H. Trends in Global Agricultural Carbon Emission Research: A Bibliometric Analysis. *Agronomy* **2024**, *14*, 2617. [CrossRef]
21. Mielcarek-Bocheńska, P.; Rzeźnik, W. Greenhouse Gas Emissions from Agriculture in EU Countries—State and Perspectives. *Atmosphere* **2021**, *12*, 1396. [CrossRef]
22. Verschuuren, J.; Fleurke, F.; Leach, M.C. Integrating Agricultural Emissions into the European Union Emissions Trading System: Legal Design Considerations. *Sustainability* **2024**, *16*, 5091. [CrossRef]
23. Bocean, C.G. The Role of Organic Farming in Reducing Greenhouse Gas Emissions from Agriculture in the European Union. *Agronomy* **2025**, *15*, 198. [CrossRef]
24. Czyżewski, A.; Michałowska, M. The Impact of Agriculture on Greenhouse Gas Emissions in the Visegrad Group Countries after the World Economic Crisis of 2008. Comparative Study of the Researched Countries. *Energies* **2022**, *15*, 2268. [CrossRef]
25. Zafeiriou, E.; Mallidis, I.; Galanopoulos, K.; Arabatzis, G. Greenhouse Gas Emissions and Economic Performance in EU Agriculture: An Empirical Study in a Non-Linear Framework. *Sustainability* **2018**, *10*, 3837. [CrossRef]
26. Basheer, S.; Wang, X.; Farooque, A.A.; Nawaz, R.A.; Pang, T.; Neokye, E.O. A Review of Greenhouse Gas Emissions from Agricultural Soil. *Sustainability* **2024**, *16*, 4789. [CrossRef]
27. Lileikis, T.; Nainienė, R.; Bliznikas, S.; Uchockis, V. Dietary Ruminant Enteric Methane Mitigation Strategies: Current Findings, Potential Risks and Applicability. *Animals* **2023**, *13*, 2586. [CrossRef]
28. Symeon, G.K.; Akamati, K.; Dotas, V.; Karatosidi, D.; Bizelis, I.; Laliotis, G.P. Manure Management as a Potential Mitigation Tool to Eliminate Greenhouse Gas Emissions in Livestock Systems. *Sustainability* **2025**, *17*, 586. [CrossRef]
29. Řezbová, H.; Slaboch, J.; Mach, J. Emissions from Managed Agricultural Soils in Context of Consumption of Inorganic Nitrogen Fertilisers in Selected EU Countries. *Agronomy* **2023**, *13*, 159. [CrossRef]
30. Oliveira, E.R.; Silva, B.T.; Lopes, D.; Corticeiro, S.; Alves, F.L.; Disperati, L.; Gama, C. The Detection of Small-Scale Open-Burning Agriculture Fires Through Remote Sensing. *Remote Sens.* **2025**, *17*, 51. [CrossRef]
31. Harsányi, E.; Bashir, B.; Almhamad, G.; Hijazi, O.; Maze, M.; Elbeltagi, A.; Alsalman, A.; Enaruvbe, G.O.; Mohammed, S.; Szabó, S. GHGs Emission from the Agricultural Sector within EU-28: A Multivariate Analysis Approach. *Energies* **2021**, *14*, 6495. [CrossRef]
32. FAO. FAOSTAT Database: Emissions. Food and Agriculture Organization of the United Nations. Available online: https://www.fao.org/faostat/en/#data/EM (accessed on 1 October 2024).
33. FAO. *The State of Food Security and Nutrition in the World 2023: Urbanization, Agrifood Systems Transformation and Healthy Diets Across the Rural–Urban Continuum*; Food and Agriculture Organization of the United Nations: Roma, Italy, 2023; Available online: https://openknowledge.fao.org/server/api/core/bitstreams/f1ee0c49-04e7-43df-9b83-6820f4f37ca9/content/state-food-security-and-nutrition-2023/notes-on-geographic-regions.html (accessed on 11 October 2024).
34. FAO. *Pathways Towards Lower Emissions—A Global Assessment of the Greenhouse Gas Emissions and Mitigation Options from Livestock Agrifood Systems*; Food and Agriculture Organization of the United Nations (FAO): Roma, Italy, 2023; Available online: https://openknowledge.fao.org/server/api/core/bitstreams/a06a30d3-6e9d-4e9c-b4b7-29a6cc307208/content (accessed on 7 October 2024).
35. FAO. *Greenhouse Gas Emissions from Agrifood Systems: Global, Regional and Country Trends, 2000–2020*; FAOSTAT Analytical Brief Series No. 50; Food and Agriculture Organization of the United Nations (FAO): Roma, Italy, 2022; Available online:

https://openknowledge.fao.org/server/api/core/bitstreams/121cc613-3d0f-431c-b083-cc2031dd8826/content (accessed on 10 October 2024).
36. FAO. *Agrifood Systems and Land-Related Emissions: Global, Regional and Country Trends, 2001–2021*; FAOSTAT Analytical Brief Series No. 73; Food and Agriculture Organization of the United Nations (FAO): Roma, Italy, 2023; Available online: https://openknowledge.fao.org/server/api/core/bitstreams/487c7f4e-91ff-4d23-b1e4-f72dd867e939/content (accessed on 17 October 2024).
37. Chen, L.; Msigwa, G.; Yang, M.; Osman, A.I.; Fawzy, S.; Rooney, D.W.; Yap, P.-S. Strategies to achieve a carbon neutral society: A review. *Environ. Chem. Lett.* **2022**, *20*, 2277–2310. [CrossRef]
38. European Commission. Progress Report 2023: Shifting Gears—Increasing the Pace of Progress Towards a Green and Prosperous Future. Climate Action. 2023. Available online: https://climate.ec.europa.eu (accessed on 5 March 2025).
39. Kausar, A.; Rasul, F.; Asghar, N. How to get green with agricultural footprint: A global analysis of carbon emissions, environmental taxes, and agrochemical use. *J. Environ. Manag.* **2024**, *370*, 122665. [CrossRef]
40. Owolabi, O.; Ogundipe, D.; Makinde, P. Optimization of solar-powered waste-to-energy systems for agricultural food waste reduction. *Int. J. Sci. Res. Arch.* **2023**, *10*, 1105–1114. [CrossRef]
41. Subbarao, P.M.V.; D'Silva, T.C.; Adlak, K.; Kumar, S.; Chandra, R.; Vijay, V.K. Anaerobic digestion as a sustainable technology for efficiently utilizing biomass in the context of carbon neutrality and circular economy. *Environ. Res.* **2023**, *234*, 116286. [CrossRef]
42. Javaid, M.; Haleem, A.; Singh, R.P.; Suman, R. Enhancing smart farming through the applications of Agriculture 4.0 technologies. *Int. J. Intell. Netw.* **2022**, *3*, 150–164. [CrossRef]
43. Gobin, A.; Uljee, I. European Green Deal Strategies for Agriculture in Dynamic Urbanised Landscapes. *Land* **2025**, *14*, 424. [CrossRef]
44. European Commission. Report from the Commission to the European Parliament and the Council on the Operation of Regulation (EU) 2018/841 ("LULUCF Regulation") Pursuant to Article 17(2) as Amended by Regulation (EU) 2023/839. 2024. Available online: https://ec.europa.eu (accessed on 7 March 2025).
45. Islam, N.F.; Gogoi, B.; Saikia, R.; Yousaf, B.; Narayan, M.; Sarma, H. Encouraging circular economy and sustainable environmental practices by addressing waste management and biomass energy production. *Reg. Sustain.* **2024**, *5*, 100174. [CrossRef]
46. He, Z.; Ding, B.; Pei, S.; Cao, H.; Liang, J.; Li, Z. The impact of organic fertilizer replacement on greenhouse gas emissions and its influencing factors. *Sci. Total Environ.* **2023**, *905*, 166917. [CrossRef] [PubMed]
47. Francaviglia, R.; Almagro, M.; Vicente-Vicente, J.L. Conservation Agriculture and Soil Organic Carbon: Principles, Processes, Practices and Policy Options. *Soil Syst.* **2023**, *7*, 17. [CrossRef]
48. Wang, L. Assessment of land use change and carbon emission: A Log Mean Divisia (LMDI) approach. *Heliyon* **2024**, *10*, e25669. [CrossRef]
49. Holka, M.; Kowalska, J.; Jakubowska, M. Reducing Carbon Footprint of Agriculture—Can Organic Farming Help to Mitigate Climate Change? *Agriculture* **2022**, *12*, 1383. [CrossRef]
50. Organic Farming Climate Change Mitigation and Beyond. In *Understanding Agriculture's Share of Greenhouse Gas Emissions and Where They Come*; IFOAM Organics Europe: Brussels, Belgium, 2024; Available online: https://read.organicseurope.bio/publication/organic-farming-climate-change-mitigation-and-beyond/understanding-agricultures-share-of-greenhouse-gas-emissions-and-where-they-come-from-2/ (accessed on 14 October 2024).
51. European Commission. Common Agricultural Policy Performance: Programme Performance Statements. Available online: https://commission.europa.eu/strategy-and-policy/eu-budget/performance-and-reporting/programme-performance-statements/common-agricultural-policy-performance_en (accessed on 11 October 2024).
52. Doukas, Y.E.; Salvati, L.; Vardopoulos, I. Unraveling the European Agricultural Policy Sustainable Development Trajectory. *Land* **2023**, *12*, 1749. [CrossRef]
53. Frelih Larsen, A.; Riedel, A.; Scheid, A.; Jägle, J.; Springer, K.; Bognar, J.; Wiltshire, J.; Freeman, D.; Crotty, F.; Kiresiewa, Z.; et al. *Towards Climate Friendly and Resilient Agri-Food Systems in Central Eastern Europe: The Role of Agroecological Practices, Sustainable Diets, and Holistic Policies*; Ecologic Institute: Berlin, Germany, 2024.
54. European Commission. Conditionality in the Common Agricultural Policy (CAP). Available online: https://agriculture.ec.europa.eu/common-agricultural-policy/income-support/conditionality_en (accessed on 17 October 2024).
55. FAO. *Standards on Good Agricultural and Environmental Conditions of Land—Introductory Handbook*; FAO Regional Office for Europe and Central Asia: Budapesta, Hungary, 2021; Available online: https://openknowledge.fao.org/server/api/core/bitstreams/979b293d-264d-43c0-b2c8-3b076449814b/content (accessed on 21 October 2024).
56. Angileri, V.; Loudjani, P.; Serafini, F. GAEC Implementation in the European Union: Situation and Perspectives. *Ital. J. Agron.* **2011**, *6*, e2. [CrossRef]
57. Borrelli, P.; Paustian, K.; Panagos, P.; Jones, A.; Schütt, B.; Lugato, E. Effect of Good Agricultural and Environmental Conditions on erosion and soil organic carbon balance: A national case study. *Land Use Policy* **2016**, *50*, 408–421. [CrossRef]

58. Paraschivu, M.; Partal, E.; Sălceanu, C. Assessment of the Application Effects of the Derogation Covering GAEC 7 and 8 Standards on Agricultural and Environmental Condition, Food Security, Environmental Preservation, and Climate Change. *Ann. Univ. Craiova-Agric. Mont. Cadastre Ser.* **2023**, *53*, 139–143. [CrossRef]
59. Poláková, J. Sustainability—Risk—Resilience: How Does the Case of the Good Agricultural and Environmental Conditions Measure up? *Sustainability* **2018**, *10*, 1614. [CrossRef]
60. Abban, O.J.; Xing, Y.H.; Nuţă, A.C.; Nuţă, F.M.; Borah, P.S.; Ofori, C.; Jing, Y.J. Policies for carbon-zero targets: Examining the spillover effects of renewable energy and patent applications on environmental quality in Europe. *Energy Econ.* **2023**, *126*, 106954. [CrossRef]
61. Shahbaz, M.; Nuţă, A.C.; Mishra, P.; Ayad, H. The impact of informality and institutional quality on environmental footprint: The case of emerging economies in a comparative approach. *J. Environ. Manag.* **2023**, *348*, 119325. [CrossRef] [PubMed]
62. Balsalobre-Lorente, D.; Shahbaz, M.; Murshed, M.; Nuţă, F.M. Environmental impact of globalization: The case of central and Eastern European emerging economies. *J. Environ. Manag.* **2023**, *341*, 118018. [CrossRef]
63. Kaufmann, J.; Cartsburg, M.; Staubach, L. *Analyses of Socio-Economic and Environmental Effects of Agroecological Practices: A Methodological Guidance*; Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH: Bonn and Eschborn, Germany, 2023.
64. Abildtrup, J.; Audsley, E.; Fekete-Farkas, M.; Giupponi, C.; Gylling, M.; Rosato, P.; Rounsevell, M. Socio-economic scenario development for the assessment of climate change impacts on agricultural land use: A pairwise comparison approach. *Environ. Sci. Policy* **2006**, *9*, 101–115. [CrossRef]
65. Gómez, M.I.; Meemken, E.; Verteramo Chiu, L.J. *Agricultural Value Chains and Social and Environmental Impacts: Trends, Challenges, and Policy Options. Background Paper for the State of Agricultural Commodity Markets (SOCO) 2020*; Food and Agriculture Organization of the United Nations (FAO): Roma, Italy, 2020; Available online: https://openknowledge.fao.org/server/api/core/bitstreams/d68206d0-c1e2-4b77-a113-1c4283dc8dda/content (accessed on 27 October 2024).
66. Pylak, K.; Pizoń, J.; Łazuka, E. Evolution of Regional Innovation Strategies Towards the Transition to Green Energy in Europe 2014–2027. *Energies* **2024**, *17*, 5669. [CrossRef]
67. Radlińska, K. Changes in the Structure of Agriculture in Central and Eastern Europe in the Light of the European Green Deal. *Sustainability* **2025**, *17*, 104. [CrossRef]
68. Mincyte, D. Subsistence and Sustainability in Post-industrial Europe: The Politics of Small-Scale Farming in Europeanising Lithuania. *Sociol. Rural.* **2011**, *51*, 101–118. [CrossRef]
69. Klikocka, H.; Zakrzewska, A.; Chojnacki, P. Characteristics of Models of Farms in the European Union. *Sustainability* **2021**, *13*, 4772. [CrossRef]
70. European Environment Agency. Agriculture. In *The European Environment—State and Outlook*; European Environment Agency: Copenhagen, Denmark, 2015; Available online: https://www.eea.europa.eu/soer/2015/europe/agriculture (accessed on 1 October 2024).
71. Stancu, V.; Pedersen, S.; Bech-Larsen, T.; Aschemann-Witzel, J. Food Sustainability Understanding in the Nordic-Baltic Countries. In *Report of the Food Sustainability Understanding in the Nordic-Baltic Region as a Basis for a Labelling Framework in Europe Project*; MAPP Centre; Aarhus University: Aarhus, Denmark, 2023.
72. European Commission. *EU Agricultural Outlook for the Agricultural Markets and Income 2017–2030*; Directorate-General for Agriculture and Rural Development: Brussels, Belgium, 2017; Available online: https://agriculture.ec.europa.eu/system/files/2018-07/agricultural-outlook-2017-30_en_0.pdf (accessed on 11 September 2024).
73. European Commission. *EU Agricultural Outlook for the Agricultural Markets and Income 2023–2035*; Directorate-General for Agriculture and Rural Development, Publications Office of the European Union: Luxembourg, 2023; Available online: https://agriculture.ec.europa.eu/system/files/2024-01/agricultural-outlook-2023-report_en_0.pdf (accessed on 21 October 2024).
74. Rotz, C.A. Modeling greenhouse gas emissions from dairy farms. *J. Dairy Sci.* **2018**, *101*, 6675–6690. [CrossRef]
75. FAO. The share of agriculture in total greenhouse gas emissions. In *Global, Regional and Country Trends 1990–2017*; FAOSTAT Analytical Brief Series No. 1; FAO: Rome, Italy, 2020; Available online: https://openknowledge.fao.org/server/api/core/bitstreams/7fe33d41-3969-4f87-95c5-4b897229350b/content (accessed on 11 October 2024).
76. Nuţă, F.M.; Nuţă, A.C.; Zamfir, C.G.; Petrea, S.-M.; Munteanu, D.; Cristea, D.S. National Carbon Accounting—Analyzing the Impact of Urbanization and Energy-Related Factors upon CO_2 Emissions in Central–Eastern European Countries by Using Machine Learning Algorithms and Panel Data Analysis. *Energies* **2021**, *14*, 2775. [CrossRef]
77. IEA. *CO2 Emissions in 2022*; IEA: Paris, France, 2022; Available online: https://www.iea.org/reports/co2-emissions-in-2022 (accessed on 9 October 2024).
78. Valin, H.; Peters, D.; van den Berg, M.; Frank, S.; Havlik, P.; Forsell, N.; Hamelinck, C. *The Land Use Change Impact of Biofuels Consumed in the EU: Quantification of Area and Greenhouse Gas Impacts*; Ecofys Netherlands B.V.; IIASA; E4tech: Utrecht, The Netherlands, 2015; Available online: https://climate.ec.europa.eu/system/files/2016-11/finalreport_agricsoils_en.pdf (accessed on 21 January 2025).

79. Nazarov, D.; Sulimin, V.; Shvedov, V.; Larionova, N. Renewable energy sources for the agricultural sector. *E3S Web Conf.* **2024**, *541*, 101002. [CrossRef]
80. Lin, B.; Johnson-Chappell, M.J.; Vandermeer, J.; Smith, G.; Quintero, E.; Kerr, R.; Griffith, D.; Ketcham, S.; Latta, S.; McMichael, P.; et al. Effects of industrial agriculture on climate change and the mitigation potential of small-scale agro-ecological farms. *CAB Rev. Perspect. Agric. Vet. Sci. Nutr. Nat. Resour.* **2011**, *6*, 1–18. [CrossRef]
81. Flammini, A.; Pan, X.; Tubiello, F.N.; Qiu, S.Y.; Souza, L.R.; Quadrelli, R.; Bracco, S.; Benoit, P.; Sims, R. Emissions of greenhouse gases from energy use in agriculture, forestry and fisheries: 1970–2019. *Earth Syst. Sci. Data* **2022**, *14*, 811–821. [CrossRef]
82. Hristov, J.; Toreti, A.; Pérez Domínguez, I.; Dentener, F.; Fellmann, T.; Elleby, C.; Ceglar, A.; Fumagalli, D.; Niemeyer, S.; Cerrani, I.; et al. *Analysis of Climate Change Impacts on EU Agriculture by 2050*; JRC PESETA IV Project—Task 3; Publications Office of the European Union: Luxembourg, 2020.
83. Song, J.; Wei, J.; Zhou, W.; Zhang, J.; Liu, W.; Zhang, F.; Zhou, H. Assessing the Influence Factors of Agricultural Soils' CH4/N2O Emissions Based on the Revised EDGAR Datasets over Hainan Island in China. *Atmosphere* **2023**, *14*, 1547. [CrossRef]
84. Vaghar Seyedin, S.M.; Zeidi, A.; Chamanehpour, E.; Nasri, M.H.F.; Vargas-Bello-Pérez, E. Methane Emission: Strategies to Reduce Global Warming in Relation to Animal Husbandry Units with Emphasis on Ruminants. *Sustainability* **2022**, *14*, 16897. [CrossRef]
85. Ghassemi Nejad, J.; Ju, M.-S.; Jo, J.-H.; Oh, K.-H.; Lee, Y.-S.; Lee, S.-D.; Kim, E.-J.; Roh, S.; Lee, H.-G. Advances in Methane Emission Estimation in Livestock: A Review of Data Collection Methods, Model Development and the Role of AI Technologies. *Animals* **2024**, *14*, 435. [CrossRef]
86. Bi, H.; Neethirajan, S. Mapping Methane—The Impact of Dairy Farm Practices on Emissions Through Satellite Data and Machine Learning. *Climate* **2024**, *12*, 223. [CrossRef]
87. Evangelista, C.; Milanesi, M.; Pietrucci, D.; Chillemi, G.; Bernabucci, U. Enteric Methane Emission in Livestock Sector: Bibliometric Research from 1986 to 2024 with Text Mining and Topic Analysis Approach by Machine Learning Algorithms. *Animals* **2024**, *14*, 3158. [CrossRef]
88. Hassan, M.U.; Aamer, M.; Mahmood, A.; Awan, M.I.; Barbanti, L.; Seleiman, M.F.; Bakhsh, G.; Alkharabsheh, H.M.; Babur, E.; Shao, J.; et al. Management Strategies to Mitigate N_2O Emissions in Agriculture. *Life* **2022**, *12*, 439. [CrossRef]
89. Tang, Y.; Qiao, Y.; Ma, Y.; Huang, W.; Komal, K.; Miao, S. Quantifying greenhouse gas emissions in agricultural systems: A comparative analysis of process models. *Ecol. Model.* **2024**, *490*, 110646. [CrossRef]
90. Wang, C.; Amon, B.; Schulz, K.; Mehdi, B. Factors That Influence Nitrous Oxide Emissions from Agricultural Soils as Well as Their Representation in Simulation Models: A Review. *Agronomy* **2021**, *11*, 770. [CrossRef]
91. Xing, Y.; Wang, X. Impact of Agricultural Activities on Climate Change: A Review of Greenhouse Gas Emission Patterns in Field Crop Systems. *Plants* **2024**, *13*, 2285. [CrossRef] [PubMed]
92. European Environment Agency. Climate Change Adaptation in the Agriculture Sector in Europe. EEA Report No 4/2019. Available online: https://www.eea.europa.eu/en/analysis/publications/cc-adaptation-agriculture (accessed on 9 November 2024).
93. Verschuuren, J. Achieving agricultural greenhouse gas emission reductions in the EU post-2030: What options do we have? *Rev. Eur. Comp. Int. Environ. Law* **2022**, *31*, 246–257. [CrossRef]

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