agriculture

Article

Quantifying the Performance of European Agriculture Through the New European Sustainability Model

Puiu-Lucian Georgescu [1], Nicoleta Barbuta-Misu [2], Monica Laura Zlati [2], Costinela Fortea [2] and Valentin Marian Antohi [2,*]

[1] Department of Chemistry, Physics and Environment, Dunarea de Jos University of Galați, 800008 Galați, Romania; lucian.georgescu@ugal.ro
[2] Department of Business Administration, Dunarea de Jos University of Galați, 800008 Galați, Romania; misunicoleta@yahoo.com (N.B.-M.); sorici_monica@yahoo.com (M.L.Z.); costinela.fortea@yahoo.com (C.F.)
* Correspondence: valentin_antohi@yahoo.com

Abstract: The study aims to assess the performance of European sustainable agriculture through a new model of agricultural sustainability, addressing a significant gap identified in the literature: the lack of a systematic framework integrating the economic, environmental, and resource efficiency dimensions of agricultural resource use in the context of the EU Common Agricultural Policy and the Green Deal. The research develops four synthetic indicators: ISPAS (Index of Sustainable Agricultural Productivity), IREA (Index of Reduced Emissions from Agriculture), ISAC (Index of Combined Agricultural Sustainability), and IESA (Index of Agricultural Land Area Efficiency), each reflecting complementary aspects of sustainable agricultural performance. The methodology is based on an econometric linear model and a dynamic Arellano–Bond model, which allows the analysis of the temporal relationships between synthetic indicators and agricultural sustainability performance, capturing the inertia effects and structural dynamics of the European agricultural sector. The modeling provides a robust approach to capture the interdependencies between agricultural emission reductions, sustainability mainstreaming, and land use efficiency. The results of the study indicate a superior quality of measurement by applying this integrated framework, highlighting significant relationships between emission reductions, the integration of economic and environmental dimensions, and the optimization of agricultural land use. The analysis also provides valuable policy implications, suggesting concrete directions for adapting European agricultural policies to the structural particularities of Member States. By integrating a dynamic methodological framework and innovative synthetic indicators, this study contributes to a thorough understanding of agricultural sustainability performance and provides a practical tool for underpinning sustainable agricultural policies in the European Union.

Keywords: agriculture; sustainability; economic development; agricultural sustainability model; public policy

check for updates

Academic Editor: Edward Osei

Received: 20 December 2024
Revised: 7 January 2025
Accepted: 17 January 2025
Published: 18 January 2025

Citation: 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. https://doi.org/10.3390/agriculture15020210

1. Introduction

Agriculture is one of the most important global economic and social sectors, playing a fundamental role not only in ensuring food security but also in maintaining ecological balance and supporting the development of rural communities. The European Union (EU) is at a critical juncture, marked by complex challenges such as climate change, the degradation of natural resources, the growth of the world's population, and the demands to reduce negative environmental impacts. These challenges have prompted policy makers to promote a strategic approach to the transformation of European agriculture, taking into account the principles of sustainable development and the Green Deal objectives. The aim of this strategic document is to guide Member States towards climate neutrality by 2050, by reducing emissions, conserving resources, and promoting sustainable farming practices. In this context, the performance of European agriculture can no longer be assessed solely in terms of traditional economic indicators but requires a multidimensional approach integrating the economic, environmental, and social dimensions of sustainability. Farmers and policy makers face an urgent need to adopt innovative practices that maximize productivity in a resource-efficient way and reduce environmental impact. For this reason, there is a pressing need to develop assessment tools that provide a clear picture of the performance of European agriculture and allow the formulation of coherent strategies adapted to today's economic and environmental realities. European agriculture is going through a period of major change, driven by the requirements of new EU policies promoting the ecological transition. European Green Pact [1] sets ambitious targets to reduce greenhouse gas emissions by 55% by 2030 and achieve climate neutrality by 2050. Agriculture plays a central role in this transition, accounting for about 10% of the EU's greenhouse gas emissions. Agriculture is also directly affected by the impacts of climate change, such as extreme events, biodiversity loss, and soil degradation. EU policies, such as the Farm to Fork Strategy and the Biodiversity Strategy, promote the transition to resource-efficient and organic farming. However, the implementation of these policies poses several challenges, including structural disparities between developed and emerging EU economies; unequal access to innovative technologies and financial resources for investment; resistance to change among farmers and slow uptake of organic practices; fragmentation of agricultural land and declining farm incomes in some regions. These challenges underline the need for a rigorous assessment of the performance of European agriculture, identifying good practices, highlighting existing gaps, and providing concrete recommendations for effective policies. The main aim of this study is to develop a European sustainability model to quantify the performance of European agriculture in the context of new economic and environmental challenges (from two perspectives linear and dynamic). The proposed models use synthetic composite indicators that integrate economic, environmental, and resource efficiency dimensions, providing a comprehensive and comparative assessment of the sustainability of agriculture at the EU Member State level. To achieve the proposed aim, the research pursues the following specific objectives:

O1. Define and develop a set of synthetic indicators that capture the relevant dimensions of agricultural sustainability. These include ISPAS (Index of Sustainable Agricultural Performance); IREA (Index of Reduced Agricultural Emissions); ISAC (Index of Combined Agricultural Sustainability); and IESA (Index of Agricultural Land Area Efficiency);

O2. Assess the performance of sustainable agriculture at the EU Member State level, using a rigorous methodology based on econometric models and validation tests;

O3. Identify structural differences between Member States and the determinants of sustainable performance, with a focus on financial resources, policies implemented, and structural characteristics of agriculture;

O4. To formulate policy recommendations for improving the performance of sustainable agriculture, considering the Green Deal objectives and bridging the gap between developed and emerging economies.

The study makes significant contributions to the literature. This study fills an important research gap by addressing the lack of a unified methodological approach capable of capturing the dynamic relationships between economic, environmental, and resource efficiency dimensions over time. Compared to other studies [2–4] that analyze agricultural sustainability from a national perspective, outlining a global framework of significant disparity in the methods and strategies adopted to achieve an optimal level of sustainable development in agriculture, this study highlights the need for intra-national research on sustainable development emphasized by the adoption by the European Union of the Common Agricultural Policy and the Green Deal Pact. While the existing literature offers fragmented analyses focusing on isolated aspects of sustainability, this research introduces a dynamic model (Arellano–Bond dynamic panel model) to examine the temporal persistence of agricultural sustainability indicators and their long-term impacts on sectoral performance. Main novel elements include the following: the integration of synthetic indicators for assessing agricultural sustainability, combining economic, environmental, and resource efficiency dimensions. This approach provides a holistic picture of the performance of European agriculture. Comparative analysis between EU Member States, highlighting structural differences and identifying the factors contributing to sustainable performance and existing gaps. Taking an integrated perspective that captures the role of agricultural policies, investments, and the adoption of modern technologies in achieving sustainability objectives. With these elements, the proposed study goes beyond traditional approaches, which focus only on isolated economic or ecological indicators, by providing an innovative methodology for assessing the performance of agriculture in the current context of the ecological transition.

This paper contributes to the literature by developing a new analytical framework and proposing a European sustainability model applicable to the assessment of agriculture at the EU Member State level. This research provides concrete answers to the need for methodological tools to capture the complexity of modern agriculture in a context of economic, technological, and environmental change. Key contributions include the following: extending the theoretical framework on agricultural sustainability by integrating innovative synthetic indicators that reflect the sector's overall performance; robust empirical applications, based on rigorous econometric analysis, validating the relevance of the determinants of sustainable performance; as well as identifying territorial and structural disparities in agricultural performance, providing a comparative perspective across EU Member States, thus contributing to the Green Deal objectives.

The article continues with the literature review, which identifies existing approaches to agricultural sustainability, the presentation of the research methodology, where the proposed indicators and the econometric methods used are described, and the presentation of the results and discussion, which presents the empirical analysis and interpretation of the main results. Conclusions and recommendations summarize the results of the study and provide future research directions.

2. Literature Review

Following the accelerated ecological transition and the increasingly stringent requirements of the European Green Pact [1], European agriculture is becoming a priority area for the implementation of sustainable policies. In this respect, the literature has evolved significantly, exploring multiple perspectives on agricultural sustainability, with a particular focus on the integration of economic, environmental, and social dimensions. Recent studies highlight the need for robust models to assess agricultural performance, capable of capturing the complexity of structural transformations and the impact of environmental policies implemented at regional and national levels [5,6].

The literature review focuses on four main strands: conceptualizing agricultural sustainability and its role in European policies, using synthetic indicators to measure agricultural performance, analyzing the impact of agricultural policies on sustainability, and highlighting regional disparities and challenges associated with the ecological transition. Recent contributions of innovative technologies, such as artificial intelligence, in improving the analysis of agricultural sustainability are also addressed. Agricultural sustainability cannot be reduced to a single dimension, but requires a harmonious interaction between economic, environmental, and social components to ensure equitable and resilient development in the long term. The literature emphasizes that integrated and holistic approaches are key to understanding the dynamics of modern agricultural systems. Recent studies [7–9] emphasize the need for models that reflect the complex interdependencies between these dimensions. These studies emphasize the importance of affordable and safe approaches to sustainable agricultural production, with a particular focus on the balance between economic efficiency, environmental responsibility, and social stability. This vision is fully aligned with the European objectives set out in the European Green Pact [1] and the Farm to Fork Strategy [10]. Recent research also highlights the key role of innovative technologies and optimized farming practices in reducing agricultural emissions and improving natural resource use efficiency. Digital technologies, smart monitoring systems, and precision farming techniques are identified as key drivers for accelerating the transition to more sustainable farming practices [11,12]. In this context, the literature indicates that sustainable agriculture performance assessments should be carried out through multidimensional methodological frameworks [13]. These frameworks must be capable of capturing not only static performance but also its persistence and evolution over time in a dynamic and adaptive way. This study responds to this need by developing a dynamic econometric model to investigate the temporal relationships between the main drivers of agricultural sustainability and the overall performance of the sector.

The integration of synthetic indicators such as ISPAS, IREA, ISAC, and IESA brings a significant advantage in this process, as it allows the quantification of complex relationships and facilitates the interpretation of the results in a coherent and policy-relevant way. Thus, this study is in line with the current literature and makes an original contribution by integrating a dynamic and multidimensional approach to the assessment of European agricultural sustainability.

2.1. Agricultural Sustainability in the European Context

Agricultural sustainability is at the heart of the European Union's policies and is addressed from multiple perspectives in the literature. This concept integrates economic, environmental, and social dimensions, with the objective of creating a resilient agricultural system capable of responding to current challenges such as climate change, degradation of natural resources, and global population growth. According to expert studies [14–16], agricultural sustainability involves balancing economic and environmental requirements by reducing greenhouse gas (GHG) emissions and increasing the efficiency of natural resource use. This approach is confirmed by other studies [8,17,18], which emphasizes that sustainability should not only be assessed in terms of environmental impacts, but also in terms of its ability to generate economic and social benefits for rural communities.

European Union strategies [10,19] are promoting the integration of organic farming practices as part of the commitment to climate neutrality by 2050. According to the European Commission's report on the future of European agriculture [20], implementing these strategies requires massive investments in agricultural infrastructure and green technologies, as well as financial support for farmers. In addition, other studies [21–23] believes that public policies, such as the Common Agricultural Policy (CAP), play a fundamental role in supporting the transition towards sustainability, but disparities between Member States affect the uniform implementation of these measures.

Technology plays a key role in modernizing European agriculture. For example, precision farming systems, presented in various studies [24–26], optimize resource use and reduce environmental impact through the use of drones, soil sensors, and smart irrigation systems. These solutions help reduce agricultural emissions and improve productivity, as highlighted in the FAO report [27], which claims that adopting advanced technologies can reduce global GHG emissions from agriculture by up to 20%.

From a social perspective, sustainable agriculture has a direct impact on rural communities. The authors' study Tomar, Sharma, and Kumar [28] (2023), and that of the authors Gamage et al. [29] shows that the promotion of organic farming practices contributes to job creation, thus improving the quality of life in rural areas. On the other hand, the authors' study Saud et al. [30] shows that the transition towards sustainability may amplify inequalities between Member States, particularly between developed and emerging economies, due to unequal access to financial and technological resources. Despite progress, the implementation of sustainable agriculture faces many challenges. According to Matthews, Fish, and Tzanopoulos [31], farmland fragmentation and farmers' resistance to change remain major barriers to the adoption of organic practices. The authors also Memo and Pieńkowski [32] have shown in a study that underdeveloped rural infrastructure in some member states, such as Bulgaria and Romania, limits the uptake of modern technologies and sustainable solutions.

A survey of the literature shows the need for an integrated approach to promoting agricultural sustainability, including effective public policies, adequate financial support, and innovative technologies. At the same time, future research should explore the use of artificial intelligence techniques and big data to optimize the performance of sustainable agriculture and to identify regionally customized solutions.

2.2. Synthetic Sustainability Indicators

The use of synthetic indicators is an innovative and growing trend in the literature to quantify the performance of sustainable agriculture in an integrated and comparable way. These indicators, constructed by combining economic, environmental, and resource efficiency variables, allow a holistic assessment of the performance of the agricultural sector, highlighting regional differences and identifying the determinants of sustainability. The role of synthetic indicators in assessing sustainability Synthetic indicators, such as those proposed in various studies [33–35] facilitates a multidimensional analysis of agricultural sustainability, providing a comprehensive picture of agricultural impacts. For example, the Index of Sustainable Agricultural Performance (ISPAS) integrates data on economic productivity and environmental impacts, assessing the balance between them, while the Index of Reduced Emissions from Agriculture (IREA) measures progress in reducing pollutant emissions from agriculture. These indicators thus not only measure agricultural performance but also highlight gaps between developed and emerging economies. In the European Union, the use of synthetic indicators has proved essential for monitoring progress towards the objectives of the European Green Pact, and they have contributed to the formulation of public policies better adapted to local realities, based on hard data and comparative analysis. The development of synthetic indicators requires a rigorous methodology, including data collection, normalization, and weighting. For example, various studies [36–38] propose the use of econometric analysis and artificial intelligence techniques to improve the accuracy of agricultural indicators. In this context, ISPAS and IREA are constructed by combining economic variables, such as gross value added in agriculture, and environmental variables, such as greenhouse gas emissions and agricultural land use. These indicators thus provide a solid basis for assessing sustainable agricultural performance.

Synthetic indicators not only facilitate the analysis of performance but also significantly influence policy decision-making. While summary indicators are valuable tools, they face certain challenges, as the collection of relevant data can be difficult in emerging economies due to limited infrastructure and a lack of centralized reporting systems [39,40]. In addition, the weighting of the variables used to construct the indicators may introduce subjectivity, thus influencing the final results. To overcome these limitations, recent studies recommend the use of advanced technologies, such as artificial intelligence, to ensure the objectivity and accuracy of assessments [26,41]. The use of synthetic indicators is an essential tool for assessing and promoting agricultural sustainability, providing a clear perspective on the progress and challenges of the agricultural sector in the context of Europe's green ambitions.

2.3. European Agricultural Policies and the Transition to Sustainability

European agricultural policies are fundamental to achieving sustainability objectives, aiming to reduce negative environmental impacts, maintain the economic competitiveness of the agricultural sector, and promote balanced rural development. The Common Agricultural Policy (CAP), the European Union's main instrument to support agriculture, has steadily evolved to integrate environmental priorities such as reducing greenhouse gas emissions and preserving biodiversity, becoming a key element in the transition towards a sustainable agricultural model. According to expert studies [42–44], the CAP provides a robust framework to support sustainable agriculture, but its effectiveness depends on the ability of Member States to implement structural reforms adapted to local challenges. The reforms needed include tackling soil degradation, managing water resources efficiently, and protecting ecosystems. Countries with advanced economies, such as Germany and France, have demonstrated their ability to access and make effective use of funding available through initiatives such as the Green Deal, supporting the transition to greener farming practices [45,46]. These countries have integrated innovative technologies and educational programs for farmers into national strategies, thus strengthening the sustainability of the agricultural sector.

In contrast, emerging economies in Eastern Europe, such as Romania and Bulgaria, face challenges in accessing funds and implementing the necessary reforms. According to various studies [47,48], these countries suffer from significant shortcomings in rural infrastructure and a lack of administrative resources to effectively manage agricultural policies. This gap leads to uneven implementation of reforms, affecting transition at the regional level.

Financial support through the CAP and other EU programs, such as the European Fund for Rural Development (EAFRD), is particularly important to support the transition towards organic farming practices. According to the analysis of various studies [49–51], These funds have contributed to the adoption of precision agriculture, which includes technologies such as drones, soil sensors, and smart irrigation systems, optimizing the use of resources and reducing environmental impact. Countries with developed economies have shown that investing in innovative technologies leads to significant benefits, such as reduced pesticide use and increased productivity. Bocean's study [52] has shown that the introduction of digital farming and artificial intelligence in the agricultural process has led to significant efficiency gains in countries such as the Netherlands and Denmark. However, these benefits are not evenly distributed. In emerging economies, farmers' access to finance is limited and education and training programs are underdeveloped. For example, in Romania and Bulgaria, administrative and bureaucratic difficulties hamper the absorption of EU funds. Lack of adequate infrastructure and farmers' reluctance to technological change exacerbates these problems, slowing the transition to sustainability. To increase the effectiveness of financial support, it is essential for the European Union to tailor the allocation of funds to regional needs and to support emerging economies in overcoming administrative barriers. Integrating digital technologies and artificial intelligence into fund management processes and farmer training can accelerate the uptake of green practices. Recent studies also recommend the creation of collaborative platforms between Member

States for the exchange of best practices and the implementation of locally customized solutions. The CAP and other European agricultural policies are key to achieving sustainability objectives. However, regional disparities and administrative barriers call for better-tailored solutions based on innovation, strengthened financial support, and cooperation between Member States and the EU.

2.4. Regional Disparities and Current Challenges

Regional disparities in the adoption and implementation of sustainable practices represent a major challenge for the European Union, affecting the equity and efficiency of environmental measures in agriculture. These disparities, influenced by economic, infrastructural, and administrative factors, are the subject of much academic debate, highlighting the significant gaps between advanced and emerging economies. Various specialized studies [53,54] showed that Central and Eastern European countries such as Romania, Bulgaria, and Hungary face major difficulties in implementing sustainable agricultural practices. These emerging economies are constrained by insufficient financial resources, poorly developed agricultural infrastructure, and weak administrative capacities. For example, some research [55–57] have shown that lack of access to modern technologies and digital networks significantly reduces the efficiency of agricultural processes, affecting the adoption of sustainable practices. The low level of environmental education among farmers also contributes to resistance to change, widening existing gaps.

In contrast, developed economies such as Germany, the Netherlands, and France have demonstrated remarkable progress in mainstreaming sustainability in the agricultural sector, mobilizing substantial resources for research and development, implementing advanced agricultural policies, and investing in innovative technologies. For example, Germany has used CAP funds to support the ecological transition, adopting precision farming solutions and advanced irrigation systems that reduce water consumption and greenhouse gas emissions [58].

Factors explaining these disparities include differences in administrative capacity and access to finance, with advanced economies benefiting from well-developed institutions capable of attracting and managing EU funds for agriculture, while emerging economies face excessive bureaucracy and a lack of qualified staff. In addition, underdeveloped rural infrastructure in Eastern Europe has limited the deployment of modern technological solutions and farmers' access to global markets. Even in advanced economies, the achievement of sustainability goals is affected by common challenges such as climate change, which influences agricultural production globally [56]. These challenges underline the importance of closer cooperation between Member States to bridge the gaps and strengthen sustainability. The transfer of technology and know-how from advanced to emerging economies can make a significant contribution to reducing these disparities.

In order to effectively address these problems, the European Union must step up its efforts to support countries with emerging economies, create dedicated financial and technical support programs to facilitate farmers' access to advanced technologies, and develop rural infrastructure. Also, continuous training programs for farmers, focusing on the benefits of environmentally friendly practices, could reduce resistance to change and improve the adoption rate of sustainable solutions. Regional disparities between EU Member States represent a significant challenge for achieving a sustainable agricultural sector at the European level. While advanced economies have demonstrated superior performance due to developed resources and capacities, emerging economies continue to face major challenges. Reducing these disparities requires a concerted approach, based on cooperation, knowledge transfer, and dedicated financial support, thus ensuring a fair and effective environmental transition for the EU.

Sustainable agriculture is a central pillar of European Union policies, highlighting the need for fair and effective solutions to facilitate the transition to climate neutrality and address the multiple challenges of the agricultural sector. The literature review highlights gaps in the implementation of current strategies and argues the importance of developing an integrated European model for sustainability. Such a holistic and well-grounded approach is the basis for formulating innovative and applicable solutions, supporting the achievement of ambitious climate neutrality goals, and ensuring a sustainable future for European agriculture.

3. Methodology

The article has been built on a rigorous methodology, integrating data normalization techniques, the calculation of composite indicators, and the application of advanced statistical tests to analyze the performance of sustainable agriculture in European countries in the context of the Green Deal objectives. This approach led to robust conclusions relevant to understanding the dynamics of agriculture in the European Union.

3.1. Collection and Processing of Data

The data used in the study were taken from official sources, i.e., the Eurostat platform, European agricultural statistics for the period 2012–2022, which included variables such as EAA—economic accounts for agriculture-values at current prices (million euro) [59]; GVAA—gross value added of the agricultural industry (million euro) [60]; GGEA—greenhouse gas emissions from agriculture (percentage) [61]; NGGE—net greenhouse gas emissions (index, 1990 = 100) [62]; AmEA—ammonia emissions from agriculture (tonne) [63]; AUOF—area under organic farming (percentage of total utilized agricultural area) [64]; and UAA—utilised agricultural area total (1000 ha) [65].

Logarithmization of the variables used in the construction of the synthetic indicators is a justified methodological choice in the context of analyzing agricultural sustainability performance. Firstly, the data used come from official sources such as Eurostat and the component variables of the indicators include heterogeneous units of measurement, such as millions of euro for the Economic Agricultural Accounts (EAA), percentages for Greenhouse Gas Emissions (GGEA), or areas expressed in hectares (UAA). This dimensional diversity creates difficulties in directly comparing the variables, and the application of log transformation allows them to be brought to a common scale, thus facilitating the interpretation of the results and the analysis of the relationships between variables. Secondly, logarithmization reduces the effect of outliers and stabilizes the variance of the data, an essential property in econometrics, especially in dynamic models such as Arellano–Bond. This is important in a context where the distribution of variables may show significant asymmetries or disproportionate values across countries. Thus, the logarithmic transformation ensures a distribution closer to normality and improves the robustness of the estimates obtained. Also, in the context of our study, the synthetic indicators ISPAS, IREA, ISAC, and IESA are constructed based on multiplicative relationships between the component variables. Log-regression is therefore justified from a mathematical point of view, since their transformation into an additive form simplifies the interpretation of the coefficients in the model.

3.2. Creating Composite Indicators

To assess the different dimensions of agricultural sustainability, four composite indicators were defined and calculated:

ISPAS (Index of Sustainable Agricultural Performance), which reflects the balance between economic performance and environmental impact (higher index values reflect robust agricultural economic performance with low environmental impact). Components: economic accounts for agriculture (EAA); gross value added of the agricultural industry (GVAA); and greenhouse gas emissions from agriculture (GGEA). The index formula is presented in Equation (1):

$$IPAS = \frac{log(EAA) + log(GVAA)}{log(GGEA)} \quad (1)$$

IREA (Index of Reduced Agricultural Emissions), which indicates the effectiveness in reducing agricultural pollution (lower values of the index reflect an effective reduction in pollutant emissions from agriculture). Components: ammonia emissions (AmEA); and net greenhouse gas emissions (NGGE). The index formula is shown in Equation (2):

$$IREA = log(NGGE) + log(AmEA) \quad (2)$$

ISAC (Index of Combined Agricultural Sustainability), which integrates economic, environmental, and research performance (higher index values reflect sustainable economic growth with a high share of organic farming and low emissions). Components: gross value added (GVAA); area under organic farming (AUOF); and ammonia emissions (AmEA). The index formula is shown in Equation (3):

$$ISAC = \frac{log(GVAA) + log(AUOF)}{log(AmEA)} \quad (3)$$

IESA (Index of Agricultural Area Efficiency), which optimizes area use for economic performance and sustainability (increasing index values reflect efficient use of agricultural area for economic production). Components: utilized agricultural area (UAA); gross value added (GVAA); and area under organic farming (AUOF). The index formula is shown in Equation (4):

$$IESA = \frac{log(GVAA)}{log(UAA) + log(AUOF)} \quad (4)$$

The formulas used for each indicator combine the respective variables by logarithm, including inverted components to reflect negative environmental impacts. This process ensures a holistic assessment of agricultural performance in a sustainable context.

3.3. Statistical Analysis

To validate the relationships and compare between countries, a series of statistical methods were applied: interdependence tests to ensure the robustness of the models used, multiple regressions to identify the impact of each indicator on overall performance, confirming by statistically significant values the relationships between the independent variables and the performance of sustainable agriculture. Correlations between variables were analyzed to exclude multicollinearity and Variance Inflation Factor (VIF) values, which indicated the absence of significant overlap between variable predictions.

3.4. Conceptualizing the Econometric Model of Agricultural Sustainability

The model used in the agricultural sustainability analysis (ASM) represents an appropriate methodological approach for assessing the performance of the decision-making units (EU27 except Malta and Luxembourg) in a context imposed by the need to decarbonize the agricultural sector. The scheme of the study is shown in Figure 1. In this schematic, the dynamic component to be tested by means of the Arellano–Bond dynamic model is also highlighted.

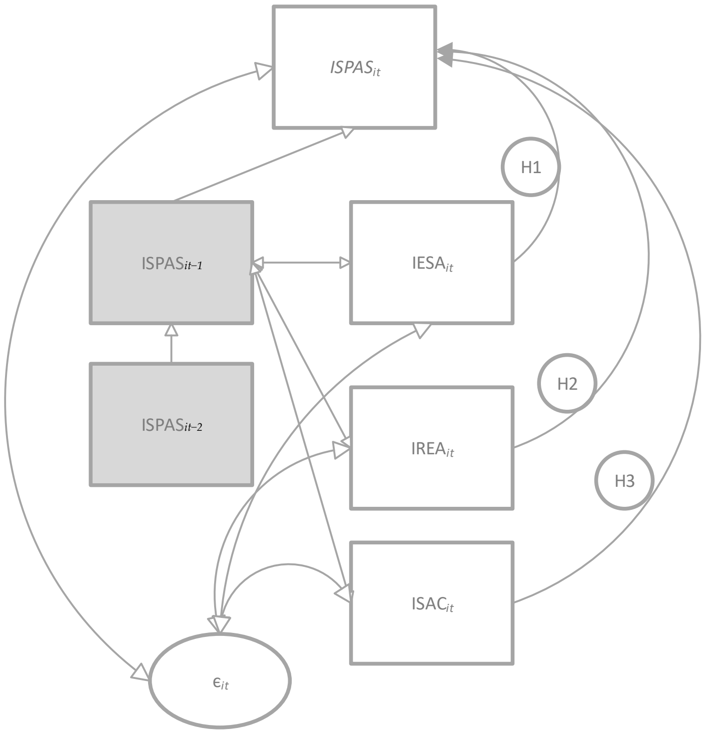

Figure 1. Logical scheme of the study (i unit at time t). Gray zone = dynamic components (time t, $t-1$, $t-2$) Source prepared by authors.

The hypotheses to be tested during the modeling (see Figure 1) are as follows:

Hypothesis 1 (H1). *Reducing agricultural emissions (IREA) has a positive but marginally significant impact on agricultural sustainability performance (ISPAS).*

The current context of European agriculture is marked by the stringent requirements of the European Green Pact and the objectives of the Farm to Fork Strategy, which require the reduction in agricultural emissions, the efficient use of agricultural land, and the integration of the economic and environmental dimensions in a coherent framework. The assumption derives from an undeniable fact: agriculture is responsible for about 10% of the European Union's greenhouse gas emissions, and policies to reduce them have become a strategic priority [66,67]. In this sense, previous research [68–70] has suggested that the impact of reduced emissions on agricultural sustainability is often positive but marginal, due to the complexity of agricultural processes and structural inertia in the sector.

Hypothesis 2 (H2). *The Combined Agricultural Sustainability Index (ISAC) has a significant positive impact on agricultural sustainability performance (ISPAS).*

Hypothesis 2 is based on a sound theoretical understanding of how economic performance, reduced environmental impacts, and the adoption of sustainable agricultural practices are interlinked to determine sustainability performance. The literature [71–73] emphasizes that the integration of these three dimensions is key to achieving sustainability goals.

Hypothesis 3 (H3). *The efficiency of agricultural area utilization (IESA) has a positive and significant impact on agricultural sustainability performance (ISPAS).*

This hypothesis is based on the evident need to optimize the use of agricultural resources in the context of increasing pressure on available land and growing demand for sustainable agricultural production. Previous studies have shown that agricultural land use efficiency is a major determinant of agricultural sustainability performance [74–76], and hypothesis H3 was formulated to test this relationship within a rigorous methodological framework.

The three hypotheses formulated therefore reflect an integrated and theoretically well-grounded approach to the key factors influencing agricultural sustainability performance in the current European context. These hypotheses not only respond to concrete challenges identified at the political and economic level, but also provide a sound analytical framework for investigating the complex relationships between emission reduction, the integration of economic and environmental dimensions, and agricultural land use efficiency. The study thus aims to contribute significantly to the understanding of the mechanisms underpinning the transition towards a more sustainable, equitable, and resilient European agriculture.

3.4.1. Conceptualizing the Linear Econometric Model of Agricultural Sustainability

By applying the multiple linear regression model to the indicators of agricultural sustainability (ISPAS, IREA, ISAC, and IESA), we were able to focus on the correlation relationships between the indicators composed of efficiency and sustainability of European agriculture. In the model, the explanatory variables—IREA (emission reduction), ISAC (combined sustainability), and IESA (farmland efficiency) are evaluated to understand their impact on ISPAS (Index of Sustainable Agricultural Performance). ASM thus allows an accurate analysis of how land use efficiency, emissions reduction, and the integration of economic and environmental sustainability influence agricultural performance. The model provides a robust and unbiased assessment of the determinants of agricultural sustainability, providing relevant support for the implementation of Green Deal policies in European agriculture. The model equation can be defined as follows:

$$\log\,(ISPAS)_i = \beta_i \log(IREA)_i + \gamma_i \log(ISAC)_i + \delta_i \log(IESA)_i + \epsilon_i \quad (5)$$

where

- $ISPAS_{it}$: the dependent variable (Sustainable Agricultural Performance Index);
- $IREA_{it}, ISAC_{it}, IESA_{it}$: independent variables;
- ϵ_i: the residual error.

3.4.2. Conceptualizing the Dynamic Arellano–Bond Panel Model of Agricultural Sustainability

The Arellano–Bond dynamic panel-data estimation model analyzes relationships in panel datasets where lagged dependent variables are included as regressors. The sustainability of agricultural performance is analyzed across different regions (DMUs-EU27 except Malta and Luxembourg) over the period 2012–2022, using composite indicators (ISPAS, IREA, ISAC, and IESA) derived from economic and environmental metrics. This methodology is valuable for assessing agricultural sustainability because it accounts for unobserved heterogeneity, endogeneity, and dynamic relationships over time. The model equation can be defined as follows:

$$\begin{aligned} \log(ISPAS)_{it} = \; & \beta_0 + \beta_1 \cdot L_{it-1} + \beta_2 \cdot L_{it-2} + \beta_3 \cdot \log(IREA)_{it} + \beta_4 \cdot \log(ISAC)_{it} \\ & + \beta_5 \cdot \log(IESA)_{it} + \varepsilon_{it} \end{aligned} \quad (6)$$

where

- $\log(ISPAS)_{it}$ is the dependent variable (for unit i at time t);

- L_{it-1} is the first lag of ISPAS;
- L_{it-2} is the second ISPAS lag;
- log(IREA$_{it}$), log(ISAC$_{it}$), log(IESA$_{it}$) are independent explanatory variables;
- ε_{it}, is the error term;
- β_0, is the constant.

The Arellano–Bond estimator uses the Generalized Method of Moments (GMM) to address endogeneity concerns. Lagged levels of the dependent variable are used as instruments for the lagged differences to remove biases due to endogeneity.

4. Results

The Variance Inflation Factor (VIF) values indicated the absence of significant overlap between the predictions of the variables (Table 1).

Table 1. Variance inflation factor.

Variables	VIF	1/VIF
IESA	1.656	0.604
IREA	1.591	0.628
ISAC	1.159	0.863
Mean VIF	1.469	0.000

Source: authors using Stata 18 software.

According to the data in Table 1, the VIF values for all variables are significantly below the critical threshold of 10, indicating the absence of multicollinearity in the model. The independent variables (IESA, IREA, and ISAC) are suitable for use in the regression model and their coefficients can be interpreted with confidence.

Table 2 presents the correlation coefficients between the variables used in the statistical analysis: ISPAS, IREA, ISAC, and IESA.

Table 2. Pairwise correlations.

Variables	(1)	(2)	(3)	(4)
(1) ISPAS	1.000			
(2) IREA	0.950 ***	1.000		
(3) ISAC	0.312 ***	0.119 **	1.000	
(4) IESA	0.573 ***	0.550 ***	−0.237 ***	1.000

*** $p < 0.01$, ** $p < 0.05$.

According to the data in Table 2, all identified correlations are statistically significant with a high level of confidence ($p < 0.01$ for most relationships). The variables show relevant relationships but with different influences on sustainable agricultural performance.

4.1. Results of Linear Econometric Model of Agricultural Sustainability

After performing the general statistical tests, it was shown that for the proposed model, the dependent variable ISPAS explained 92.31% of the variance of the independent variables IREA, ISAC, and IESA. The Root MSE value = 0.10984 indicates that the regression model is very accurate in estimating the sustainable performance of agriculture (ISPAS). The mean errors are small and the predictions are very close to the true values, which reinforces the robustness and validity of the models.

In analyzing the relationship between indicators of agricultural sustainability and overall agricultural performance, the regression model (Table 3) rigorously confirms the validity of the proposed hypotheses.

Table 3. Regression results.

ISPAS	Coef.	St.Err.	*t*-Value	*p*-Value	[95% Conf Interval]		Sig
IREA	0.920	0.017	53.12	0.000	0.886	0.954	***
ISAC	1.908	0.096	19.84	0.000	1.718	2.097	***
IESA	0.991	0.083	11.93	0.000	0.828	1.155	***
Constant	−5.403	0.121	−44.50	0.000	−5.642	−5.164	***
Mean dependent var			3.587	SD dependent var			0.572
R-squared			0.964	Number of obs			250
F-test			2169.529	Prob > *F*			0.000
Akaike crit. (AIC)			−390.933	Bayesian crit. (BIC)			−376.847

*** $p < 0.01$. Source: authors using Stata 18 software.

The obtained results demonstrate the different impact of each indicator on the ISPAS (Index of Sustainable Agricultural Performance), providing a clear picture of the factors influencing agricultural sustainability. The first hypothesis that IREA (Index of Reduced Agricultural Emissions) has a positive, significant impact on the sustainable performance of agriculture is partially confirmed. The estimated coefficient for IREA has a positive value of 0.920, indicating a favorable relationship between agricultural emission reduction and sustainability performance. Statistical significance is high, with a p-value < 0.001, suggesting that the effect is sufficiently strong. This significant positive influence suggests that policies and interventions aimed at reducing agricultural emissions had a significant effect on sustainability performance. The second hypothesis that the ISAC (Combined Agricultural Sustainability Index) has a positive and significant impact on sustainable agricultural performance is fully validated by the results. The ISAC coefficient is 1.908, demonstrating a considerable contribution to the growth of the ISPAS. Moreover, the statistical significance at an extremely high level (p-value < 0.001) confirms the robustness of the relationship between the two variables. This result emphasizes that an integrated approach, combining economic performance, environmental sustainability, and agricultural efficiency, is essential for improving agricultural sustainability performance. The central role of ISAC underlines the importance of well-coordinated policies capable of harmonizing economic and environmental requirements. The third hypothesis, which argues that the IESA has a positive and significant impact on the ISPAS, is also confirmed by the model results. The estimated coefficient for IESA, with a value of 0.991, positive and significant ($p < 0.001$), demonstrates a substantial influence on sustainable agricultural performance. This demonstrates that optimizing the use of agricultural land is a key determinant of overall agricultural sustainability performance. This relationship suggests that efficiency in farmland management, through modern technologies and sustainable practices, plays a significant role in achieving the Green Deal objectives and is a strategic direction for the future of European agriculture. It is confirmed by demonstrating the working hypotheses that both ISAC, IREA, and IESA have a significant and positive impact on the sustainable performance of agriculture, highlighting the central role of farmland efficiency and integrated sustainability, concomitant with the adoption of appropriate measures to reduce agricultural emissions as a key determinant of sustainability. The results underline the importance of a balanced and integrated approach, where economic, environmental, and resource use policies are aligned to improve sustainable agricultural performance at the EU level. The full model provides a robust and robust assessment of the relationships between agricultural sustainability indicators and overall agricultural performance. ISAC and IESA are key drivers for achieving sustainability goals, while IREA suggests opportunities to approach Green Deal goals through agricultural policies geared towards reducing emissions. Model validation by econometric tests confirms the consistency of the estimates and the results provide clear directions for policy interventions and strategies to develop sustainable agriculture at the European level.

4.2. Results of Dynamic Arellano–Bond Panel Model of Agricultural Sustainability

The Arellano–Bond dynamic panel model effectively captures the interplay between economic performance, environmental impact, and efficiency in agricultural sustainability. The results of the dynamic panel-data Arellano–Bond model provide a complex perspective on the determinants of agricultural sustainability, using logarithmic data to reduce variance and facilitate the interpretation of elasticities. The Wald test, with a value of 5660.47 and an associated probability of 0.0000 (Table 4), indicates that the explanatory variables included in the model are significant as a whole and robustly explain the variation in agricultural sustainable performance (ISPAS). This global validation emphasizes the suitability of the model for analyzing the dynamic relationships among the indicators under consideration. The mean of the dependent variable ISPAS is 3.591, with a standard deviation of 0.572, suggesting a moderate dispersion of values around the mean. This relative stability of the dependent variable indicates that differences between the EU Member States analyzed are present but not extreme. The model uses an adequate number of instruments (48) and the GMM effectively corrects for endogeneity.

Table 4. Dynamic Arellano–Bond panel model one-step results.

ISPAS	Coef.	St.Err.	*t*-Value	*p*-Value	[95% Conf Interval]		Sig
L	0.193	0.031	6.28	0.000	0.133	0.254	***
L2	0.094	0.025	3.79	0.000	0.045	0.142	***
IREA	0.126	0.031	4.03	0.000	0.065	0.187	***
ISAC	1.513	0.034	44.20	0.000	1.446	1.58	***
IESA	1.578	0.052	30.45	0.000	1.476	1.679	***
Constant	−0.924	0.296	−3.12	0.002	−1.505	−0.343	***
Mean dependent var		3.591	SD dependent var		0.572		
Number of obs		200	Wald Chi-square (5)		5660.468		
Number of instruments		48	Prob > Chi-square		0.000		

*** $p < 0.01$.

According to Table 4, the estimated coefficients for the lags of the dependent variable ISPAS (L1 and L2) are positive and significant. The first lag (0.193, $p = 0.000$) suggests that past performance in agricultural sustainability has a positive and persistent effect on current performance. This relationship confirms the presence of inertia effects in the evolution of agricultural sustainability. The second lag (0.094, $p = 0.000$) indicates a similar effect, but of lower intensity, suggesting that the influence of historical performance diminishes in the longer term, but remains significant.

The coefficient associated with the IREA indicator (0.126, $p = 0.000$) shows that reducing agricultural emissions has a positive effect on sustainable performance. However, the relatively small magnitude of the coefficient indicates a marginal impact compared to other indicators. This relationship validates hypothesis H1 that emission reductions contribute positively, but more modestly, to agricultural sustainability.

The ISAC coefficient (1.513, p = 0.000) is significant and has the highest magnitude among the explanatory variables. This result indicates that the integration of economic, environmental, and sustainable agricultural practices dimensions is essential for agricultural sustainability performance. The strength of this relationship validates hypothesis H2 and suggests that agricultural policies should simultaneously target these three dimensions to achieve robust results.

The IESA (1.578, p = 0.000) also exhibits a high and significant coefficient, indicating a strong relationship between land use efficiency and agricultural sustainability performance. This relationship suggests that optimal farmland management in relation to economic performance and environmental practices is a key factor in improving sustainability. Thus, hypothesis H3 is validated, and the results emphasize the importance of optimizing agricultural land use.

The constant term of the model (−0.924, p = 0.002) is negative and significant, suggesting that, in the absence of positive contributions from the explanatory variables, agricultural sustainability could be negatively affected by structural or contextual factors that are not directly captured by the model and that require additional adjustments to the Common Agricultural Policies. These factors include social factors such as farmer well-being and social equity which are not included in the indicator framework. The dynamic Arellano–Bond model provides strong evidence to validate the working hypotheses. Reducing agricultural emissions (IREA) contributes positively, but marginally, to agricultural sustainability performance. The integration of economic, environmental, and technological dimensions through ISAC has the strongest impact, followed by agricultural land use efficiency (IESA). The persistence of historical performance emphasizes the importance of long-term sustainable agricultural policies. These results suggest that future strategies should focus on an integrated approach combining pollution reduction, efficient land use, and sustainable economic development to support agricultural sustainability performance. The interpretation of the descriptive statistics for the period 2012–2022, aimed at analyzing the implementation of the Green Deal in the agricultural sector of the EU Member States (excluding Luxembourg and Malta), reveals significant differences between the countries analyzed. This analysis is based on four composite indicators summarizing economic performance, environmental sustainability, and investment efficiency (Table 5).

Table 5. Descriptive statistics.

Indicator	N	Mean	Std. Deviation	Minimum	Maximum	Percentiles		
						25th	50th (Median)	75th
ISPAS	275	3.584853	0.5713003	2.4895	4.6505	3.165100	3.572100	3.979000
IREA	275	7.069645	0.5083147	6.1133	8.0161	6.686700	7.061200	7.341900
ISAC	275	0.891145	0.0789199	0.6531	1.0652	0.839000	0.892900	0.950100
IESA	275	0.789098	0.1081901	0.5119	1.0866	0.714100	0.799000	0.856400

Source: authors using Stata 18 software.

The Index of Sustainable Agricultural Performance (ISPAS) reflects the ability of countries to balance agricultural economic performance with environmental impacts. The index average of 3.58 suggests that, in general, the countries surveyed maintain a moderate balance between these objectives. The low dispersion of the values, with a standard deviation of 0.57, indicates moderate variation across states. The extreme values, with a minimum of 2.49 and a maximum of 4.65, show that some countries perform considerably better in implementing this balance, while others have difficulties in reducing their environmental impact. The median percentile of 3.57 confirms that half of the countries have reached this threshold, indicating moderate convergence in sustainable agricultural performance. The Index of Reduced Agricultural Emissions (IREA) provides insight into states' efforts to reduce agricultural pollution, with a focus on ammonia and greenhouse gas emissions. The average IREA value of 7.07 indicates a moderate reduction in polluting emissions in agriculture. The dispersion of the values, with a standard deviation of 0.51, reflects moderate variations between countries. The minimum of 6.11 suggests that some states have made significant progress in reducing emissions, while other states still have high emissions, with values close to the maximum of 8.01. These data show that while there are overall improvements, implementation of emission reduction measures is not uniform. The Combined Agricultural Sustainability Index (CASI) is an overall indicator of sustainable performance, including economics, ecology, and research. The mean of 0.89 and the low standard deviation of 0.07 suggest greater convergence among the countries analyzed in implementing sustainable agricultural development. The extreme values are also moderate, with a minimum of 0.65 and a maximum of 1.06, indicating that most countries fall within a similar range in terms of overall sustainability. The Farmland Area Efficiency Index (FEAI) measures agricultural area utilization in relation to economic performance and sustainability. The average of 0.78 and the maximum of 1.08 indicate that some countries are efficiently optimizing their agricultural land, resulting in notable economic performance. In contrast, the minimum of 0.51 indicates that some countries make less efficient use of available agricultural land.

The data were analyzed by means of ranking tests (Kruskal–Wallis and K-Means) the results contributing to the design of 5 performance clusters as presented in Table 6.

The analysis of Table 6, in which the Kruskal–Wallis ranking is correlated with the K-Means clustering, provides insight into the differences in the sustainable agricultural performance of EU Member States. The ranking method used in the test highlights the relative variability between countries according to the indicators analyzed, and the clustering allows the identification of distinct patterns in agricultural policies and practices. The cluster representation diagram is presented in Figure 2 below.

Figure 2. Cluster representation diagram.

Table 6. Ranking test results.

Test	DMU	Mean Rank	N	ISPAS	IREA	ISAC	IESA
Kruskal–Wallis Test	Belgium	1	11	156.73	143.18	101.45	218.55
	Bulgaria	2	11	99.09	107.55	15.91	166.55
	Czechia	3	11	112.91	150.00	151.14	48.27
	Denmark	4	11	151.45	147.09	154.00	131.82
	Germany	5	11	246.36	252.27	162.73	198.68
	Estonia	6	11	14.82	6.55	185.77	9.09
	Ireland	7	11	119.82	215.00	9.82	245.64
	Greece	8	11	193.36	141.18	237.00	140.09
	Spain	9	11	241.36	258.55	211.23	166.23
	France	10	11	259.73	265.73	168.18	205.00
	Croatia	11	11	64.64	67.91	92.45	124.64
	Italy	12	11	266.55	237.09	261.27	212.59
	Cyprus	13	11	10.73	16.45	49.45	254.18
	Latvia	14	11	30.09	28.00	153.05	14.36
	Lithuania	15	11	68.55	67.27	101.00	69.64
	Hungary	16	11	170.27	166.45	69.59	157.91
	Netherlands	17	11	224.91	202.73	149.45	270.00
	Austria	18	11	158.00	176.27	255.18	87.14
	Poland	19	11	216.09	226.36	62.23	177.59
	Portugal	20	11	154.18	116.27	179.50	118.23
	Romania	21	11	203.64	194.27	69.95	208.36
	Slovenia	22	11	34.64	40.73	105.18	88.64
	Slovakia	23	11	51.91	49.18	92.36	27.73
	Finland	24	11	84.18	90.55	181.05	61.00
	Sweden	25	11	116.00	83.36	231.05	48.09
K-Means		Cluster		ISPAS	IREA	ISAC	IESA
		Cluster 1		3.56	6.99	0.94	0.75
		Cluster 2		2.93	6.50	0.89	0.66
		Cluster 3		4.45	7.79	0.94	0.89
		Cluster 4		2.77	6.38	0.81	0.89
		Cluster 5		3.70	7.29	0.79	0.85

Source: authors using SPSS program, version 26.

According to Figure 2, Cluster 1 includes countries such as Belgium, Denmark, Austria, Portugal, Finland, Greece, and the Czech Republic. These countries, with an average ISPAS of 3.56, reflect a balanced agricultural performance, supported by moderately rich ISAC values (0.94). In the Kruskal–Wallis's test, Belgium has an average rank of 156.73, indicating an intermediate position, and Portugal, with 154.18, confirms this convergence. These countries have implemented public policies aimed at reducing agricultural emissions, supported by significant investments in research and development. However, they do not reach the intense economic performance of some countries in other clusters, focusing rather on sustainability and agricultural efficiency. Cluster 2 is made up of countries such as Estonia, Latvia, Lithuania, Slovenia, Slovakia, and Latvia. These countries have a lower average ISPAS (2.93). Within this cluster, Estonia has a very low average rank of 14.82, indicating a more modest contribution to ISPAS. Public policies in this cluster have favored organic farming and efficient use of agricultural land, but the overall level of sustainability (ISAC of 0.88) suggests an incomplete transition to a low-emission agricultural model. Cluster 3 is composed of countries such as Germany, France, Italy, and Spain, Poland, is notable for its very high ISPAS (4.45) and high levels of agricultural emissions (IREA of 7.79). In the Kruskal–Wallis's test, Germany and France rank among the highest, with 246.36 and 259.73, respectively. This reflects the fact that, despite being leaders in agricultural productivity, these countries have difficulties in reducing emissions. Their policies have focused more on maximizing production for domestic and foreign markets, with limited investment in the ecological transition. Cluster 4 includes countries such as Hungary, Bulgaria, Romania, and Croatia, standing out with the lowest ISPAS (2.77). Bulgaria has a low average rank (99.09) in the Kruskal–Wallis's test, indicating poorer performance in overall sustainability, while Romania, with a rank of 203.64, suggests a more intermediate position. The public policies of these countries have prioritized economic revenues, but have made insufficient steps in reducing agricultural emissions, which places them in a vulnerable position in the transition towards sustainability. Cluster 5 includes countries such as Sweden, Cyprus, Ireland, and the Netherlands. They stand out with an average ISPAS of 3.69 and a balance between emissions and organic farming performance (IREA of 7.28). In the Kruskal–Wallis's test, Cyprus has a low rank (10.73), indicating a lower contribution to the ISPAS, while the Netherlands, with a rank of 224.91, shows a much stronger performance. These countries have adopted integrated policies focused on optimizing agricultural areas and reducing emissions, supported by modern infrastructure and public support for sustainable agriculture.

Significance tests (Kruskal–Wallis H, asymptotic significance test, and Monte Carlo test) are presented in Table 7.

Table 7. Results of significance tests.

Test Statistics [a,b]			ISPAS	IREA	ISAC	IESA
Kruskal–Wallis H			268.175	270.279	214.056	256.859
df			24	24	24	24
Asymp. Sig.			0.000	0.000	0.000	0.000
Monte Carlo Sig.	Sig.		0.000 [c]	0.000 [c]	0.000 [c]	0.000 [c]
	99% Confidence Interval	Lower Bound	0.000	0.000	0.000	0.000
		Upper Bound	0.000	0.000	0.000	0.000

[a] Kruskal–Wallis test; [b] grouping variable: DMU; [c] based on 10,000 sampled tables with starting seed 2,000,000. Source: authors using SPSS program, version 26.

The results of the Kruskal–Wallis's test presented in the table confirm the existence of statistically significant differences between the DMU groups for all the indicators analyzed (ISPAS, IREA, ISAC, and IESA). The Kruskal–Wallis H test returns high values for each indicator, ranging from 214.056 (for ISAC) to 270.279 (for IREA). This suggests an uneven distribution of DMU performance for all indicators. The asymptotic significance (Asymp. Sig.) and Monte Carlo significance (Sig.) are 0.000, indicating that the results are highly statistically significant at a 99% confidence level. The high statistical significance validates the robustness of the methodology used and highlights clear variations in performance across the groups analyzed. The median test applied to the sustainable performance indicators

(ISPAS, IEAE, IREA, IREA, IVAE, ISAC, and IESA) shows significant discrepancies between the countries analyzed. These variations are not only the result of different agricultural strategies but reflect distinct levels of economic development and absorption capacity of Green Deal funds.

5. Discussions

Table 8 presents the results of the median test applied to the performance indicators ISPAS, IREA, ISAC, and IESA for each of the 25 Decision-Making Units (DMUs) represented by the Member States of the European Union. The purpose of this test is to identify those countries that perform above the median (values marked in green) and those that perform below the median (values marked in red) for each of the four summary indicators.

Table 8. Results of the median test applied to performance indicators.

DMU		Belgium	Bulgaria	Czechia	Denmark	Germany	Estonia	Ireland	Greece	Spain	France	Croatia	Italy	Cyprus	Latvia	Lithuania	Hungary	Netherlands	Austria	Poland	Portugal	Romania	Slovenia	Slovakia	Finland	Sweden
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**
ISPAS	>Median	9	1	1	8	11	0	1	11	11	11	0	11	0	0	0	11	11	10	11	7	11	0	0	0	1
	≤Median	2	10	10	3	0	11	10	0	0	0	11	0	11	11	11	0	0	1	0	4	0	11	11	11	10
IREA	>Median	7	0	7	7	11	0	11	5	11	11	0	11	0	0	0	11	11	11	11	1	11	0	0	0	0
	≤Median	4	11	4	4	0	11	0	6	0	0	11	0	11	11	11	0	0	0	0	10	0	11	11	11	11
ISAC	>Median	1	0	5	7	8	10	0	11	11	7	2	11	0	6	3	0	6	11	0	10	2	4	2	8	11
	≤Median	10	11	6	4	3	1	11	0	0	4	9	0	11	5	8	11	5	0	11	1	9	7	9	3	0
IESA	>Median	11	5	0	4	11	0	11	7	11	11	2	11	11	0	0	8	11	0	11	1	11	0	0	0	0
	≤Median	0	6	11	7	0	11	0	4	0	0	9	0	0	11	11	3	0	11	0	10	0	11	11	11	11

Source: Authors using SPSS program.

Analysis of the data in Table 8 highlights the sustainability of agricultural performance (ISPAS) in countries such as Germany, Greece, Spain, France, Italy, Hungary, Netherlands, Austria, Poland, and Romania, which stand out as outperformers with a high number of units above the median. Germany, a highly industrialized economy, has benefited from substantial Green Deal allocations for agriculture, directed towards sustainable practices and modernization of the sector. Emerging economy states such as Hungary, Poland, and Romania, although emerging economies have demonstrated an effective use of EU funds for agriculture, particularly for rural infrastructure development and technologization. In contrast, Estonia, Slovenia, and Slovakia perform below average. Estonia, with a small agrarian economy and limited funds for ecological transition, has difficulties in implementing sustainable strategies. Italy and Belgium, with developed economies, have been hampered by the fragmented structure of the agricultural sector and delays in absorbing funds. The performance of economies such as Estonia, Croatia, Cyprus, Latvia, Lithuania, Latvia, Lithuania, Slovenia, Slovakia, and Finland, which have below-average values for the ISPAS indicator, reflects a combination of structural, economic and political constraints. First, the small size of the agricultural sector in these countries plays a key role. In Estonia, Latvia, and Lithuania, economies with a predominantly industrial and digital orientation, agriculture has a peripheral share in GDP and there is limited investment directed towards this sector. Similarly, Cyprus and Slovenia face geographical challenges such as limited space or arid land, which affect agricultural productivity and limit the uptake of sustainable practices. Fragmentation of agricultural land is another determining factor in Slovakia, Latvia, Lithuania, and Croatia. This situation, inherited from the post-Soviet period or resulting from economic restructuring, reduces farm efficiency and discourages investment in modern technologies. Limited access to Green Deal funds and low absorption capacity also contribute to poor performance. Slovakia and Croatia experienced difficulties in implementing agricultural projects, while Estonia and Latvia, hampered by underdeveloped rural infrastructure, encountered obstacles in adopting green initiatives. Another relevant aspect is the low level of R&D investment in agriculture. Cyprus, Lithuania, and Latvia allocate limited resources to this area, and the implementation of green technologies such as precision farming is at a slower pace compared to Western European countries. In parallel, traditional agriculture predominates in Slovenia, Croatia, and Lithuania, where low mechanization and outdated technologies lead to low productivity and inefficient use of resources. unfavorable natural and climatic conditions pose an additional challenge for northern European countries such as Estonia, Finland, and Latvia. The cold climate, short growing seasons, and poor soil quality limit crop diversification and thus the sustainable performance of agriculture. This is compounded by incoherent or locally unsuited agricultural policies, as seen in Cyprus and Slovakia, where the implementation of green strategies is fragmented. Even Finland, a country with a high level of development, is showing an economic orientation that reduces the importance of agriculture and focuses on other sectors with a more significant economic contribution. The below median results for the ISPAS indicator in these countries are the consequence of the interaction of structural factors such as the small size and fragmentation of the agricultural sector, limitations in the absorption of Green Deal funds, insufficient investment in research, and unfavorable natural conditions. Without economy-specific interventions, such as technological upgrading, consolidation of agricultural land, and optimization of fund absorption strategies, these countries will continue to lag significantly behind Europe's performing economies. To improve the performance of sustainable agriculture in economies such as Estonia, Croatia, Cyprus, Latvia, Lithuania, Latvia, Lithuania, Slovenia, Slovakia, and Finland, an integrated approach tailored to the specific context of each country is needed. Solutions must aim at modernizing the agricultural sector, increasing resource efficiency, and better absorption of Green Deal funds. The adoption of precision farming technologies and digital solutions is essential to increase productivity and reduce environmental impact. Investments in drones, soil sensors, smart irrigation systems, and farm management software can optimize the use of natural resources and reduce operational costs. Excessive fragmentation of agricultural land in countries such as Latvia, Lithuania, and Slovakia calls for farm consolidation policies. Creating national schemes to encourage cooperation between small farmers or even land mergers can lead to larger, more efficient, and more competitive farms. Countries like Cyprus, Lithuania, and Croatia need to prioritize applied agricultural research geared towards the development of sustainable solutions adapted to local conditions. Investments in the development of climate-resilient varieties, soil management techniques and efficient methods to reduce agricultural emissions are essential. In the case of Nordic countries such as Estonia and Finland, where the climate limits crop diversity, it is important to adapt agricultural production by growing cold-hardy crops and developing complementary industries such as niche farming (e.g., berries, and medicinal plants). The economies of Germany, Ireland, Spain, France, Italy, Germany, Italy, Hungary, the Netherlands, Austria, Poland, Romania, and the Netherlands are above average for the IREA indicator due to a combination of structural, political and economic factors, reflecting their commitments to reduce agricultural emissions. Germany, France, and the Netherlands have implemented ambitious policies in line with the Green Deal objectives, aimed at reducing greenhouse gas and ammonia emissions, using advanced technologies and strict regulations on manure and fertilizer management. These interventions have been supported by substantial subsidies for farmers who adopt green solutions, which have led to a significant decrease in agricultural emissions. Another key factor explaining this performance is the massive investment in modern farming technologies, such as precision farming systems and ammonia capture and reduction equipment, which have been successfully deployed in countries such as Germany, the Netherlands, and Austria. These technologies optimize resource use and reduce the environmental impact of agriculture, even in highly industrialized farming sectors. At the same time, countries such as Spain, Poland, and Romania, which rely on traditional farming practices, have been able to achieve high IREA indicator values thanks to simple environmental interventions such as crop rotation and the use of natural grassland, which generate low emissions. Moreover, substantial financial support from EU funds for the ecological transition has contributed significantly to the performance of economies such as Hungary, Poland, and Romania, where farmers have been supported to adopt sustainable farming practices. Ireland and Italy have also demonstrated increased efficiency in the use of agricultural resources by optimizing water and energy use and introducing efficient crop rotations. In addition, Germany, France, and the Netherlands stand out for their considerable investment in research and development aimed at identifying innovative solutions to reduce emissions, such as the development of more resilient crop varieties and methane abatement technologies for livestock. These efforts highlight a high capacity to adapt to modern environmental requirements and a firm alignment with Green Deal objectives, which justifies the high IREA indicator values for these economies. The below average values of the IREA indicator for emerging European economies (Bulgaria, Estonia, Croatia, Cyprus, Latvia, Lithuania, Lithuania, Slovenia, and Slovakia) reflect the interplay between structural constraints in agriculture, limited investment in technology and research, low prioritization of emission reduction in national strategies and country-specific economic and natural challenges. To improve these results, an integrated approach is needed that combines investment in modern agricultural infrastructure, the promotion of stricter policies, and support for the greening transition through better use of EU funds. The economies of Greece, Spain, Italy, Italy, Austria, and Sweden show above-average values for the ISAC (Index of Combined Agricultural Sustainability) indicator in the median test due to a distinct set of structural, economic, and policy factors that support the effective integration of the economic, environmental and technological dimensions of agriculture. ISAC measures the overall sustainability of agriculture by combining economic performance, share of organic farming, and low agricultural emissions, and the results of these countries reflect a balance between these components. In the case of Greece, Spain, and Italy, the high performance can be explained by the significant share of organic farming in their agricultural structure, supported by favorable natural conditions and sustainability-oriented policies. These countries have invested in promoting organic farming as a solution to diversify the rural economy and to respond to the growing demand for organic products in domestic and international markets. Extensive organic crop regions and the adoption of traditional farming practices with low environmental impact have contributed to high ISAC scores. Austria stands out as a European leader in organic farming, with a high percentage of its agricultural area used in this way, combined with coherent policies to reduce emissions and support farmers. This performance is the result of a strategic commitment by the Austrian government to integrate sustainability objectives into all aspects of agricultural policy. Investments in research and development, coupled with strict regulations on resource use and the management of agricultural environmental impacts, have enabled Austria to achieve an optimal balance between agricultural production and environmental protection. In Sweden, high performance for ISAC reflects a strong focus on agricultural sustainability through technological innovation and strict regulations. Swedish agriculture benefits from the integration of green technologies such as precision farming and advanced emission management solutions, particularly in the livestock sector. Sweden also promotes an efficient use of natural resources and integrated management of agricultural land, which contributes to high values for ISAC. These countries have successfully integrated the economic, environmental, and technological dimensions of agriculture, with an agricultural structure well adapted to Green Deal requirements. The economies of Bulgaria, Ireland, Cyprus, Hungary, Poland, and Cyprus show below average values for the ISAC (Index of Combined Agricultural Sustainability) indicator in the median test, reflecting the significant challenges these countries face in integrating economic, environmental, and technological sustainability in the agricultural sector. Below average results indicate shortcomings in achieving a balance between agricultural economic performance, the share of organic farming, and low levels of agricultural emissions. A central factor explaining these results is the low share of organic farming in the agricultural structure of these countries. In Bulgaria, Cyprus, and Poland in particular, the agricultural area used for organic farming practices is limited and the transition to organic farming is proceeding at a slow pace due to economic constraints and underdeveloped infrastructure. Government support for the expansion of organic farming also remains low, preventing farmers from adopting sustainable solutions. In the case of Ireland and Hungary, poor performance can be attributed to high levels of agricultural emissions, particularly from the intensive livestock sector. Ireland, for example, has a heavily livestock-oriented agricultural industry with significant emissions of methane and ammonia. National policies to reduce emissions have not yet been implemented effectively enough to offset the impact of this sector, which contributes to the low ISAC scores. Hungary, although benefiting from EU financial support, has difficulties in reducing agricultural pollution due to a lack of strict regulations and slow implementation of modern technologies. Another relevant issue is the high dependence on conventional agriculture and the prioritization of economic production over environmental sustainability. Poland and Bulgaria, for example, rely on traditional and volume-oriented farming models, which creates a conflict between economic performance and environmental objectives. In Cyprus, natural constraints, such as water scarcity and arid land, limit options for expanding sustainable agriculture, contributing to the low performance of ISAC. The above-average performance for the IESA indicator (in Belgium, Germany, Spain, France, Italy, Netherlands, Poland, and Romania is due to a combination of advanced technologies, optimized farming practices, strategic use of natural land, and coherent agricultural policies. These countries demonstrate a high capacity to adapt agriculture to the Green Deal requirements and to capitalize on available resources to maximize the efficiency of agricultural areas while ensuring economic and environmental sustainability.

The analysis shows that European agricultural policies are an essential building block for achieving sustainability objectives, aiming to reduce negative environmental impacts, maintain the economic competitiveness of the agricultural sector, and promote balanced rural development. The Common Agricultural Policy (CAP) has steadily evolved, integrating environmental priorities such as the reduction in greenhouse gas emissions and the conservation of biodiversity, becoming a central element in the transition towards a sustainable agricultural model. In this context, structural analysis of the differences between Member States has highlighted that the successful implementation of these policies depends significantly on the capacity of each Member State to carry out structural reforms tailored to local challenges. Countries with advanced economies have demonstrated a superior capacity to absorb and make efficient use of available funds through initiatives such as the Green Deal, thus reinforcing the transition towards greener farming practices. They have integrated innovative technologies and farmer education programs into national strategies, achieving remarkable results in reducing pesticide use and increasing productivity through modern farming practices. Emerging economies, on the other hand, face difficulties in accessing EU funds and implementing the necessary reforms, affected by structural constraints, under-developed rural infrastructure, and limited administrative resources. In order to reduce these regional disparities and increase the effectiveness of EU agricultural policies, it is essential that the European Union tailor the allocation of funds to the specific needs of each region. The integration of digital technologies and artificial intelligence in fund management processes and in farmer training is a viable solution to accelerate the adoption of green practices and optimize available resources. In addition, the creation of collaborative platforms between Member States for the exchange of best practices and the implementation of locally customized solutions can help bridge existing gaps. Another key issue is the flexibility of agricultural policies to respond to structural differences between developed and emerging economies. Reforms need to address soil degradation, efficient management of water resources, and protection of ecosystems. In this respect, developing educational programs for farmers and supporting small farms with adapted financial instruments can be concrete steps towards sustainable and equitable agriculture. We appreciate that European agricultural policies provide a solid framework for achieving sustainability objectives, but their success depends on effective implementation at the national and regional levels. By tailoring interventions to country-specific challenges and promoting technological innovation and cross-border cooperation, agricultural policies can become a powerful driver of the transition towards a more sustainable and resilient European agricultural sector. The results of the study show significant differences in agricultural sustainability performance between EU Member States, confirming the findings of other recent studies on agricultural sustainability [77–79]. The Kruskal–Wallis analysis and the dynamic Arellano–Bond model provided a solid insight into the structure of the differences between advanced and emerging economies, suggesting that sustainability performance is mainly influenced by the integration of agricultural policies, investments in modern technologies, and the administrative capacity of each country. The study confirms observations from recent expert studies [54,79–81] on the impact of structural and administrative differences on the performance of sustainable agriculture, particularly in the context of emerging economies. Similarly, other research [52,82,83] emphasizes the importance of digital technologies and smart monitoring to accelerate the transition to sustainable farming practices, findings are also reflected in this study. However, the present study makes a significant contribution by integrating a dynamic model (Arellano–Bond), which allows to capture of inertia effects and temporal relationships between sustainability indicators. This aspect has been less addressed in the previous literature, which has predominantly focused on static or comparative cross-sectional analyses. The study identified five clusters of sustainable agricultural performance using K-Means analysis, consolidating results from other research [84–86]. Western European Member States (Germany, France, and the Netherlands) have shown superior performance due to the effective implementation of green agricultural policies and sustained investment in advanced agricultural technologies. In contrast, Eastern European countries (Romania, Bulgaria, and Poland) had difficulties in accessing funds and implementing emission reduction policies. The cluster analysis shows that Western European countries benefit from a solid agricultural infrastructure and well-defined policies, while Eastern European countries face administrative and financial barriers in adopting modern technologies and implementing sustainability strategies. The integrated approach of the four synthetic indicators (ISPAS, IREA, ISAC, and IESA) is an innovative contribution, whereas the literature has often dealt with these dimensions separately [34,74]. In particular, the significant positive coefficient associated with the ISAC indicator (1.513, $p < 0.01$) confirms the hypothesis that the integration of economic and environmental dimensions is essential for agricultural sustainability performance.

The Arellano–Bond model provides a detailed analysis of the temporal relationships between economic performance, agricultural land use efficiency, and agricultural emission reductions, providing a dynamic perspective on the mechanisms that determine sustainability.

In order to improve agricultural sustainability performance, an integrated approach is needed, including investments in advanced agricultural technologies, strengthening rural infrastructure, and adjusting public policies to the economic and social particularities of each Member State.

6. Conclusions

This study establishes a solid basis for analyzing the performance of European agriculture in the context of the ecological transition promoted by the European Green Pact. The proposed study makes a significant contribution to the literature by developing an innovative model of sustainability, applicable at the EU Member State level. By integrating synthetic indicators and using rigorous econometric methods, the research provides a robust tool for assessing the performance of sustainable agriculture and formulating effective policies capable of ensuring a fair and sustainable transition for European agriculture. The research revealed structural differences in sustainable agricultural performance between EU Member States. The results of the econometric model highlighted the performance of agricultural sustainability (which varies significantly between Member States); the importance of ISAC and IESA in determining overall performance; and the potential sustainability impact of agricultural emission reductions (IREA). Thus, the analysis demonstrated significant discrepancies in agricultural performance between developed and emerging economies. Countries such as Germany, France, the Netherlands, and Austria stand out with consistently positive values for all sustainability indicators, due to the effective integration of modern technologies, green agricultural policies, and investments in research. In contrast, Eastern European countries such as Bulgaria, Romania, and Poland have difficulties in achieving sustainable performance due to structural constraints and limited financial resources. Regression results indicate that the Index of Combined Agricultural Sustainability (ICASI) and the Index of Land Area Efficiency (IESA) have a positive and significant impact on sustainable performance (ISPAS). ICASI emphasizes the central role of integrating economic and environmental dimensions, while IESA emphasizes the importance of optimizing the use of agricultural resources through efficient practices and modern technologies. At the same time, the Agricultural Emission Reduction Index (AERI) contributes positively to agricultural sustainability performance, its significance indicating the need for further measures to enhance the effectiveness of emission reduction policies. This finding suggests that current efforts to reduce the pollutant impact of agriculture are not yet at their maximum efficiency and have a high potential effect on improving the sustainability of the European agricultural sector.

Countries that have been able to make effective use of EU funds for the greening transition have achieved superior results in terms of agricultural sustainability. Well implemented agricultural policies, such as support for organic farming and investments in green infrastructure, have been key factors in the positive performance.

The recommendations developed in the study aim to improve sustainable performance by stimulating organic farming, increasing the uptake of EU funds, and deploying innovative technologies. These policies are aligned with the Green Deal objectives and aim to reduce the gap between developed and emerging economies. The results provide a grounded theoretical framework with immediate practical implications for the harmonization of agricultural policies and the promotion of the green transition.

The indicator framework is developed based on the specific context of the European Union, and its applicability to other regions or countries might be limited. Adjustments and modifications would be necessary to account for regional differences when applying this framework in other contexts.

The limitations of the study are the delimited temporal dimension and the use of the linearity assumption between variables. The regression model assumes a linear relationship between the explanatory indicators (IREA, ISAC, and IESA) and agricultural sustainability performance (ISPAS). The relationships may be non-linear or may exhibit threshold effects, especially in the context of structural differences between developed and emerging economies. This simplification may limit the ability of the model to capture the complexity of agricultural phenomena. In the future, we aim to develop this research both by complementing the temporally limiting dataset to extend the correlational analysis and improve the proposed sustainability model, and by using machine learning and artificial intelligence techniques. Thus, we aim to complement traditional regression methods with modern machine learning techniques (Random Forest, 2022 Version 4.7-1.2, XGBoost, 2024 Version 2.1.3) to explore complex relationships between variables and identify hidden patterns in the data for more accurate predictions of agricultural performance under different future scenarios. We appreciate that there are limitations associated with the use of equal weights and believe that the inclusion of PCA in an additional analysis could improve the research, particularly in the stage of validating the structure of the synthetic indicators and checking the robustness of the relationships identified. A future direction for research will be to apply a combination of PCA for weighting and K-Means for clustering to ensure both methodological robustness and clarity of interpretation of the results. As shown when detailing the results of the dynamic model, agricultural sustainability could be negatively affected by structural or contextual factors that are not directly captured by the model. Future research could consider a more comprehensive indicator system that incorporates these social aspects to provide a more holistic evaluation of sustainable agriculture. The reality of agricultural systems is often characterized by non-linear relationships, threshold effects, and dynamic interdependencies that cannot be fully captured by traditional linear econometric methods. There are critical points in the dynamics of agricultural emissions or land use efficiency beyond which the marginal effects of policies become significantly different. Thus, integrating non-linear approaches, such as Threshold Regression or Smooth Transition Regression models, could provide a better capture of these complex dynamics and identify areas of optimal policy intervention. As for the application of artificial intelligence (AI) techniques, we see them as a direction to propound the analysis and address current limitations. Algorithms such as Artificial Neural Networks, Decision Trees, or Support Vector Machines can model much more complex relationships between variables without a priori assuming a rigid functional structure. The use of neural networks could allow the detection of hidden patterns in the data and improve the prediction of synthetic indicators of agricultural sustainability based on extended time series and finer granularity datasets. Complementarily, machine learning techniques can help to optimize the weights for the component variables of the indicators, providing a more flexible alternative to assigning equal weights or even using Principal Component Analysis (PCA). Algorithms such as Random Forests or Gradient Boosting Machines can provide valuable information about the relative importance of each variable in determining the sustainable performance of agriculture. The integration of AI in our future analysis could follow two main directions. First, by using AI-based predictive models to identify future trends and critical points in agricultural sustainability performance. By using unsupervised learning algorithms, such as clustering based on algorithms such as DBSCAN (Density-Based Spatial Clustering of Applications with Noise), finer-grained groupings and typologies of the decision units under analysis can be identified. In terms of implementing these directions, the first step will be to extend the database to include longer time series and additional variables to efficiently train machine learning algorithms. Subsequently, linear and non-linear models could be systematically compared to identify the most appropriate approach for each indicator or dimension analyzed.

Author Contributions: Conceptualization, P.-L.G., N.B.-M., M.L.Z., C.F. and V.M.A.; methodology, P.-L.G., N.B.-M., M.L.Z., C.F. and V.M.A.; software, P.-L.G., N.B.-M., M.L.Z., C.F. and V.M.A.; validation, P.-L.G., N.B.-M., M.L.Z., C.F. and V.M.A.; formal analysis, P.-L.G., N.B.-M., M.L.Z., C.F. and V.M.A.; investigation, P.-L.G., N.B.-M., M.L.Z., C.F. and V.M.A.; resources, P.-L.G., N.B.-M., M.L.Z., C.F. and V.M.A.; data curation, P.-L.G., N.B.-M., M.L.Z., C.F. and V.M.A.; writing—original draft preparation, P.-L.G., N.B.-M., M.L.Z., C.F. and V.M.A.; writing—review and editing, P.-L.G., N.B.-M., M.L.Z., C.F. and V.M.A.; visualization, P.-L.G., N.B.-M., M.L.Z., C.F. and V.M.A.; supervision, P.-L.G., N.B.-M., M.L.Z., C.F. and V.M.A.; project administration, P.-L.G., N.B.-M., M.L.Z., C.F. and V.M.A.; funding acquisition, P.-L.G., N.B.-M., M.L.Z., C.F. and V.M.A. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by a grant from the Ministry of Research, Innovation and Digitization, CNCS/CCCDI-UEFISCDI, project number PN-IV-P8-8.1-PRE-HE-ORG-2024-0212, within PNCDI IV.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. European Commission a European Green Deal. Available online: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en (accessed on 3 December 2024).
2. Bergez, J.-E.; Béthinger, A.; Bockstaller, C.; Cederberg, C.; Ceschia, E.; Guilpart, N.; Lange, S.; Müller, F.; Reidsma, P.; Riviere, C.; et al. Integrating Agri-Environmental Indicators, Ecosystem Services Assessment, Life Cycle Assessment and Yield Gap Analysis to Assess the Environmental Sustainability of Agriculture. *Ecol. Indic.* **2022**, *141*, 109107. [CrossRef]
3. Pandey, S.C.; Modi, P.; Pereira, V.; Fosso Wamba, S. Empowering Small Farmers for Sustainable Agriculture: A Human Resource Approach to SDG-Driven Training and Innovation. *Int. J. Manpow.* **2024**. [CrossRef]
4. Streimikis, J.; Balezentis, T. Agricultural Sustainability Assessment Framework Integrating Sustainable Development Goals and Interlinked Priorities of Environmental, Climate and Agriculture Policies. *Sustain. Dev.* **2020**, *28*, 1702–1712. [CrossRef]
5. Shang, L.; Wang, J.; Schäfer, D.; Heckelei, T.; Gall, J.; Appel, F.; Storm, H. Surrogate Modelling of a Detailed Farm-Level Model Using Deep Learning. *J. Agric. Econ.* **2024**, *75*, 235–260. [CrossRef]
6. Reidsma, P.; Accatino, F.; Appel, F.; Gavrilescu, C.; Krupin, V.; Manevska Tasevska, G.; Meuwissen, M.P.M.; Peneva, M.; Severini, S.; Soriano, B.; et al. Alternative Systems and Strategies to Improve Future Sustainability and Resilience of Farming Systems across Europe: From Adaptation to Transformation. *Land Use Policy* **2023**, *134*, 106881. [CrossRef]
7. Chomać-Pierzecka, E. Pharmaceutical Companies in the Light of the Idea of Sustainable Development—An Analysis of Selected Aspects of Sustainable Management. *Sustainability* **2023**, *15*, 8889. [CrossRef]
8. Hariram, N.P.; Mekha, K.B.; Suganthan, V.; Sudhakar, K. Sustainalism: An Integrated Socio-Economic-Environmental Model to Address Sustainable Development and Sustainability. *Sustainability* **2023**, *15*, 10682. [CrossRef]
9. Robinson, G.M. Global Sustainable Agriculture and Land Management Systems. *Geogr. Sustain.* **2024**, *5*, 637–646. [CrossRef]
10. European Commission Farm to Fork Strategy. Available online: https://food.ec.europa.eu/horizontal-topics/farm-fork-strategy_en (accessed on 4 December 2024).
11. Karunathilake, E.M.B.M.; Le, A.T.; Heo, S.; Chung, Y.S.; Mansoor, S. The Path to Smart Farming: Innovations and Opportunities in Precision Agriculture. *Agriculture* **2023**, *13*, 1539. [CrossRef]
12. Balyan, S.; Jangir, H.; Tripathi, S.N.; Tripathi, A.; Jhang, T.; Pandey, P. Seeding a Sustainable Future: Navigating the Digital Horizon of Smart Agriculture. *Sustainability* **2024**, *16*, 475. [CrossRef]
13. Darmaun, M.; Chevallier, T.; Hossard, L.; Lairez, J.; Scopel, E.; Chotte, J.-L.; Lambert-Derkimba, A.; de Tourdonnet, S. Multidimensional and Multiscale Assessment of Agroecological Transitions. A Review. *Int. J. Agric. Sustain.* **2023**, *21*, 2193028. [CrossRef]
14. Maraveas, C.; Karavas, C.-S.; Loukatos, D.; Bartzanas, T.; Arvanitis, K.G.; Symeonaki, E. Agricultural Greenhouses: Resource Management Technologies and Perspectives for Zero Greenhouse Gas Emissions. *Agriculture* **2023**, *13*, 1464. [CrossRef]

15. Bhatti, U.A.; Bhatti, M.A.; Tang, H.; Syam, M.S.; Awwad, E.M.; Sharaf, M.; Ghadi, Y.Y. Global Production Patterns: Understanding the Relationship between Greenhouse Gas Emissions, Agriculture Greening and Climate Variability. *Environ. Res.* **2024**, *245*, 118049. [CrossRef] [PubMed]
16. Feng, T.; Xiong, R.; Huan, P. Productive Use of Natural Resources in Agriculture: The Main Policy Lessons. *Resour. Policy* **2023**, *85*, 103793. [CrossRef]
17. Nelson, K.S.; Nguyen, T.D.; Francois, J.R.; Ojha, S. Rural Sustainability Methods, Drivers, and Outcomes: A Systematic Review. *Sustain. Dev.* **2023**, *31*, 1226–1249. [CrossRef]
18. Stanciu, S.; Virlanuta, F.O.; Dinu, V.; Zungun, D.; Antohi, V.M. The Perception of the Social Economy by Agricultural Producers in the North-East Development Region of Romania. *Transform. Bus. Econ.* **2019**, *18*, 879–899.
19. European Commission Biodiversity Strategy for 2030. Available online: https://environment.ec.europa.eu/strategy/biodiversity-strategy-2030_en (accessed on 4 December 2024).
20. European Commission Main Initiatives: Strategic Dialogue on the Future of EU Agriculture. Available online: https://agriculture.ec.europa.eu/common-agricultural-policy/cap-overview/main-initiatives-strategic-dialogue-future-eu-agriculture_en (accessed on 3 December 2024).
21. OECD. *Policies for the Future of Farming and Food in the European Union*; OECD: Paris, France, 2023.
22. Manta, A.G.; Doran, N.M.; Bădîrcea, R.M.; Badareu, G.; Gherțescu, C.; Lăpădat, C.V. Does Common Agricultural Policy Influence Regional Disparities and Environmental Sustainability in European Union Countries? *Agriculture* **2024**, *14*, 2242. [CrossRef]
23. European Commission. The Common Agricultural Policy at a Glance. Available online: https://agriculture.ec.europa.eu/common-agricultural-policy/cap-overview/cap-glance_en (accessed on 3 December 2024).
24. Kumar, V.; Sharma, K.V.; Kedam, N.; Patel, A.; Kate, T.R.; Rathnayake, U. A Comprehensive Review on Smart and Sustainable Agriculture Using IoT Technologies. *Smart Agric. Technol.* **2024**, *8*, 100487. [CrossRef]
25. Godavari, H.; Vidya Madhuri, E.; Tulasi, B.; Manoj, M.S.; Manideep, S.; Keerthika, N.; Paschapur, A.U. Precision Farming Solutions: Integrating Technology for Sustainable Pest Management. *J. Adv. Biol. Biotechnol.* **2024**, *27*, 33–54. [CrossRef]
26. Padhiary, M.; Saha, D.; Kumar, R.; Sethi, L.N.; Kumar, A. Enhancing Precision Agriculture: A Comprehensive Review of Machine Learning and AI Vision Applications in All-Terrain Vehicle for Farm Automation. *Smart Agric. Technol.* **2024**, *8*, 100483. [CrossRef]
27. FAO. The State of Food and Agriculture 2023—Revealing the True Cost of Food to Transform Agrifood Systems. Available online: https://www.fao.org/agrifood-economics/publications/detail/en/c/1661488/?utm_source=chatgpt.com (accessed on 3 December 2024).
28. Tomar, S.; Sharma, N.; Kumar, R. Effect of Organic Food Production and Consumption on the Affective and Cognitive Well-Being of Farmers: Analysis Using Prism of NVivo, Etic and Emic Approach. *Environ. Dev. Sustain.* **2024**, *26*, 11027–11048. [CrossRef]
29. Gamage, A.; Gangahagedara, R.; Gamage, J.; Jayasinghe, N.; Kodikara, N.; Suraweera, P.; Merah, O. Role of Organic Farming for Achieving Sustainability in Agriculture. *Farming Syst.* **2023**, *1*, 100005. [CrossRef]
30. Saud, S.; Haseeb, A.; Haider Zaidi, S.A.; Khan, I.; Li, H. Moving towards Green Growth? Harnessing Natural Resources and Economic Complexity for Sustainable Development through the Lens of the N-Shaped EKC Framework for the European Union. *Resour. Policy* **2024**, *91*, 104804. [CrossRef]
31. Matthews, P.G.; Fish, R.D.; Tzanopoulos, J. Overcoming Barriers to Agri-Environmental Management at Landscape Scale: Balancing Farmer Coordination and Collaboration with the Aid of Facilitators and Pioneers. *J. Environ. Manag.* **2024**, *369*, 122278. [CrossRef] [PubMed]
32. Memo, U.; Pieńkowski, D. Sustainable rural development indicators in Bulgaria, Germany, Poland, Romania and the Netherlands: A Review of Data. *Front. Environ. Sci.* **2023**, *11*, 1323688. [CrossRef]
33. Orou Sannou, R.; Kirschke, S.; Günther, E. Integrating the Social Perspective into the Sustainability Assessment of Agri-Food Systems: A Review of Indicators. *Sustain. Prod. Consum.* **2023**, *39*, 175–190. [CrossRef]
34. Amaruzaman, S.; Bardsley, D.K.; Stringer, R. Analysing Agricultural Policy Outcomes in the Uplands of Indonesia: A Multi-Dimensional Sustainability Assessment. *Sustain. Dev.* **2023**, *31*, 1937–1950. [CrossRef]
35. Sass, K.S.; Konak, A.; Batalini de Macedo, M.; Benso, M.R.; Shrimpton, E.; Balta-Ozkan, N.; Sarmah, T.; Mendiondo, E.M.; Jesus da Silva, G.; Câmara da Silva, P.G.; et al. Enhancing Drought Resilience and Vulnerability Assessment in Small Farms: A Global Expert Survey on Multidimensional Indicators. *Int. J. Disaster Risk Reduct.* **2024**, *110*, 104616. [CrossRef]
36. Espinel, R.; Herrera-Franco, G.; Rivadeneira García, J.L.; Escandón-Panchana, P. Artificial Intelligence in Agricultural Mapping: A Review. *Agriculture* **2024**, *14*, 1071. [CrossRef]
37. Mana, A.A.; Allouhi, A.; Hamrani, A.; Rehman, S.; el Jamaoui, I.; Jayachandran, K. Sustainable AI-Based Production Agriculture: Exploring AI Applications and Implications in Agricultural Practices. *Smart Agric. Technol.* **2024**, *7*, 100416. [CrossRef]
38. Sarku, R.; Clemen, U.A.; Clemen, T. The Application of Artificial Intelligence Models for Food Security: A Review. *Agriculture* **2023**, *13*, 2037. [CrossRef]
39. Egala, S.B.; Amoah, J.; Bashiru Jibril, A.; Opoku, R.; Bruce, E. Digital Transformation in an Emerging Economy: Exploring Organizational Drivers. *Cogent Soc. Sci.* **2024**, *10*, 2302217. [CrossRef]

40. Delechat, C.C.; Melina, G.; Newiak, M.; Papageorgiou, C.; Wang, K.; Spatafora, N. Economic Diversification in Developing Countries—Lessons from Country Experiences with Broad-Based and Industrial Policies. *Dep. Pap.* **2024**, A001. [CrossRef]
41. Memarian, B.; Doleck, T. A Review of Assessment for Learning with Artificial Intelligence. *Comput. Hum. Behav. Artif. Hum.* **2024**, *2*, 100040. [CrossRef]
42. Doukas, Y.E.; Salvati, L.; Vardopoulos, I. Unraveling the European Agricultural Policy Sustainable Development Trajectory. *Land* **2023**, *12*, 1749. [CrossRef]
43. Cuadros-Casanova, I.; Cristiano, A.; Biancolini, D.; Cimatti, M.; Sessa, A.A.; Mendez Angarita, V.Y.; Dragonetti, C.; Pacifici, M.; Rondinini, C.; Di Marco, M. Opportunities and Challenges for Common Agricultural Policy Reform to Support the European Green Deal. *Conserv. Biol.* **2023**, *37*, e14052. [CrossRef] [PubMed]
44. European Commission. The Common Agricultural Policy: 2023-27. Available online: https://agriculture.ec.europa.eu/common-agricultural-policy/cap-overview/cap-2023-27_en (accessed on 3 December 2024).
45. Wang, D.; Dong, L.; Mei, J. An Advanced Review of Climate Change Mitigation Policies in Germany, France, and the Netherlands. *Environ. Res. Lett.* **2023**, *18*, 103001. [CrossRef]
46. Geels, F.W.; Pereira, G.I.; Pinkse, J. Moving beyond Opportunity Narratives in COVID-19 Green Recoveries: A Comparative Analysis of Public Investment Plans in France, Germany, and the United Kingdom. *Energy Res. Soc. Sci.* **2022**, *84*, 102368. [CrossRef]
47. Borisov, P.; Petrov, K.; Tsonkov, N. Integration Perspectives for Improving Regional Policy in Rural Areas of Bulgaria. *Agric. Resour. Econ. Int. Sci. E-J.* **2024**, *10*, 260–283. [CrossRef]
48. Feurich, M.; Kourilova, J.; Pelucha, M.; Kasabov, E. Bridging the Urban-Rural Digital Divide: Taxonomy of the Best Practice and Critical Reflection of the EU Countries' Approach. *Eur. Plan. Stud.* **2024**, *32*, 483–505. [CrossRef]
49. European Commission. Common Agricultural Policy Funds. Available online: https://agriculture.ec.europa.eu/common-agricultural-policy/financing-cap/cap-funds_en (accessed on 3 December 2024).
50. European Commission. Rural Development. Available online: https://agriculture.ec.europa.eu/common-agricultural-policy/rural-development_en (accessed on 3 December 2024).
51. Masi, M.; De Rosa, M.; Vecchio, Y.; Bartoli, L.; Adinolfi, F. The Long Way to Innovation Adoption: Insights from Precision Agriculture. *Agric. Food Econ.* **2022**, *10*, 27. [CrossRef]
52. Bocean, C.G. A Cross-Sectional Analysis of the Relationship between Digital Technology Use and Agricultural Productivity in EU Countries. *Agriculture* **2024**, *14*, 519. [CrossRef]
53. Shvets, N.; Shevtsova, H.; Pidorycheva, I.; Prokopenko, O.; Maslosh, O. Sustainable Development of Agriculture Based on the Smart Specialisation Approach: Cases of the Central and Eastern European Countries. *Agric. Resour. Econ. Int. Sci. E-J.* **2023**, *9*, 260–282. [CrossRef]
54. Hurduzeu, G.; Pânzaru, R.L.; Medelete, D.M.; Ciobanu, A.; Enea, C. The Development of Sustainable Agriculture in EU Countries and the Potential Achievement of Sustainable Development Goals Specific Targets (SDG 2). *Sustainability* **2022**, *14*, 15798. [CrossRef]
55. Giua, C.; Materia, V.C.; Camanzi, L. Smart Farming Technologies Adoption: Which Factors Play a Role in the Digital Transition? *Technol. Soc.* **2022**, *68*, 101869. [CrossRef]
56. MacPherson, J.; Voglhuber-Slavinsky, A.; Olbrisch, M.; Schöbel, P.; Dönitz, E.; Mouratiadou, I.; Helming, K. Future Agricultural Systems and the Role of Digitalization for Achieving Sustainability Goals: A Review. *Agron. Sustain. Dev.* **2022**, *42*, 70. [CrossRef] [PubMed]
57. Costa, F.; Frecassetti, S.; Rossini, M.; Portioli-Staudacher, A. Industry 4.0 Digital Technologies Enhancing Sustainability: Applications and Barriers from the Agricultural Industry in an Emerging Economy. *J. Clean. Prod.* **2023**, *408*, 137208. [CrossRef]
58. Geppert, F.; Krachunova, T.; Bellingrath-Kimura, S.D. *Digital and Smart Technologies in Agriculture in Germany: Identification of Key Recommendations for Sustainability Actions*; Expertenkommission Forschung und Innovation (EFI): Berlin, Germany, 2024.
59. Eurostat Economic Accounts for Agriculture—Values at Current Prices. Available online: https://ec.europa.eu/eurostat/databrowser/view/AACT_EAA01/default/table?lang=en (accessed on 5 December 2024).
60. Eurostat Gross Value Added of the Agricultural Industry—Basic and Producer Prices. Available online: https://ec.europa.eu/eurostat/databrowser/view/tag00056/default/table?lang=en (accessed on 5 December 2024).
61. Eurostat Greenhouse Gas Emissions from Agriculture. Available online: https://ec.europa.eu/eurostat/databrowser/view/tai08/default/table?lang=en (accessed on 5 December 2024).
62. Eurostat Net Greenhouse Gas Emissions. Available online: https://ec.europa.eu/eurostat/databrowser/view/sdg_13_10/default/table?lang=en (accessed on 5 December 2024).
63. Eurostat Ammonia Emissions from Agriculture. 2024. Available online: https://ec.europa.eu/eurostat/databrowser/view/sdg_02_60/default/table?lang=en&category=sdg.sdg_02 (accessed on 5 December 2024).
64. Eurostat Area Under Organic Farming. Available online: https://ec.europa.eu/eurostat/databrowser/view/sdg_02_40/default/table?lang=en (accessed on 5 December 2024).

65. Eurostat Utilised Agricultural Area by Categories. Available online: https://ec.europa.eu/eurostat/databrowser/view/tag00025/default/table?lang=en (accessed on 5 December 2024).
66. European Commission. Climate Action. Available online: https://climate.ec.europa.eu/news-your-voice/news/looking-how-mitigate-emissions-agriculture-2023-11-13_en (accessed on 5 December 2024).
67. Luo, B.; Rauf, A.; Osei-Kusi, F.; Sundas, R.; Mehmood, R. Exploring the Impacts of Agricultural Emissions from Natural Gas on Ecological Footprint. *Ecol. Process.* **2024**, *13*, 83. [CrossRef]
68. Burland, A.; von Cossel, M. Towards Managing Biodiversity of European Marginal Agricultural Land for Biodiversity-Friendly Biomass Production. *Agronomy* **2023**, *13*, 1651. [CrossRef]
69. Kreft, C.; Finger, R.; Huber, R. Action-versus Results-Based Policy Designs for Agricultural Climate Change Mitigation. *Appl. Econ. Perspect. Policy* **2024**, *46*, 1010–1037. [CrossRef]
70. Khanna, M.; Chen, L.; Basso, B.; Cai, X.; Field, J.L.; Guan, K.; Jiang, C.; Lark, T.J.; Richard, T.L.; Spawn-Lee, S.A.; et al. Redefining Marginal Land for Bioenergy Crop Production. *GCB Bioenergy* **2021**, *13*, 1590–1609. [CrossRef]
71. Rosli, M.N.; Abdul Mutalib, M.; Shamsuddin, A.S.; Lani, M.; Ariati, I.; Tang, S. Navigating the Environmental, Economic and Social Impacts of Sustainable Agriculture and Food Systems: A Review. *Front. Agric. Sci. Eng.* **2024**, *11*, 652–673. [CrossRef]
72. Rizzo, G.; Migliore, G.; Schifani, G.; Vecchio, R. Key Factors Influencing Farmers' Adoption of Sustainable Innovations: A Systematic Literature Review and Research Agenda. *Org. Agric.* **2024**, *14*, 57–84. [CrossRef]
73. Fusco, G.; Campobasso, F.; Laureti, L.; Frittelli, M.; Valente, D.; Petrosillo, I. The Environmental Impact of Agriculture: An Instrument to Support Public Policy. *Ecol. Indic.* **2023**, *147*, 109961. [CrossRef]
74. Viana, C.M.; Freire, D.; Abrantes, P.; Rocha, J.; Pereira, P. Agricultural Land Systems Importance for Supporting Food Security and Sustainable Development Goals: A Systematic Review. *Sci. Total Environ.* **2022**, *806*, 150718. [CrossRef]
75. Ma, Y.; Zheng, M.; Zheng, X.; Huang, Y.; Feng, X.; Wang, X.; Liu, J.; Lv, Y.; Liu, W. Land Use Efficiency Assessment under Sustainable Development Goals: A Systematic Review. *Land* **2023**, *12*, 894. [CrossRef]
76. Hasler, B.; Termansen, M.; Nielsen, H.Ø.; Daugbjerg, C.; Wunder, S.; Latacz-Lohmann, U. European Agri-Environmental Policy: Evolution, Effectiveness, and Challenges. *Rev. Environ. Econ. Policy* **2022**, *16*, 105–125. [CrossRef]
77. Nowak, A.; Różańska-Boczula, M. A Comparative View of the Level of Agricultural Sustainability—The Case of European Union Member States. *Sustain. Dev.* **2024**, *32*, 2638–2652. [CrossRef]
78. European Commission. EU Agricultural Outlook for Markets, 2023–2035. Available online: https://agriculture.ec.europa.eu/system/files/2024-01/agricultural-outlook-2023-report_en_0.pdf (accessed on 3 December 2024).
79. Castillo-Díaz, F.J.; Belmonte-Ureña, L.J.; López-Serrano, M.J.; Camacho-Ferre, F. Assessment of the Sustainability of the European Agri-Food Sector in the Context of the Circular Economy. *Sustain. Prod. Consum.* **2023**, *40*, 398–411. [CrossRef]
80. Peng, B.; Melnikiene, R.; Balezentis, T.; Agnusdei, G.P. Structural Dynamics and Sustainability in the Agricultural Sector: The Case of the European Union. *Agric. Food Econ.* **2024**, *12*, 31. [CrossRef]
81. European Commission. Strategic Dialogue on the Future of EU Agriculture. Available online: https://agriculture.ec.europa.eu/document/download/171329ff-0f50-4fa5-946f-aea11032172e_en?filename=strategic-dialogue-report-2024_en.pdf (accessed on 3 December 2024).
82. Abbate, S.; Centobelli, P.; Cerchione, R. The Digital and Sustainable Transition of the Agri-Food Sector. *Technol. Forecast. Soc. Change* **2023**, *187*, 122222. [CrossRef]
83. Metta, M.; Ciliberti, S.; Obi, C.; Bartolini, F.; Klerkx, L.; Brunori, G. An Integrated Socio-Cyber-Physical System Framework to Assess Responsible Digitalisation in Agriculture: A First Application with Living Labs in Europe. *Agric. Syst.* **2022**, *203*, 103533. [CrossRef]
84. Herman, E. Sustainable Agriculture and Its Impact on the Rural Development in EU Countries: A Multivariate Analysis. *Land* **2024**, *13*, 947. [CrossRef]
85. Huseynov, R.; Aliyeva, N.; Bezpalov, V.; Syromyatnikov, D. Cluster Analysis as a Tool for Improving the Performance of Agricultural Enterprises in the Agro-Industrial Sector. *Environ. Dev. Sustain.* **2024**, *26*, 4119–4132. [CrossRef]
86. Di Vita, G.; Zanchini, R.; De Cianni, R.; Pippinato, L.; Mancuso, T.; Brun, F. Sustainable Livestock Farming in the European Union: A Study on Beef Farms in NUTS 2 Regions. *Sustainability* **2024**, *16*, 1098. [CrossRef]