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Assessing Agricultural Impact on Greenhouse Gases in the European Union: A Climate-Smart Agriculture Perspective

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Abstract: With the increasing concern about climate change and its impacts on agriculture, understanding the dynamics of greenhouse gas (GHG) emissions in the European Union (EU) agricultural sector is essential for devising effective mitigation strategies. This study aims to assess the impact of agriculture on GHG within the EU and to examine how climate-smart agricultural practices can affect these emissions. The research investigates the complex relationship between agricultural activities and GHG emissions within the European Union during the period of 2017–2022 using structural equation modeling based on data from Eurostat and the European Commission. Furthermore, the study examines the influence of the digital economy on labor productivity in agriculture, recognizing the pivotal role of digital technologies in fostering climate-smart agricultural practices. The findings unveil significant positive influences encompassing the digital economy, agricultural productivity, agricultural output, and GHG emissions, underscoring the imperative of integrating climate-smart methodologies into agricultural frameworks. However, the influence of digital technologies is not significant as a result of opposing forces. Digital technologies exert positive indirect influences by increasing agricultural productivity and agricultural output, while they have negative influences by improving production processes through automation and precision agriculture. Digitalization and climate-smart agricultural practices have a significant potential to improve the efficiency and sustainability of the agricultural sector, contributing to food security and environmental protection by reducing GHG emissions. This study highlights the EU's potential to achieve its environmental objectives through the reduction of GHG emissions and the enhancement of resilience within the agricultural sector, emphasizing the necessity of adopting climate-smart strategies.

Keywords: climate-smart agriculture; labor productivity; digital economy; agricultural output; GHG emissions; European Union

Citation: Vărzaru, A.A. Assessing Agricultural Impact on Greenhouse Gases in the European Union: A Climate-Smart Agriculture Perspective. *Agronomy* **2024**, *14*, 821. https://doi.org/10.3390/agronomy14040821

Academic Editor: Dener Márcio da Silva Oliveira

Received: 17 March 2024
Revised: 7 April 2024
Accepted: 13 April 2024
Published: 15 April 2024

1. Introduction

The impact of climate change on the agricultural sector has significant implications for food security, the global economy, and human well-being. Changes in climate patterns and extreme weather conditions can lead to a decrease in agricultural production and increase uncertainty regarding food availability and accessibility [1]. These conditions can negatively affect the food security of millions of people, especially in economically and climatically vulnerable regions [2].

The increase in greenhouse gas emissions (GHG) from agriculture contributes to exacerbating climate change, which can lead to an increase in extreme weather events such as droughts, floods, and storms, all negatively affecting agricultural production [3]. These changes can affect the economic stability of agricultural communities [4]. The effects of climate change on agriculture can have global consequences through a decrease in global agricultural production and an increase in food prices, which can lead to increased social and political tensions and regional and global instability [1,5].

Overpopulation and climate change are significant issues with profound consequences for the entire planet. Their impact manifests in all aspects of human life and the environment, including the agricultural sector. The implementation of climate-smart agricultural (CSA) practices stands as a pivotal response to these challenges. CSA endeavors not only to enhance productivity and resilience but also to mitigate GHG, thereby aiding in the global effort to address climate change [6]. Enhancing the adaptability and resilience of agriculture to extreme weather conditions, CSA can contribute to upholding food security and diminishing the risk of environmental degradation. Promoting and implementing CSA can have significant economic benefits for farmers by increasing crop yields and incomes. Moreover, reducing GHG through more efficient agricultural practices can contribute to global efforts to combat climate change.

This study aims to assess the impact of agriculture on GHG within the European Union (EU) and to examine how CSA practices can affect these emissions. Assessing the impact of agriculture on GHG emissions within the EU is vital due to environmental concerns, policy development needs, international commitments to reduce emissions, promotion of sustainable agricultural practices, and the economic significance of the agricultural sector. The study aims to bridge a significant research gap by exploring the influence of digitalization on agricultural productivity and its subsequent impact on GHG emissions. The investigation strives to provide valuable insights into the efficacy of CSA practices in reducing GHG emissions, elucidating the complex dynamics between these variables. This comprehensive analysis contributes to filling the existing knowledge void regarding the interplay between agricultural activities, digital technologies, and environmental sustainability in the EU context.

The study's originality lies in its innovative use of structural equation modeling to investigate this complex relationship, integrating variables such as agricultural labor productivity, the digital economy, agricultural output, and GHG emissions. This method allows for a comprehensive analysis of how these variables interact, providing deeper insights into the dynamics of the agricultural sector's impact on GHG emissions. The research underscores the vital importance of incorporating CSA practices to mitigate GHG emissions and promote sustainable agricultural development within the EU. This approach highlights the dynamics between agricultural activities and environmental impact, offering valuable insights for policymakers and stakeholders seeking to address climate change challenges in the agricultural sector.

2. Materials and Methods

2.1. Digitalization in Agriculture

2.1.1. The Role of Digitalization in Agriculture

Currently, digital technologies not only assist in addressing contemporary challenges but can also serve as a significant driver for promoting sustainability [7]. Technologies such as artificial intelligence and big data analysis can be used to identify patterns and trends in climate change and develop innovative solutions for adapting to these changes. Furthermore, blockchain technologies can ensure data transparency and security, thereby enhancing trust and efficiency across various areas, including agriculture and the environment. The integration of these technologies can contribute to enhancing economic, ecological, and social sustainability, thus building a more sustainable future for all [8].

Agricultural digitalization enables the optimization of agricultural resource use by monitoring and managing water inputs, fertilizer use, and pesticides more efficiently [9]. Agricultural digitalization also contributes to reducing risks for farmers and improving their resilience to external factors. Collecting and analyzing real-time data enables farmers to make more informed and quicker decisions to maximize crop yields and minimize losses. Furthermore, digital technologies facilitate access to precise weather information and forecasts, allowing farmers to take preventive measures against extreme weather conditions or climate change. Agricultural digitalization can facilitate the implementation of sustainable agricultural practices, thereby contributing to environmental protection and providing safer and healthier food products for consumers [9–11]. These practices contribute to increasing the sustainability and resilience of agriculture. The implementation of a digital economy in agriculture facilitates access to innovative resources and technologies, as well as international markets and information. It can stimulate co-operation and knowledge exchange among stakeholders in the agricultural industry, contributing to enhancing the competitiveness and sustainability of the sector [12,13].

2.1.2. Digital Technologies Used in Agriculture

Digital technologies such as remote sensing, the Internet of Things (IoT), and artificial intelligence (AI) can play a crucial role in adapting agriculture to climate change and reducing its negative impact on the environment, thereby contributing to building a more sustainable future. Investments in innovative agricultural technologies can bring significant benefits, both for farmers and for the environment and society as a whole [14]. Remote sensing provides significant opportunities for monitoring and managing agricultural practices within regional-scale smart agriculture. Through remote sensing, farmers gain a deeper understanding of changes in extensive agricultural landscapes and how they are affected by factors such as climate change and resource management [15–17].

Technological advancements driven by technologies such as IoT and AI [18,19] offer significant opportunities for modernizing and streamlining the agricultural sector, thereby enhancing productivity and profitability while reducing environmental impact. IoT enables the collection and monitoring of real-time data about the agricultural environment and crops, enabling farmers to make more informed decisions and increasing the efficiency of resource use, such as water and fertilizers [20]. However, the adoption of IoT in agriculture presents challenges, including high initial costs for equipment and infrastructure [21]. Concerns also arise regarding data security, as farm and crop information collected may be valuable to competitors or malicious users. Ensuring a robust network infrastructure and reliable internet connection in agricultural areas can be challenging, particularly in underdeveloped regions or developing countries [17]. Nevertheless, with careful planning and implementation, IoT technology holds the potential to revolutionize agriculture and make significant contributions to sustainability goals.

AI enhances efficiency and productivity, reducing environmental impact, and can contribute to optimizing agricultural processes, such as irrigation management, precise application of pesticides and fertilizers, and crop forecasting [17,22]. AI can contribute to reducing the negative environmental impact by managing agricultural resources more precisely [23] and crop losses and managing risks associated with extreme weather phenomena [22]. However, AI implementation can also have specific social and economic consequences, such as the impact on jobs in the agricultural sector and the accessibility of technology in disadvantaged communities.

It is crucial to establish appropriate political, legal, and economic frameworks to design a sustainable digital transformation in agriculture and socially responsible innovations [24–26]. However, digital transformation is an ongoing process, and its future technological developments depend on the interventions and governance measures, as well as on the academic, social, and political discourses that influence perceptions and collective actions [25].

The first hypothesis of this paper concerns the effects of digitalization on labor productivity in agriculture:

Hypothesis 1 (H1). *Digitalization has a significantly positive influence on labor productivity in agriculture.*

2.2. Climate-Smart Agriculture

2.2.1. The Impact of CSA

CSA represents a crucial framework for addressing the complexity of agricultural and climate-related issues globally, integrating multiple approaches, and involving various stakeholders to develop region-specific solutions [27,28]. The three pillars of CSA—increasing incomes, building resilience, and reducing GHG emissions—are fundamental for enhancing the sustainability and resilience of agricultural systems facing climate change and food security challenges [29,30]. The holistic approach of CSA covers various aspects of agriculture and the environment, emphasizing the need for an integrated perspective to address agricultural and climate-related issues [31].

The implementation of CSA practices not only aims to improve agricultural technologies but also to adapt to unstable climatic conditions, ensuring sustainable and reliable food production [32,33]. However, the variety of findings in the literature underscores the complexity of implementing CSA practices, requiring consideration of local circumstances and long-term impact evaluation [34–37]. Supporting farmers in adopting sustainable agricultural practices is essential for successful CSA implementation [28,38,39].

CSA practices and technologies have significant local and global implications, including reducing food insecurity, mitigating GHG emissions, conserving soil, water, and biodiversity, and increasing farmers' resilience and incomes [40,41]. The active participation of farmers is crucial in adopting CSA practices, demanding access to education, training, and resources tailored to their specific needs and conditions [42–45]. Promoting and implementing CSA practices not only improves farmers' livelihoods but also the environment and society [42].

2.2.2. Benefits of CSA

The adoption of sustainable agricultural practices and nutrient management technologies can significantly enhance water and fertilizer use efficiency, leading to increased agricultural productivity and reduced GHG emissions [17]. Organic fertilizers such as manure and compost can improve soil quality and fertility, thereby decreasing reliance on chemical fertilizers and associated emissions. The implementation of these sustainable agricultural technologies and practices plays a crucial role in agriculture's adaptation to climate change [46], primarily by reducing GHG emissions from the agricultural sector and enhancing resilience to extreme weather events. Increasing food production through CSA practices can alleviate food insecurity and promote sustainable rural development [47].

While the long-term benefits of CSA, including enhanced agricultural resilience and reduced dependence on external inputs, outweigh the associated costs [48,49], it is essential to address challenges related to technology accessibility and use, particularly among small- and medium-sized farmers in developing countries. Protecting farmers' data privacy and confidentiality regarding information generated by these technologies is paramount [42]. The successful implementation of CSA practices requires holistic approaches and substantial investments from farmers, agricultural organizations, and governments, encompassing access to innovative technologies, farmer training, agricultural infrastructure development, and financial support to facilitate the transition to more sustainable practices [50]. Promotion efforts for CSA must be tailored to the specific needs and conditions of each agricultural community to ensure their effectiveness and relevance in the local context.

A second hypothesis of this paper concerns the effects of increased labor productivity in agriculture due to the implementation of CSA practices on agricultural production:

Hypothesis 2 (H2). *Increased labor productivity in agriculture resulting from digitalization has a significant positive influence on agricultural production.*

2.3. Impact of Agriculture on GHG Emisssions

2.3.1. The Effects of Agricultural Production on GHG Emissions

Climate change has far-reaching implications for the environment and society, impacting human health, food security, and economic stability [51–55], exacerbating existing inequalities, disproportionately affecting vulnerable communities, and draining developing economies. This issue emphasizes the urgency of implementing adaptation and mitigation measures such as investing in resilient infrastructure, promoting sustainable agriculture, and reducing GHG emissions [56–60]. According to Czyzewski and Kryszak [59], agricultural practices contribute approximately 25–30% of GHG, highlighting the importance of addressing issues related to GHG in the agricultural sector. Reducing these emissions can play a crucial role in efforts to combat climate change and adapt to its effects [60].

Although agriculture plays a significant role in contributing to GHG, it also has the potential to become part of the solution to climate change [61–63]. Adopting sustainable agricultural technologies and practices can help reduce carbon emissions, create a more resilient and equitable food system, and reduce GHG [64,65]. This complex interaction between agriculture and GHG emissions highlights the need for policymakers and decision-makers to integrate GHG emissions mitigation approaches into agricultural policies and programs [66]. Considering the interaction between agriculture and the environment, more effective strategies can be developed to address GHG emissions challenges and promote more sustainable and resilient agriculture [28,67–69].

GHG emissions from various anthropogenic sources, such as industry, agriculture, and deforestation, have a substantial impact on the atmosphere and global climate [67,69]. Measures must be taken to reduce GHG emissions and promote more sustainable practices in all aspects of our lives to reduce environmental impact and limit the adverse effects of climate change [70]. Agricultural activities have a significant impact on GHG emissions. CH_4 and N_2O emissions from agricultural processes have substantial contributions to climate change because these gases have a much higher warming potential than CO_2 [67]. Organic agriculture can be a more sustainable solution with lower GHG than conventional agriculture. Therefore, promoting more ecological agricultural practices and raising awareness of the impact of agricultural activities can help reduce GHG and improve sustainability in agriculture [50].

Critical measures can be assumed to adapt agriculture to climate change and reduce its impact [29,30,71]. Firstly, avoiding or displacing GHG in the agricultural value chain contributes to reducing the carbon footprint of agriculture by using renewable energy sources and avoiding fossil fuel consumption. This action not only reduces direct GHG but also supports the transition to a more sustainable and greener economy [72]. The use of organic fertilizers can also reduce water, nitrogen, and carbon footprints and increase carbon sequestration [73,74]. Building carbon sinks and sequestering them is an effective way to offset GHG and contribute to combating climate change [34]. Furthermore, increasing carbon sequestration can enhance crop yield [75]. This way involves implementing agricultural practices that promote carbon sinking in soil and vegetation, such as tree planting and ecosystem restoration [29]. These measures provide essential opportunities to reduce agriculture's negative impact on GHG emissions and the environment [30].

A third hypothesis of this paper concerns the effects of agricultural output on GHG emissions in agriculture:

Hypothesis 3 (H3). *Agricultural output can significantly increase GHG emissions in agriculture.*

2.3.2. The Direct and Indirect Effects of Digitalization on GHG Emissions

CSA practices carry considerable implications for the sustainability and resilience of the agricultural sector amidst climate change [61]. These practices play a crucial role in mitigating GHG, adjusting to evolving climatic conditions, and safeguarding food security. Promoting CSA enables a balance between agricultural production needs and the conservation of natural resources, thereby contributing to maintaining biodiversity and healthy ecosystems [62].

Digital technologies have a significant impact on transforming agri-food systems regarding agricultural productivity, sustainability, and economic efficiency [76,77]. Digital technologies such as the Internet, remote sensors, IoT, and AI can significantly improve efficiency in agricultural output, supply chain management, and food distribution. By monitoring and managing agricultural processes more precisely, farmers can optimize resource use, thereby reducing environmental impact and production costs while increasing labor productivity. Furthermore, these technologies can enhance transparency and traceability in the supply chain, allowing consumers to make informed choices regarding the origin and quality of the food they purchase.

Israel et al. [60] highlight the importance of socio-economic factors and access to resources and services for engaging agricultural households in activities that generate GHG. They suggest that adopting CSA reduces GHG, turning investments in these practices into an effective tool for mitigating climate change in agricultural sectors [60]. These practices can reduce the negative impact of agricultural activities on the environment and can contribute to improving the sustainability of agricultural systems [59].

The fourth and final hypothesis of the study focuses on the effects of digitalization on GHG emissions in agriculture:

Hypothesis 4 (H4). *Digitalization has a significant direct and indirect negative influence on GHG emissions in agriculture.*

The theoretical model illustrates the relationships between the variables and hypotheses proposed in the study (Figure 1). This theoretical model serves as a conceptual framework for analyzing the interactions among the various aspects or factors investigated.

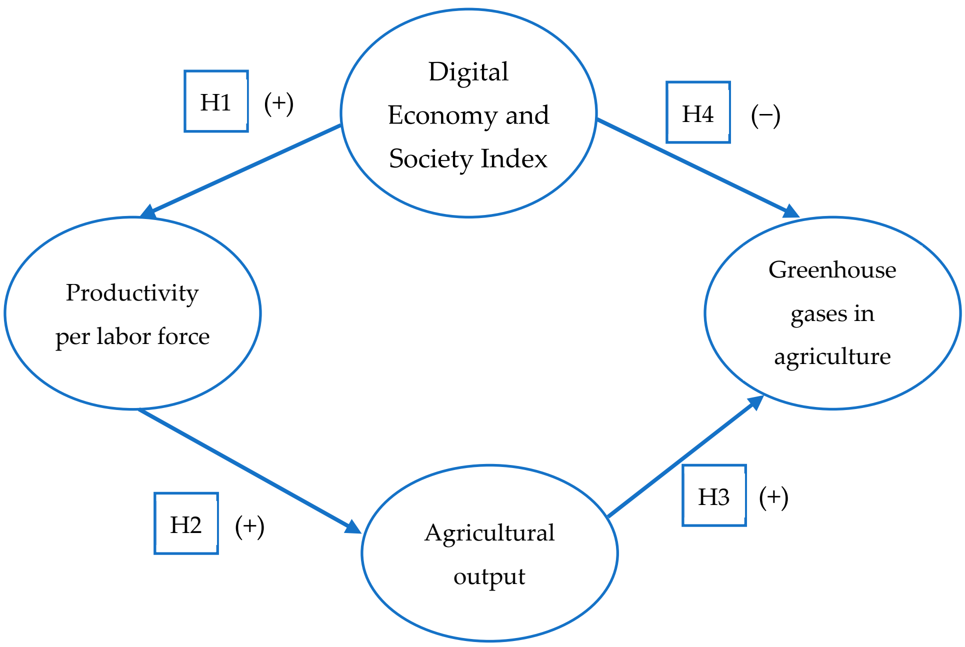

Figure 1. Theoretical model. Source: Author's design.

2.4. Research Methodology

The data used in the research are collected from Eurostat [78–82] and characterize agricultural output (crop output and animal output), labor force used in agriculture, and the level of GHG emitted by the agricultural sector within the EU countries. This paper uses the Digital Economy and Society Index (DESI) calculated by the European Commission [83] to illustrate digitalization. DESI indicates the level of digitalization and the openness of countries to digital technologies. The data series used in this research covers the period from 2017 to 2022 for all 27 European Union countries. DESI comprises four components: connectivity, digital public services, human capital, and digital technology integration. Connectivity concerns the availability and quality of broadband infrastructure, including fixed and mobile networks. Digital public services evaluate the availability and quality of online public services provided by governments. Human capital in the context of digital transformation refers to the skills and competencies of the workforce related to digital technologies. Digital technology integration assesses the adoption and use of digital technologies such as AI, IoT, big data, cloud computing, and e-commerce. DESI is calculated by the European Commission using a specific methodology, which involves assessing a set of relevant indicators for digitalization. The calculation methodology may vary depending on the specific components included in the index and the weights assigned to them. Generally, DESI calculations may involve a combination of statistical data, reports, and indicators collected from the EU member states, as well as other relevant sources. The final calculation of the DESI index is the result of aggregating all these components and indicators, either using complex mathematical formulae or other weighting and aggregation methods [81]. Table 1 illustrates the research variables, data collection sources, and measures.

Table 1. Variables used, measures, and sources.

Variable	Data	Measures	Period	Sources
C	Connectivity	Score	2017–2022	[81]
DPS	Digital public services	Score	2017–2022	[81]
HC	Human capital	Score	2017–2022	[81]
IDT	Integration of digital technology	Score	2017–2022	[81]
AGRO	Agricultural output	Million purchasing power standards (PPS)	2017–2022	[77]
CRO	Crop output	Million purchasing power standards (PPS)	2017–2022	[78]
ANO	Animal output	Million purchasing power standards (PPS)	2017–2022	[79]
LFI	Total labor force input	1000 annual work units	2017–2022	[76]
PLF	Productivity per labor force	Million purchasing power standards (PPS)/1000 annual work units	2017–2022	[74]
GHGAGR	GHGs in agriculture	Tons	2017–2022	[74]

Source: Developed by the author based on [59–67].

The PLF variable is calculated as a ratio between agricultural output and total labor force input.

$$PLF = \frac{AGRO}{LFI} \quad (1)$$

LFI—total labor force input;
AGRO—agricultural output;
PLF—productivity per labor force.

The suitable method for investigating the four hypotheses is structural equation modeling (SEM). Previous studies [84–86] have demonstrated that SEM is a powerful and flexible method for analyzing the complex relationships among multiple variables affecting GHG from the agricultural sector. SEM allows the modeling of latent variables, which are unobserved constructs inferred from multiple observed variables. These latent variables represent underlying concepts or constructs that cannot be directly measured. According to Garson [87] and Hair et al. [88], SEM is ideal for testing and validating complex theoretical models involving multidimensional interactions between observed and unobserved variables. Using these constructs, SEM enables the examination of causal relationships among variables, allowing researchers to assess the direct and indirect effects of one variable on another within a hypothesized model [87,88].

One of the advantages of the SEM model is path analysis, which estimates the direct and indirect effects of variables. SEM allows for the modification of the hypothesized model based on theoretical considerations or model fit indices, enabling the refinement of the model to represent the underlying data structure better. Furthermore, SEM was effective in integrating and analyzing data from various sources, as noted by Kline [89]. Therefore, data from Eurostat, which provides information on agricultural output and GHG emissions in the EU, as well as data from the European Commission, which highlights the digital economy, can be analyzed within the SEM framework to enhance understanding of the interrelationships among these variables. SEM enables the integration of these heterogeneous datasets to elucidate the relationships among agricultural productivity, digitalization, and environmental outcomes.

The SEM model was employed using the SmartPLS v3.0 software (SmartPLS GmbH, Oststeinbek, Germany), which allows for a better understanding of complex models [90]. The applied model is a formative partial least-squares (PLS) model. The endogenous latent variables illustrated in Figure 1 are the Digital Economy and Society Index, productivity per labor force, agricultural output, and GHG in agriculture. The Digital Economy and Society Index dimensions serve as an exogenous observable variable, comprising the index components: connectivity, digital public services, human capital, and digital technology integration. Agricultural output is represented by the exogenous variables crop output and agriculture output. Productivity per labor force and GHG in agriculture each have an exogenous variable (the level of labor productivity and the level of GHG emissions).

Variance inflation factor (VIF) verifies the robustness and reliability of the formative SEM-PLS model. VIF is used to assess collinearity among explanatory variables in the model. Excessive collinearity can affect the accuracy of coefficient estimates and may lead to misinterpretations of relationships between variables [87]. Table 2 presents VIF values for the SEM model.

Table 2. Assessment of the variables' collinearity.

Variable	VIF
C	1.760
DPS	3.238
HC	3.597
IDT	3.598
CRO	4.522
ANO	4.522
PLF	1.000
GHGAGR	1.000

Source: Author's design based on data using SmartPLS v3.0.

Standardized root-mean-square residual (SRMR) and normed fit index (NFI) are measures used in SEM analysis to evaluate the reliability, validity, and adequacy of the model [87,88]. SRMR measures the degree of discrepancy between the estimated model and observed data. SRMR values below 0.08 are considered adequate to indicate a good model fit [88]. NFI compares the model fit to that of a baseline model. NFI values above 0.90 are often considered to indicate a good model fit [87]. Table 3 presents the model fit indices, indicating good reliability and validity of the model.

Table 3. Evaluation of the model's reliability, validity, and adequacy.

	Saturated Model
SRMR	0.073
d_ULS	0.19
d_G	0.117
Chi-Square	84.360
NFI	0.934

Source: Author's design based on data using SmartPLS v3.0.

3. Results

Figure 2 shows the empirical model of the research obtained after applying the PLS algorithm with the SmartPLS v3.0 software. Outer weights characterize the relationships between the observable variables and the latent constructs. The path coefficients illustrate the relationships between the latent variables, indicating both the direction and intensity of the relationships between these variables. These values provide information on the strength and directionality of the causal connections between latent constructs within the model.

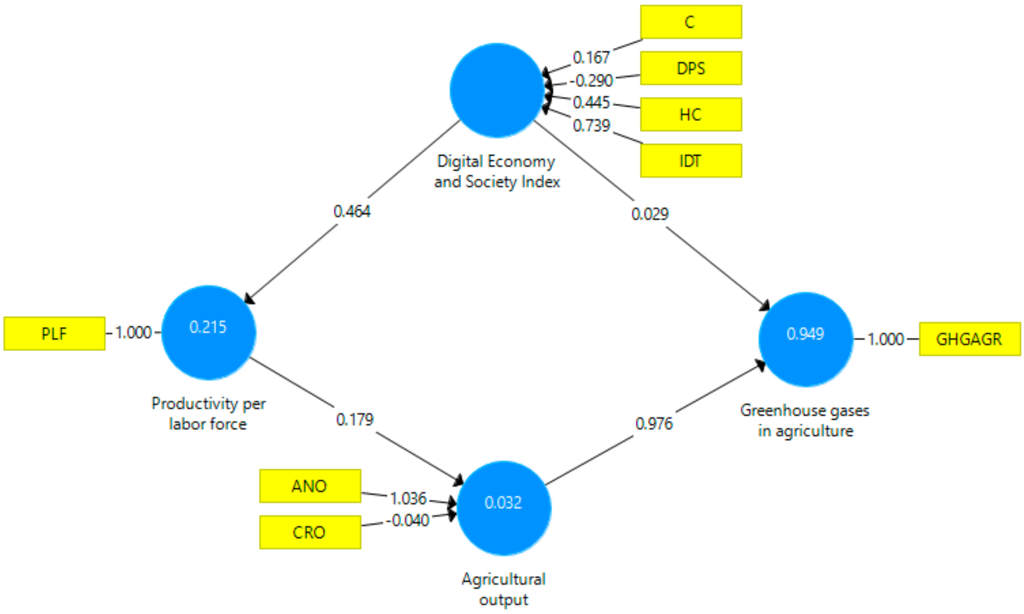

Figure 2. Empirical model. Source: Author's design.

The investigation used a bootstrap procedure to calculate the path coefficients. Using the bootstrap procedure with a bias-corrected, two-tailed significance at a level of 0.05 allows for a more robust evaluation of the uncertainty associated with model parameters and a more precise interpretation of research results. Table 4 presents the results of this procedure.

Table 4. Model path coefficients acquired through the bootstrapping procedure.

	Original Sample	Sample Mean	Standard Deviation	T Statistics	*p* Values	Hypotheses
Digital Economy and Society Index → Productivity per labor force (H1)	0.464	0.475	0.07	6.612	0.000	Validated
Productivity per labor force → Agricultural output (H2)	0.179	0.185	0.067	2.675	0.008	Validated
Agricultural output → Greenhouse gases in agriculture (H3)	0.976	0.977	0.006	162.242	0.000	Validated
Digital Economy and Society Index → Greenhouse gases in agriculture (H4)	0.029	0.026	0.021	1.384	0.167	Invalidated

Source: Author's design based on data using SmartPLS v.3.0.

Analyzing the path coefficient between the Digital Economy and Society Index and Productivity per labor force (0.464) with a p-value < 0.001, a statistically significant positive relationship can be found. This outcome suggests that, as the degree of digitalization within an economy increases, there is a noteworthy improvement in labor productivity in agriculture, thus confirming the validity of the H1 hypothesis.

Upon investigating the correlation between productivity per labor force and agricultural output, a path coefficient of 0.179 and a p-value = 0.008 can be observed, indicating that an increase in labor productivity per unit corresponds to a substantial rise in agricultural output. This finding lends support to the validity of the H2 hypothesis.

The path coefficient between Agricultural output and GHGs in agriculture is 0.976, with a solid statistical significance ($p < 0.001$). This result emphasizes a robust and positive association between Agricultural output and the level of GHG in the agricultural sector. Unambiguously, it suggests that an increase in agricultural production may lead to a proportional growth in GHG emissions, thereby confirming the validity of the H3 hypothesis.

In contrast, when examining the path coefficient between the Digital Economy and Society Index and GHG in agriculture (0.029) with a p-value = 0.167, we encountered a lack of statistical significance. This finding indicates that the level of digitalization of an economy does not significantly impact GHG emissions in agriculture, thereby invalidating Hypothesis H4.

Studying specific indirect effects within the SEM model also suggests a rejection of Hypothesis H4 (Table 5).

Table 5. Specific indirect effects among the variables.

	Original Sample	Sample Mean	Standard Deviation	T Statistics	p Values
Digital Economy and Society Index → Productivity per labor force → Agricultural output	0.083	0.086	0.031	2.686	0.007
Productivity per labor force → Agricultural output → Greenhouse gases in agriculture	0.175	0.18	0.065	2.692	0.007
Digital Economy and Society Index → Productivity per labor force → Agricultural output → Greenhouse gases in agriculture	0.081	0.084	0.03	2.707	0.007

Source: Author's design based on data using SmartPLS v.3.0.

The influence of digitalization on GHG in agriculture is predominantly positive. The rise in labor productivity resulting from digitalization correlates with increased agricultural output and GHG emissions in agriculture. This result shows that, while modern agricultural technologies and practices can improve efficiency and production, they can also intensify pressure on natural resources and contribute to GHG emissions. In essence, investments in technology and digital infrastructure can enhance productivity and agricultural output, yet they may also entail adverse effects on GHG emissions in agriculture by increasing agricultural output [91]. This result highlights the need to adopt a balanced approach to promote sustainable development, considering both economic and ecological aspects [29].

Invalidating Hypothesis H4 suggests that the link between digitalization and GHG in agriculture is complex and depends on multiple factors, including how digital technologies are implemented and integrated into agricultural practices and supply chains. A careful evaluation of the long-term impact of digitalization on GHG emissions is necessary to understand this relationship better and to develop effective strategies for reducing emissions in the agricultural sector. CSA needs to become predominant for digital technologies to have the expected effect of reducing GHG emissions.

4. Discussion

4.1. Research Results Discussion

The adoption and implementation of digital technologies in agriculture have significant implications for the agricultural sector and the environment. The use of insulation panels and innovative shading systems can contribute to optimizing environmental conditions in greenhouses and reducing energy consumption for heating or cooling [89]. At the same time, smart greenhouse management systems can allow farmers to monitor and control greenhouse conditions in real time, which can increase crop efficiency and productivity [92].

This paper investigates the impact of agriculture on GHG emissions within the EU and promotes the broad implementation of CSA practices to mitigate these emissions. The validation of the H1 Hypothesis supports the idea that digitalization exerts a significantly positive influence on labor productivity in agriculture, which is in line with the findings of other researchers [41,91,92]. The study revealed that the adoption and implementation of digital technologies in agriculture have significant implications for the agricultural sector and the environment. Similar to Maraveas et al. [91] and Ruijs and Benninga [92], the results confirmed that digitalization could significantly contribute to increasing labor productivity in agriculture, with a positive impact on the environment and the economy. This paper's finding is significant because the positive impact of digitalization on labor productivity in agriculture suggests that investing in digital technologies could lead to increased efficiency and profitability within the agricultural sector. Moreover, by improving productivity without necessarily expanding land use, digitalization may contribute to reducing the environmental footprint of agriculture, aligning with broader sustainability goals.

The validation of the Hypothesis H2 highlighted that, by increasing productivity and adapting to climate change, CSA can contribute to increased agricultural production and, consequently, global food security. Therefore, integrating CSA practices into agriculture can help agricultural communities better cope with extreme events and climate fluctuations, representing a holistic and integrated approach to transforming agricultural systems towards sustainability and resilience [93]. As this study indicates, the integration of digital technologies into agricultural practices can enhance efficiency and resilience, enabling farmers to produce more food sustainably while mitigating the adverse effects of climate change on crop yields. This finding underscores the critical role of CSA in addressing the interconnected challenges of food security and climate change, highlighting the importance of further research and policy interventions to promote its adoption and implementation on a broader scale.

The research findings are consistent with the findings of Idris [41] and Abegunde and Obi [40], indicating that the adoption of CSA practices has significant implications for productivity, sustainability, and resilience. By increasing productivity and adapting to climate change, CSA can contribute to improving global food security [41]. Reducing GHG through the implementation of these practices can contribute to efforts to combat climate change and achieve global emissions reduction goals [40]. Adopting CSA practices can support local agricultural communities, especially those in regions vulnerable to climate change [94].

The adoption of these digital technologies may be limited by high initial costs and access to the resources and expertise needed for implementation and maintenance. Therefore, governments, non-governmental organizations, and the private sector need to collaborate in developing policies and programs that facilitate the adoption and use of these technologies in agriculture, particularly among small- and medium-sized farmers in developing countries [91]. Through investments in research and development, training, and technical assistance, the transition to a more sustainable and energy-efficient agriculture can be supported, contributing to mitigating climate change and improving global food security [95].

Investigating Hypothesis H3, our study has revealed that agricultural production is positively associated with GHG in agriculture. Several factors can explain this finding. On the one hand, intensifying agricultural production may involve the extensive use of agricultural inputs, such as chemical fertilizers and pesticides, which can contribute to GHG. Furthermore, the management of agricultural soils, including tillage and excessive irrigation, can lead to the release of gases such as carbon dioxide (CO_2) and nitrous oxide (N_2O) into the atmosphere. This acknowledgment is crucial for policymakers, as it emphasizes the need for targeted interventions to mitigate GHG emissions while ensuring sustainable agricultural production. Comprehending and tackling the connection between agricultural production and GHG emissions allow stakeholders to strive towards achieving both environmental sustainability and food security goals holistically.

These findings are consistent with previous research, such as that of Mizik [6], which has shown that agricultural production can be an essential factor in determining GHG. Moreover, Khumalo et al. [96] have emphasized that CSA can have a significant impact on GHG, suggesting that more efficient and innovative agricultural practices could contribute to their reduction. The empirical study findings are in line with the perspective of Khumalo et al. [96], according to whom CSA has a profound impact on how agriculture adapts to climate change and manages associated risks. Promoting sustainable agricultural practices and innovative technologies, CSA can enhance farmers' adaptability to extreme weather conditions and contribute to reducing GHG in the agricultural sector [96]. This finding has significant implications for food security and global sustainability, as it helps protect natural resources and improve the resilience of food systems to impending climate change. Furthermore, adopting CSA can increase farmers' incomes and economic security, contributing to poverty reduction and rural development worldwide.

The research results also align with the findings of Robertson [97], suggesting a series of measures that could mitigate GHG in the agricultural sector to limit global warming and preserve fragile ecosystems and biodiversity. Furthermore, more economically sustainable agriculture could lead to more efficient resource management and reduced long-term production costs. Improving agricultural output efficiency could contribute to increased food production and food security for the population, while improved economic opportunities for farmers could help reduce poverty and improve living standards in rural communities. Ultimately, these measures could bring significant benefits, contributing to a healthier environment, a more stable economy, and a more prosperous and equitable society.

Intensive greenhouse agriculture can lead to increased GHG due to high energy consumption and the use of chemical fertilizers [98]. GHG emissions from the agricultural sector not only significantly contribute to climate change but can also have other adverse effects on the environment and global sustainability. Excessive energy consumption in agriculture can lead to the depletion of natural resources and affect soil and groundwater quality [91]. Moreover, GHG from the agricultural sector can contribute to phenomena such as global warming and climate change, which can have devastating consequences for ecosystems and biodiversity.

Invalidating Hypothesis H4 suggests that there is no significant relationship between digitalization and GHG emissions in agriculture. Digitalization in agriculture can have complex and varied effects, and some of these effects may counterbalance potential GHG emission reductions. Digital technologies can lead to an intensification of agricultural production or increased reliance on chemical inputs, which could ultimately increase GHG emissions. The implementation of digital technologies, such as smart farm machinery or automated irrigation systems, may require additional electricity consumption. In several cases, these technologies can lead to increased energy consumption, which could indirectly result in increased GHG emissions associated with agricultural production. Digitalization can influence not only farm-level agricultural practices but also the entire supply chain and distribution. The increased demand for transportation and logistics to ensure the functioning of digital technologies can contribute to increased GHG emissions in other areas of the agricultural sector. Digital technologies can facilitate the growth and transportation of food products to remote areas or out of season, which could increase the global carbon footprint of the food system. This finding highlights the complexity of the effects of digitalization in agriculture, which can have varied and sometimes counterbalancing impacts on GHG emissions. While digitalization holds promise for enhancing productivity and sustainability in agriculture, it is essential to recognize that certain digital technologies and practices may inadvertently contribute to GHG emissions through factors such as increased energy consumption or changes in land use patterns.

Issues identified in the adoption of CSA in Europe indicate significant challenges to a successful transition to more sustainable and climate-resilient agricultural practices. Economic barriers, such as hidden costs and difficulties accessing capital, can discourage farmers from adopting new and innovative practices. Furthermore, behavioral obstacles, such as conflicts with traditional agricultural practices and farmers' education levels, can create resistance to change and slow CSA adoption. On the other hand, the lack of adequate regulatory frameworks and institutional support can limit the development and efficient implementation of CSA in the European Union. Poor access to information and technologies necessary for implementing CSA practices can also constitute a significant barrier to their adoption, exacerbating inequalities between regions and farmers [99]. To address challenges hindering CSA adoption in Europe, stakeholders should offer financial incentives and accessible financing, along with educational programs to enhance farmers' skills. Advocating for supportive regulatory frameworks and improving access to technology and information can further facilitate CSA implementation. Lastly, fostering community engagement and collaboration among stakeholders is crucial for promoting the widespread uptake of sustainable agricultural practices in Europe.

Climate-resilient agriculture is essential to ensure that farmers can cope with challenges related to climate variability and natural resource degradation, as well as to maintain agricultural production and ensure access to nutritious and safe food for the population [6,100–102]. Farmers could benefit from innovative agricultural technologies and practices that enable them to achieve higher yields and reduce negative environmental impacts [62,103–107]. For example, technologies like efficient irrigation, drought-resistant seed varieties, and soil conservation practices could contribute to increased crop yields and the conservation of water and soil resources [108]. Implementing these techniques and technologies can provide significant opportunities for farmers to improve their food security and incomes, reduce risks associated with climate change, and mitigate the agricultural sector's impact on the environment [109,110].

The effectiveness of the CSA approach significantly hinges on the active involvement and support of farmers. Hence, it is vital to ensure that farmers have access to sufficient resources and knowledge necessary for embracing and executing sustainable agricultural practices that are adaptable to climate change. Collaboratively addressing these challenges enables the establishment of a more resilient and sustainable agricultural sector, effectively tackling climate issues and contributing to enhanced food security, reduced GHG emissions, and sustainable development [49]. These actions necessitate active engagement and participation from all stakeholders, including policymakers, agricultural organizations, research institutions, and local communities, to provide support and a conducive environment for the adoption and success of sustainable agriculture initiatives.

Combining multiple CSA practices and technologies enables farmers to optimize production, safeguard natural resources, and enhance food security tailored to the specific needs and conditions of each agricultural region. This flexible and diversified approach is crucial for constructing a more resilient and sustainable agricultural system in response to climate challenges and other threats [111]. Adequate investments in capacity and resources for CSA implementation can lead to the creation of a more climate-resilient and sustainable agricultural environment [64,107,112–114]. Embracing CSA practices and investing in climate-resilient agricultural infrastructure is essential to ensure that agriculture can thrive despite increasingly severe climate challenges.

4.2. Theoretical Implications

In the context of a growing population and climate challenges, the adoption of digital technologies in agriculture becomes crucial to meet the demands for sustainable food production. Digital technologies such as precision agriculture, satellite monitoring, and data analysis can help farmers optimize resource use and adapt agricultural practices to changing environmental conditions. Furthermore, these technologies can contribute to reducing water waste, pesticide, and fertilizer inputs, thus protecting soil health and ecosystems. Therefore, agricultural digitalization not only supports the economic growth of the agricultural sector but also ensures food security and protects the environment for future generations.

The implementation of these digital technologies in agriculture could have a significant impact on environmental sustainability. Digital technology fosters environmental sustainability in agriculture through precision farming, data-driven decision-making, and transparent supply chains, aligning with principles of sustainable intensification and adaptive management. However, its application may exacerbate socioeconomic inequalities, widen the digital divide, and pose risks to data privacy and security, necessitating the careful consideration of social, economic, and ethical implications to ensure equitable and sustainable development. Balancing technological innovation with regulatory safeguards is crucial for maximizing the benefits of digital agriculture while minimizing adverse impacts on the environment and society.

The adoption of new technologies within CSA can bring significant benefits to the agricultural sector, improving the efficiency and sustainability of agricultural production. However, a careful and balanced approach is essential in order to maximize the benefits and minimize the risks associated with implementing these technologies in current agricultural practices. The digital transformation, while offering promising solutions, can also have adverse effects, such as increased energy consumption and agricultural production, ultimately resulting in higher GHG emissions. Thus, it is imperative to carefully consider the potential trade-offs and implement strategies to mitigate any adverse impacts while leveraging the benefits of digital technologies in agriculture.

4.3. Practical Implications

The adoption and promotion of CSA practices have significant implications for food security, climate change adaptation, GHG emissions mitigation, and the conservation of natural resources, with the potential to transform the agricultural system into a more sustainable and resilient one in the face of future challenges. Facilitating CSA adoption involves specific strategies such as providing training and resources for farmers, transferring relevant technologies, and implementing supportive policies. Collaboration between stakeholders in research, innovation, and policy-making is crucial for tailoring CSA practices, overcoming barriers, and promoting sustainable agricultural systems resilient to climate change. Investing in capacity building, technology transfer, and policy support can advance CSA adoption, enhance food security, and mitigate climate change impacts in agriculture.

Collaborative partnerships between governments, NGOs, research institutions, and private sector entities facilitate knowledge exchange, resource sharing, and collective action towards CSA goals. These partnerships enable the pooling of expertise, resources, and funding to develop and scale up innovative CSA solutions tailored to local contexts. Partnerships can help bridge gaps in access to technology, finance, and markets while fostering inclusive decision-making processes that empower farmers and communities to adopt and sustain CSA practices effectively. Through collaborative efforts and multi-stakeholder partnerships, stakeholders can leverage collective strengths, tackle systemic barriers, and accelerate the transition towards resilient and sustainable agricultural systems in the face of climate change.

The paper's results demonstrate that a balance must be struck between economic development needs and environmental protection. Adopting more sustainable agricultural practices can be a solution that allows for both economic growth and reduced environmental impact in these countries. Addressing measures to reduce GHG emissions in agriculture requires close collaboration between governments, agricultural organizations, research institutions, and local communities to ensure the efficient adoption and implementation of sustainable and climate-adaptive practices. Governments and interested organizations should consider developing and implementing policies and programs to facilitate access to resources, technologies, and agricultural extension services for farmers, with a focus on promoting CSA practices.

4.4. Limitation and Further Research

The potential limitations of this study include methodological aspects concerning the limited number of variables used in exploring relationships. Furthermore, the generalizability of the results may be affected by the specific context of the EU and the variability of data between member states. Given the diverse agricultural landscapes and climate conditions worldwide, findings from studies conducted in the EU may not fully represent the challenges and opportunities faced by farmers in other regions. Other limitations may include limited access to accurate climate data, inadequate research infrastructure, and the complexity of assessing the multidimensional impacts of CSA practices. Moreover, future research could address these limitations by using more complex methodologies to capture the interactions between variables better, expanding the number of variables considered, extending the study to a global or regional level, and improving data quality by collecting more precise data and using innovative methods to evaluate the impact of sustainable agricultural measures on GHG and overall agricultural sustainability.

5. Conclusions

Digitalization in agriculture represents a significant opportunity to reduce costs and environmental impact while simultaneously improving crop yields, farmer incomes, and food quality. This study seeks to evaluate the influence of agriculture on GHG emissions within the European Union (EU) and to investigate the impact of CSA practices driven by digital technologies on these emissions. However, there are concerns about potential inequalities and risks associated with this transformation. Socioeconomic disparities between high-income and low-income countries could exacerbate inequalities, and farmers in low-income countries may be marginalized or lack access to advanced digital technologies. Increasing dependence on high-tech companies could also increase farms' vulnerability to market changes or corporate policies that are not always farmer- or community-oriented. Strategic policy interventions are necessary to address the challenges of CSA, focusing on equitable access and justice for farmers with varying human resource abilities. These interventions include investing in tailored digital infrastructure, promoting inclusive innovation ecosystems, and implementing regulatory frameworks to ensure the fair distribution of benefits. Moreover, policies should prioritize providing support mechanisms and incentives to empower all farmers, regardless of their skills or resources, to effectively use digital technologies for sustainable agricultural development.

In addition to these aspects, digitalization can contribute to reducing resource waste and improving resource management through the precise monitoring of crop growth conditions and environmental factors. Moreover, implementing digital technologies in agriculture can have significant implications for reducing GHG, thus contributing to global efforts to combat climate change. Digitalization and CSA practices have significant potential to improve the efficiency and sustainability of the agricultural sector, contributing to food security and environmental protection by reducing GHG emissions. However, the digital transformation, while offering promising solutions, can also have adverse effects, such as increased energy consumption and agricultural production, ultimately resulting in higher GHG emissions. An integrated approach and adequate support are needed to overcome challenges and ensure a transition to a more sustainable and resilient agriculture. This integrated approach can be enhanced through multi-stakeholder collaboration. This collaboration involves engaging diverse stakeholders, including governments, farmers, NGOs, researchers, and businesses, to address agricultural issues collectively from multiple angles. Fostering dialogue and partnerships among stakeholders facilitates knowledge sharing, promotes inclusive decision-making, and increases the likelihood of achieving sustainable agricultural outcomes that align with social, economic, and environmental priorities.

Funding: This research received no external funding.

Data Availability Statement: Research data are publicly available at: https://digital-strategy.ec.europa.eu/en/library/digital-economy-and-society-index-desi-2017 (accessed on 29 February 2024); https://digital-strategy.ec.europa.eu/en/library/digital-economy-and-society-index-2018-report (accessed on 29 February 2024); https://digital-strategy.ec.europa.eu/en/library/digital-economy-and-society-index-desi-2019 (accessed on 29 February 2024); https://digital-strategy.ec.europa.eu/en/library/digital-economy-and-society-index-desi-2020 (accessed on 29 February 2024); https://digital-strategy.ec.europa.eu/en/library/digital-economy-and-society-index-desi-2021 (accessed on 29 February 2024); https://digital-strategy.ec.europa.eu/en/library/digital-economy-and-society-index-desi-2022 (accessed on 29 February 2024); https://ec.europa.eu/eurostat/databrowser/view/aact_ali01/default/table?lang=en&category=agr.aact.aact_ali (accessed on 29 February 2024); https://ec.europa.eu/eurostat/databrowser/view/aact_eaa07__custom_10308459/default/table?lang=en (accessed on 29 February 2024); https://ec.europa.eu/eurostat/databrowser/view/tag00054/default/table?lang=

en&category=t_agr.t_aact (accessed on 29 February 2024); https://ec.europa.eu/eurostat/databrowser/view/tag00055/default/table?lang=en&category=t_agr.t_aact (accessed on 29 February 2024); https://ec.europa.eu/eurostat/databrowser/view/env_ac_ainah_r2__custom_10308538/default/table?lang=en (accessed on 29 February 2024).

Conflicts of Interest: The author declares no conflicts of interest.

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