Original scientific paper
Journal of Central European Agriculture, 2025, 26(3), p.812-824
DOI: /10.5513/JCEA01/26.3.4646

ICT and e-government in agricultural development: A European perspective with insights from the Western Balkans (a case study of Albania)

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Received: December 18, 2024; accepted: April 18, 2025

ABSTRACT

This article investigates the relationship between the adoption of Information and Communication Technologies (ICTs) and advancements in e-government, focusing on their impact on the agricultural sectors of Albania and the Western Balkans. While the analysis draws on data from 38 European countries to provide a broader context, the study specifically focuses on the Western Balkans, with Albania serving as a key case study due to its unique combination of high agricultural dependency and relatively advanced e-government services. The study examines indicators such as the E-Government Development Index, Network Readiness Index, and agriculture's contribution to GDP by drawing on 2022 data from the World Bank, UN databases, and the Network Readiness Index reports. The findings reveal a significant negative correlation between ICT development and agriculture's contribution to GDP in Europe, suggesting that while ICT adoption and e-government services have advanced, their integration into the agricultural sector remains inconsistent. This limited integration contrasts with other economic sectors that capitalize more effectively on technological progress. The research utilizes correlation analysis, multivariate statistical methods, and cluster analysis to classify 38 European countries into three clusters based on ICT engagement, e-government development, and agriculture's contribution to GDP. Albania's profile demonstrates a heavy reliance on agriculture and relatively advanced e-government services, yet it has a lower Network Readiness level compared to its regional peers. The study underscores the potential benefits of targeted policies that enhance digital infrastructure, foster digital literacy, and promote ICT adoption and e-government initiatives.

Keywords: e-agriculture, digital infrastructure, ICT adoption, policy implications, cluster analysis

INTRODUCTION

Digital transformation is reshaping every sector of the global economy, and agriculture is no exception. As countries strive to ensure food security, reduce rural poverty, and build climate resilience, integrating technology into agricultural systems has become increasingly vital. Information and Communication Technologies (ICT) offer tools that can modernize traditional practices and improve outcomes for farmers and stakeholders across the agricultural value chain.

E-agriculture

The integration of ICT in agriculture, commonly referred to as e-agriculture, is transforming the sector by enhancing sustainability and promoting socioeconomic development. These digital technologies aim to improve agricultural practices, create digital marketplaces, and empower farmers (Hosen, 2023). E-agriculture involves the conceptualization, design, development, and implementation of innovative ICT solutions tailored for rural areas, with a strong focus on agricultural practices. The agricultural sector encompasses multiple stages, such as crop production, water management, pest control, and food marketing (Anshari et al., 2019). E-agriculture has considerable potential to improve decision-making and provide relevant information to end-users. However, its widespread adoption faces challenges, such as the lack of adequate digital infrastructure in rural areas and insufficient digital literacy among farmers (Hosen, 2023; Mhlanga, 2024). The challenges above necessitate collaborative efforts to improve digital infrastructure and provide training (Hosen, 2023). E-agriculture, driven by advancements in information and communication technology, integrates digital innovations into agricultural practices, enhancing efficiency, production, and sustainability. E-agriculture also encompasses precision agriculture and real-time livestock monitoring, which provide data-driven insights to enhance farmers' capabilities (Ayoub Shaikh et al., 2022; Niloofar et al., 2021). In the context of pressing global challenges, including climate change and population growth, e-agriculture emerges as a viable approach to sustainability, especially in resource-constrained and economically disadvantaged nations (Aker et al., 2016; Balafoutis et al., 2017).

E-government

The advent of e-agriculture and e-government has significantly transformed public service delivery globally, enhancing both agricultural productivity and the quality of services (Maumbe, 2009; Nikam, 2011). These programs improve governmental operations, integrate agricultural and commercial partners, connect farmers, and empower personnel (Nikam, 2011). Despite challenges posed by the digital divide, poor infrastructure, and financial constraints, digital tools facilitate improvements in farm management and farmers' decision-making processes (Panganiban, 2019). E-government initiatives enhance online services to increase value within agricultural departments and strengthen stakeholder relationships (Nikam, 2011). The implementation of these initiatives has the potential to significantly improve the agriculture sector through the strategic use of information and communication technology. Nonetheless, these e-government initiatives face various economic, social, political, and legal challenges during implementation (Bhat et al., 2024; Maumbe, 2009). The integration of e-government within the agricultural sector significantly improves administrative efficiency, promotes transparency, and supports inclusive growth (Bournaris, 2020).

Recent studies on e-government in the agricultural sector have emphasized the critical role of digital public services in streamlining administrative processes and enhancing communication between government agencies and farming communities. Kabir and Hoque (2023) illustrate how effective e-government service delivery in rural Bangladesh can yield significant economic benefits, while Sheikh and Berenyi (2023) propose a framework for digital technology adaptation by smallholder farmers that demonstrates the revolutionary potential of e-government. Malodia et al. (2021) provide an integrated conceptual framework that highlights the need for cohesive digital strategies in public service provision, and Abdulai et al. (2023) identify key factors influencing rural farmers' participation in digital agricultural services. Complementary insights are offered by Emeana et al. (2020) and Goedde et al. (2021), who show that mobile-enabled e-government platforms and digital tools can substantially improve the efficiency of agri-food systems. Additionally, Mushi et al. (2024) emphasize that digital information systems focused on users are essential for ongoing agricultural growth, while Reissig et al. (2022) and Vázquez-López and Marey-Perez (2021) look into the real-world difficulties and factors affecting the use of e-government in agriculture. Together, these studies highlight that strong e-government programs are crucial for reducing administrative hurdles and enhancing the effectiveness of digital technologies in agriculture, thereby supporting broader e-agriculture efforts.

Context and research gap

The existing literature reveals a significant gap concerning the effects of information and communication technologies, as well as e-government initiatives, within the framework of European agricultural economics. While numerous studies have explored the separate impacts of ICT and e-government within agricultural contexts, there is a notable scarcity of systematic analyses that investigate their joint effects across various European countries. The disparity is particularly evident in understanding how varying levels of ICT adoption and e-government practices influence agricultural productivity and economic development in regions with distinct conditions, such as the Western Balkans, especially Albania.

For instance, research from Alam and Shaba (2022) stresses the importance of user-centric ICT applications and suggests metrics for evaluating their success; however, it does not explore how these technologies are adopted in different European contexts for agricultural enhancement. Similarly, Amaluddin et al. (2024) demonstrate that rural ICT penetration significantly influences agricultural performance, but their focus on Eastern Indonesia limits the transferability of their findings to Europe. Zejnullahu et al. (2023) emphasize the value of e-government services in Kosovo without providing a comparative framework involving other European countries.

Furthermore, existing research, including that conducted by Kossi (2015), indicates a significant gap in the exploration of the role of ICTs in fostering economic inclusion and enhancing productivity within developing regions. However, there remains a lack of focus on the specific implications of these findings for the agricultural sectors in Europe. This research seeks to fill the existing gap by synthesizing data from 38 European nations, with a primary emphasis on the Western Balkans, and providing actionable recommendations for policymakers in Albania and comparable economies. The following analysis, presented in the Results section, demonstrates regional differences by grouping countries and highlighting Albania as an example of a country that relies heavily on agriculture yet has fairly well-developed e-government services.

E-agriculture and e-government strategies and policies in the Western Balkans

E-agriculture employs information and communication technologies, including mobile market pricing applications and satellite crop monitoring (Dlodlo and Kalezhi, 2015), to enhance agricultural productivity and ensure food security (FAO and ITU, 2016). This methodology provides timely, data-driven insights in the context of market fluctuations and challenges posed by climate change (Kamble et al., 2020), while also tackling information disparities in developing regions (Aker et al., 2016). Various global governments and organizations promote the integration of information and communication technologies with developmental goals in the field of e-agriculture (Maumbe, 2009). E-agriculture represents a revolutionary approach to the use of information within the agricultural domain. Agriculture is crucial to the economies of the Western Balkans (e.g., Albania, Bosnia and Herzegovina, and Serbia); consequently, the significance of e-agriculture becomes increasingly pronounced as these countries pursue modernization and align with European standards. Information and Communication Technologies (ICTs) are essential for advancing agricultural growth, securing food supply, and fostering rural development (Radovanovic et al., 2023). The countries in the Western Balkans prioritize digitization and e-government initiatives to achieve their goals for EU accession (Ördögh, 2023). Despite the establishment of e-public administration portals and efforts to enhance digital services, a discrepancy exists between stated objectives and the actual execution of agricultural policies under the Common Agricultural Policy (CAP) (Erjavec et al., 2021). Although a strategic framework and legislation for digital transformation in agriculture exist in Bosnia and Herzegovina, additional amendments are necessary to comply with EU requirements (Vico et al., 2021). Political pressures and economic interests often influence agricultural policy decisions, leading to a gap between policy aspirations and actual outcomes in the EU accession process. Serbia's "E-agriculture" platform provides real-time data and facilitates access to subsidies, whereas North Macedonia's pilot projects utilize precision agriculture and digital services to improve farmer productivity (Radović et al., 2021; Trajkovikj, 2020). To align with the digital ambitions of the EU, the Western Balkans need to formulate coherent e-agriculture policies that tackle challenges, including infrastructure and training (Kilibarda, Kotsev and Cetl, 2020). These strategies offer advantages, including enhanced market connections and improved resilience to climate change. Significant e-government infrastructures, including Albania's "e-Albania" portal, Bosnia's Integrated Business Registry System, and Serbia's comprehensive e-government platform, reflect the region's persistent commitment to modern governance (European Commission, 2022). The e-agriculture landscape features precision farming initiatives, digital agricultural databases, and real-time market analytics platforms. However, there are obstacles to these advancements, including a significant gap in internet access between rural and urban areas, varying levels of digital skills among farming communities, and the need for well-organized policies.

The 2022 Report from the Western Balkans Digital Economy Society Index (WB DESI) shows that the region has significant differences in digital performance in areas like education, internet access, use of technology, and online public services. The report reveals that although certain Western Balkan economies—particularly Montenegro, Serbia, and Albania—demonstrate relatively strong outcomes in selected digital indicators, overall performance remains below EU benchmarks. These findings highlight substantial gaps in digital infrastructure and skills, demonstrating the need for targeted policy interventions to accelerate digital transformation. Such interventions are critical not only for enhancing ICT adoption and e-government services but also for leveraging digital technologies to improve agricultural practices. Data from the WB DESI 2022 report provides a strong foundation for this study on how ICT, e-government, and agriculture affect GDP in the Western Balkans.

The Western Balkans demonstrate potential in e-government and e-agriculture; however, practical infrastructural enhancements, policy adjustments, and stakeholder cooperation are crucial for achieving optimal outcomes (Kilibarda, Kotsev and Cetl, 2020). While the Western Balkans share common challenges, such as gaps in digital infrastructure and inconsistent integration of ICT and e-government in agriculture, regional variability is evident. The subsequent analysis, presented in the Results section, employs a cluster-based approach to compare the digital profiles of these countries. Notably, Albania emerges as a representative case within a cluster characterized by high agricultural dependency and relatively advanced e-government services, underscoring its unique position in the region. While previous studies focused on either ICT or e-government in single countries or small regions, this research is the first to examine both factors across 38 European economies jointly. It employs correlation analysis, multivariate regression, PCA, and k-means clustering to identify distinct digital–agricultural profiles and derive cluster-specific policy recommendations, with special focus on Albania as a case study.

MATERIALS AND METHODS

This article analyzes data from 38 European countries. Although 44 countries were initially considered, six were excluded due to insufficient data. Focusing on European countries provides a relatively consistent context in economic, social, and technological terms, which offers a meaningful basis for comparative analysis given the diversity in e-government and ICT development within Europe.

Study area

The selected countries represent a mix of those with 2022 data from the World Bank and the United Nations e-government Database. Data availability and relevance to agricultural and ICT indicators influenced the sampling, ensuring a robust dataset for correlation, multivariate, and cluster analyses.

Sampling techniques

Using a purposive sampling method, countries were chosen based on data availability from the World Bank and the UN e-government database. This approach ensured that the selected sample included all required indicators (e.g., agriculture's contribution to GDP, the NRI, and the E-Government Development Index), thereby enabling robust correlation, multivariate, and cluster analyses.

Measurement of variables

Agriculture's contribution to the GDP: This variable is quantified by the "agriculture, forestry, and fishing, value added (% of GDP" provided by the World Bank (World Bank Group, 2023).

ICT Development: The study uses the Network Readiness Index (NRI) (Portulans Institute, 2022), replacing the former ICT Development Index (IDI) due to changes in the IDI methodology.

E-government Progression: This is assessed using the E-government Development Index (EGDI) and its parts, which include the E-Participation Index, Online Service Index, Human Capital Index, and Telecommunication Infrastructure Index (UN E-government Knowledgebase, 2022).

Data analysis

To gain a thorough understanding of how digital transformation impacts agricultural economics, a suite of statistical techniques was employed. This multi-method approach includes measuring relationships between individual factors (correlation analysis), examining overall effects (multivariate regression), simplifying data (principal component analysis, PCA), and identifying performance clusters (k-means clustering). Employing multiple analytical techniques provides robust, complementary insights into the interplay of ICT, e-government, and agriculture's contribution to GDP across diverse European countries. The study applies several statistical techniques to analyze the relationships between agricultural contributions, ICT engagement, and e-government progression across European countries. A Pearson correlation analysis was performed using SPSS to assess the strength of association between agriculture's GDP contribution and various indices: the E-Government Development Index (EGDI), the Network Readiness Index (NRI), and the EGDI's sub-indices (E-Participation, Online Service, Human Capital, and Telecommunication Infrastructure Index). Pearson's correlation coefficient (r), ranging from −1 to +1, quantifies the degree of linear association between these variables. This analysis tests the following hypotheses:

H1: E-government advancement is related to the economic contribution of the agricultural sector.

H2: ICT engagement in a country correlates with its agricultural economic contribution.

Significance levels (p-values) are reported alongside the correlation coefficients to assess their statistical significance.

A multivariate regression model was constructed to investigate further the impact of ICT and e-government indices on agriculture's contribution to GDP. The model includes agriculture's contribution to GDP as the dependent variable, with the e-government Development Index and Network Readiness Index as independent variables. The regression equation is as follows:

$$Agriculture's\ Contribution = \beta_0 + \beta_1 \times EGDI + \beta_2 \times NRI + \epsilon$$

- β_0 Intercept, representing the baseline level of agriculture's contribution to the GDP when both indices are zero
- β_1 Coefficient for the e-government Development Index, indicating the change in agriculture's contribution to the GDP per unit increase in e-government Development Index, holding other factors constant
- β_2 as the coefficient for the Network Readiness Index, indicating the change in agriculture's contribution to the GDP per unit increase in the Network Readiness Index, holding other factors constant
- The symbol ϵ represents the error term, which indicates the unexplained variation in the model.

This regression analysis, performed using Python with scikit learn, was used to test the hypothesis:

H3: Variations in ICT and e-government indices significantly explain the variability in agriculture's contribution to GDP.

This model assesses the direct impacts of both indices on agricultural contributions. At the same time, the Mean Squared Error (MSE) and R-squared values are used to evaluate model fit and explanatory power.

Principal Component Analysis (PCA)

Principal Component Analysis (PCA) is a statistical technique for dimensionality reduction and data simplification developed by Pearson and Hotelling (Sewell, 2008). It transforms multivariate data into uncorrelated principal components that maximize variance, with the first component capturing the most variance (Abdi and Williams, 2010). PCA is achieved by computing the covariance matrix and its eigenvectors and eigenvalues (Mishra et al., 2017). This method increases data interpretability while minimizing information loss, making it useful for large datasets (Jolliffe and Cadima, 2016). PCA is a technique for reducing the dimensionality of datasets, increasing interpretability while minimizing information loss. It transforms the data into a new coordinate system, where the most significant variances lie on the first few principal components, which are the linear combinations of the original variables.

The transformation is represented as

$$Z = X\,W$$

X is the original data matrix, *W* is the matrix of eigenvectors (principal components), and *Z* represents the transformed data in the principal component space. The first two principal components capture approximately 96.76% of the total variance, enabling a simplified yet effective data representation for clustering purposes. This analysis tests the hypothesis:

H4: A limited number of principal components will capture the majority of the variance in ICT and e-government indicators, supporting a practical summary of the data.

Cluster analysis and the elbow method

To identify groups of similar countries, k-means clustering was applied to the PCA-transformed data. The optimal number of clusters was determined using the elbow method, which involves plotting the within-cluster sum of squares (inertia) against the number of clusters and finding the 'elbow' point where adding more clusters yields only minor improvements. In this approach, inertia (within-cluster sum of squares) is plotted against the number of clusters to find the 'elbow' point at which adding additional clusters results in only marginal reductions in inertia. Inertia is calculated as

$$Inertia = \sum_{i=1}^{n} \min_{\mu_j \epsilon C} \left\| x_i - \mu_j \right\|^2$$

where x_i represents a data point, μ_i the centroid of cluster C_j, C is the set of all clusters, and n is the total number of data points.

The "elbow" point suggests an optimal balance between cluster compactness and the number of clusters, guiding the selection of three clusters for this study. The k-means algorithm repeatedly adjusts the center points of clusters to reduce inertia until a stable grouping is formed, organizing countries based on similar ICT, e-government, and agricultural traits. This cluster analysis, visualized using Tableau, tests the hypothesis:

H5: The countries can be grouped into a limited number of clusters that reflect distinct digital profiles regarding ICT engagement, e-government development, and agriculture's contribution to GDP.

Combining these analytical techniques, the study comprehensively examines how ICT and e-government factors affect agricultural contribution across European countries.

RESULTS

The results highlight that countries with higher Network Readiness Index and E-Government Development Index scores tend to have a lower economic reliance on agriculture, suggesting a negative relationship between technological advancement and agriculture's contribution to GDP. This conclusion is primarily drawn from the Pearson correlation analysis (Table 1), which showed strong negative relationships between agriculture's share of GDP and both the Network Readiness Index (r = –0.717, *P* < 0.01) and the E-Government Development Index (r = –0.560, *P* < 0.01).

Pearson correlation

The data for agriculture, forestry, and fishing value added (% of GDP) were obtained from the World Bank. The ICT engagement and e-government index values were sourced from the UN E-Government Knowledgebase and the Network Readiness Index reports. Table 1 presents the correlation analysis results, as calculated using SPSS, for these variables.

Table 1 shows a strong negative correlation between agriculture's contribution to GDP and the Telecommunication Infrastructure Index. There is also a moderate negative correlation between the E-Government Development Index and the Human Capital Index, and a weak negative correlation between the Online Service Index and the E-Participation Index. It also reveals a strong negative correlation between agriculture's contribution to GDP and the Network Readiness Index. Consequently, the findings support both hypotheses:

H1: E-government advancement is related to the economic contribution of the agricultural sector.

H2: ICT engagement in a country correlates with its agricultural economic contribution.

In summary, the findings indicate that higher levels of ICT engagement and e-government development are associated with a lower economic reliance on agriculture, as measured by agriculture's contribution to GDP. This empirical evidence underlines the significant role that digital transformation plays in shaping agricultural economics across European contexts.

Table 1. Correlations of the EGDI score, E-Participation Index, Online Service Index, Telecommunication Infrastructure Index, Agriculture, Network Readiness Index, Forestry, and fishing Value Added (% of GDP in 2022)

	Correlations					Network Readiness Index 2022
	e-government Development Index (2022)	E-Participation Index	Online Service Index	Human Capital Index	Telecommunication Infrastructure Index	
Agriculture, forestry, and fishing (value added (% of GDP), 2022	-.560**	-0.120	-0.234	-0.507**	-0.729**	-0.717**
	0.000	0.474	0.158	0.001	0.000	0.000

Source: Authors' elaboration using SPSS

Table 2. Multivariate Analysis

Parameter	Coefficient	Std. Error	*T*-Value	*P*-value	95% CI
Intercept (β_0)	13.7004	5.028	2.70	0.0107**	[3.359, 23.74]
E-government Development Index (β_1)	10.9387	10.5028	1.21	0.2332	[–8.579, 34.064]
Network Readiness Index (β_2)	–0.3045	0.0800	–4.07	0.0003***	[–0.4884, –0.1634]
Mean Squared Error (MSE)	1.6991				
R-squared	0.7311				

Source: Authors' elaboration using Python

As shown in Table 2, agriculture's contribution to GDP increases by approximately 10.94 units for every one-unit increase in the E-Government Development Index, holding the Network Readiness Index constant. Conversely, agriculture's contribution to GDP decreases by about 0.30 units for every one-unit increase in the Network Readiness Index, holding the E-Government Development Index constant. The intercept of 13.70 is the expected value of agriculture's contribution to GDP when the E-government Index and Network Readiness Index are zero. However, since these indices typically do not reach zero, this value is more of a statistical artifact than a practical finding. The MSE of 1.70 indicates the average squared difference between the actual and predicted values. A lower MSE is generally better, but its interpretation depends on the context of the data and the scales used. An R-squared value of 0.73 suggests that the E-government Development Index and Network Readiness Index explain about 73% of the variation in agriculture's contribution to GDP. This is a relatively strong model fit. The model suggests a significant positive relationship between the E-Government Development Index and agriculture's contribution to GDP. However, the effect of the Network Readiness Index is modest and not statistically significant, providing only partial support for H3. Table 2 displays not only the coefficient estimates but also the standard errors, t-values, and p-values for each variable. These statistics indicate that the coefficient for the E-Government Development Index is statistically significant ($P < 0.05$). In contrast, the effect of the Network Readiness Index, although negative, does not reach statistical significance. Notably, although the Pearson correlation shows a negative link between EGDI and agriculture's share of GDP, the multivariate regression (controlling for the Network Readiness Index) reveals a strong positive association. This suggests that accounting for the Network Readiness Index mitigates confounding factors, indicating that e-government development positively affects agricultural economic performance. It is also important to remember that correlation does not imply causation, and these results should be interpreted with caution. Other factors not included in the model might also influence agriculture's contribution to GDP.

Principal Component Analysis (PCA)

The first principal component accounts for roughly 81.41% of the variance, and the second principal component contributes an additional 15.35%. Using just these two components preserves about 96.76% of the total variance, which is highly advantageous for visualization and analysis. The Elbow Method plot assists in identifying the ideal number of clusters. Ideally, one looks for the point at which inertia diminishes markedly more slowly—the commonly termed "elbow." In the plot (Figure 1), this elbow appears around the 2- or 3-cluster mark. Determining the exact number of clusters can be somewhat subjective and depends on the specific application. K-means clustering was executed on the PCA-transformed data using three chosen clusters. This PCA analysis addresses hypothesis H4, which posits that a small number of principal components will capture most of the variance in the ICT and e-government indicators. In our results, the first two principal components account for ~96.76% of the total variance, thereby supporting H4.

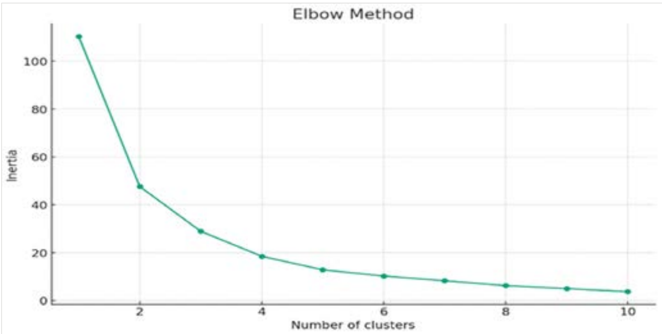

Figure 1. Elbow method for optimal number of clusters

Following this, the k-means clustering, applied to the data transformed by PCA, tests hypothesis H5 by categorizing countries into distinct groups based on their digital characteristics. The findings indicate that the countries can be classified into three clusters that reflect different levels of ICT engagement, e-government development, and agriculture's contribution to GDP, thus supporting H5.

The scatter plot in Figure 2 visualizes these clusters in the space defined by the first two principal components.

Figure 2. Clusters on PCA-transformed data by the authors

Each cluster is a group of countries with similar characteristics in terms of their E-government Index, Network Readiness Index, and agricultural contribution to GDP, as transformed by PCA.

- Cluster 0: Represented by the blue points.
- Cluster 1: Represented by the orange points.
- Cluster 2: Represented by the green points.

Each cluster groups countries with similar scores and contributions across the selected indices, which could reflect similarities in their technological infrastructure, government digital services, and the relative size of their agricultural sector.

Countries in each cluster

Countries in each cluster are displayed in Figure 3:

- Cluster 0: Austria, Belgium, Denmark, Estonia, Finland, France, Germany, Ireland, Luxembourg, Netherlands, Norway, Portugal, Slovenia, Spain, Sweden, Switzerland, and the United Kingdom. This cluster is made of countries with a low percentage of agriculture's contribution to the GDP, a high E-government Index, and a high Network Readiness Index.
- Cluster 1: Albania, Bosnia and Herzegovina, Montenegro, North Macedonia, and Serbia. These countries have a higher Agriculture contribution to the GDP, a lower E-government Index, and a lower Network Readiness Index than Cluster 0.
- Cluster 2: Bulgaria, Croatia, the Czech Republic, Greece, Hungary, Italy, Latvia, Lithuania, Poland, Romania, Slovakia, and the Russian Federation. This cluster includes countries with a moderate Agriculture contribution to the GDP, a moderate E-government Index, and Network Readiness Index values between Clusters 0 and 1.

Figure 3. Countries in each cluster using Tableau for data visualization

Cluster 0 consists of technologically advanced countries with a minimal relative contribution of agriculture to GDP. In contrast, Cluster 1 includes countries with a higher reliance on agriculture and lower technological index scores. Cluster 2 falls in between, with moderate agricultural contributions to GDP and intermediate technology index scores.

Albania in the cluster analysis

Table 4 contains results related to Albania as a special case study. It was singled out for detailed discussion because its profile within Cluster 1 is notably distinct. Despite being grouped with other Western Balkan countries with relatively higher agricultural reliance, Albania exhibits an exceptionally high agricultural contribution to GDP (18.63%) compared to the Cluster 1 average (8.99%). Additionally, while Albania's E-government Development Index (0.7413) exceeds the cluster average (0.7202), its Network Readiness Index (46.50) is somewhat lower than the cluster mean (48.88). This combination of strong digital government performance and high dependency on agriculture indicates that Albania's digital transformation, particularly in enhancing agricultural outcomes, follows a different trajectory from its peers. Such a unique profile makes Albania an instructive case for illustrating the potential for targeted policy interventions in the region.

Table 3. Cluster characteristics

Cluster 0 (Low Agriculture, High Tech):	Cluster 1 (Higher Agriculture, Lower Tech):	Cluster 2 (Moderate Agriculture and Tech):
Agriculture Contribution to GDP: ~1.50%	Agriculture Contribution to GDP: ~8.99%	Agriculture Contribution to GDP: ~3.44%
E-Government Development Index: ~0.90	E-Government Development Index: ~0.72	E-Government Development Index: ~0.82
Network Readiness Index: ~72.65	Network Readiness Index: ~48.88	Network Readiness Index: ~59.71

Source: Authors' elaboration using Python

Table 4. Albania analysis

Index	Albania	Cluster 1 Average
Agriculture, forestry, and fishing (value added (% of GDP), 2022	18.63%	8.99%
E-Government Development Index 2022	0.7413	0.7202
Network Readiness Index 2022	46.50	48.88

Source: Authors' elaboration using Python

DISCUSSION

The analyses provide evidence that digital transformation influences agricultural economics across European countries. This research differs from previous studies that focused on a single country or method. It provides a careful comparison of 38 European countries, plus a detailed case study of Albania, by using multiple analytical techniques (correlation, regression, PCA, k-means clustering) to highlight unique digital–agricultural profiles and previously unexamined groupings.

The Pearson correlation results validate hypotheses H1 and H2. In particular, higher e-government advancement is associated with a lower economic contribution from the agricultural sector (H1), and greater ICT engagement correlates with agriculture's contribution to GDP (H2). Elevated e-government development correlates with less dependence on agriculture, whereas ICT engagement shows a slight negative correlation with agriculture's contribution to the GDP. The results demonstrate a marginal negative correlation between ICT engagement and agriculture's contribution to GDP. This observation corresponds with Kivarina and Yurina's (2024) assessment, which indicates that, despite the government's initial emphasis on digital transformation, agriculture frequently scores worse in implementation compared to other sectors. Their evaluation indicates that although digitalization presents benefits, agricultural industries may fall behind due to sluggish adoption rates and infrastructural limitations. Loi Nguyen's (2022) work on Vietnam reflects a stance of cautious optimism regarding the significance of ICT in digital agriculture, given prevailing economic dependencies. Eremina et al. (2022) emphasize that the sluggish advancement of digitalization in agriculture has specific consequences for enterprise productivity. Their research indicates a necessity for robust digital platforms to connect governmental management with agricultural practices, similar to the conclusions of this study regarding the importance of ICT engagement for improving agricultural productivity.

The multivariate regression analysis further quantifies these relationships: agriculture's contribution to GDP increases by approximately 10.94 units for every one-unit increment in the E-government Development Index, whereas it decreases by about 0.30 units per one-unit increment in the Network Readiness Index. The analysis reveals a positive relationship between e-government development and agricultural economic contribution, leading to increased productivity as agricultural reliance diminishes. This result is consistent with Sazonov and Sazonova (2023), who emphasize the potential for digital transformation in agriculture through government initiatives. Their model illustrates how e-government can stimulate agricultural reforms in the context of the digital economy, supporting the notion that digital engagement can streamline agricultural processes and increase economic contributions.

Similarly, Leng and Tong (2022) found that digital technology plays a crucial role in enhancing the sustainable development of agriculture, suggesting that coordination between ICT applications and agricultural practices is essential for transforming the agricultural sector and maximizing its economic potential in other regions, such as China. This underscores that enhancements in agricultural productivity through digital means transcend geographical boundaries, impacting economic performance in various national contexts.

Principal component analysis shows that two principal components account for nearly 96.76% of the total variance in the digital indicators, supporting the idea that a few components can effectively summarize the data (H4). This finding aligns with Beksultanova et al. (2023), who highlight that digital transformation in agriculture requires new processes and that identifying key components can help focus research on the most critical areas. Subsequent K-means clustering, visualized using Tableau, groups the 38 European countries into three distinct clusters (H5). Cluster 0 includes countries like Austria, Belgium, and Denmark, which have advanced digital technology and depend less on farming; Cluster 1 includes Albania, Bosnia and Herzegovina, and North Macedonia, which rely more on farming and have lower digital technology levels; and Cluster 2 consists of countries that have a mix of digital technology and farming contributions. The resulting cluster visualization is novel, but it echoes findings in studies such as Zheng et al. (2024), which discusses a tripartite model of governance in the digital transformation of farmers' cooperatives in China. Their focus on tailored governmental policies, as catalyzed by comprehensive data analysis, points to the potential for targeted strategies based on specific regional needs.

CONCLUSIONS

Overall, the study's findings indicate that higher levels of e-government development are positively associated with agriculture's contribution to GDP, while increased ICT engagement (as measured by the NRI) shows a modest negative correlation. Principal component analysis confirmed that two main components capture nearly all digital variance, and clustering analysis revealed three distinct country profiles based on digital and agricultural characteristics.

Considering the study's findings, specific interventions are essential for enhancing agricultural productivity, diversifying rural economies, and fostering sustainable economic growth. Policymakers, especially in the Cluster 1 countries, should strategically invest in ICT infrastructure, implement comprehensive digital literacy programs, and develop customized e-government services explicitly tailored to the agricultural sectors. Such targeted measures will ensure equitable access to digital agricultural resources, thereby boosting agricultural productivity and achieving long-term economic stability. Additionally, comprehensive policy frameworks are necessary to effectively guide digital transformation efforts while safeguarding the agricultural sector from potential vulnerabilities.

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