Do digitalization and technological innovation foster the achievement of the sustainable development goals? Evidence from EU's newer member states

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Abstract

Purpose – This study aims to evaluate the impact of digitalization and technological innovation on the achievement of Sustainable Development Goals (SDGs) in 11 EU member states that joined after 2004. The research specifically investigates how the influence of these factors varies across different levels of sustainability performance in the post-accession period.

Design/methodology/approach – Using annual data from 2000 to 2023, the study applies the quantile regression method to capture heterogeneous effects across countries with differing SDG performance levels. This approach allows for an in-depth analysis of whether and how digitalization and innovation affect sustainability outcomes at lower, median and higher levels of development.

Findings – The results reveal that digitalization has a consistently positive and statistically significant impact on SDG performance across all quantiles, with stronger effects observed in countries with lower sustainability scores. In contrast, technological innovation shows a more limited and diminishing effect at higher quantiles, suggesting that innovation alone is not sufficient without complementary policy or institutional support. The study confirms the crucial role of digital transformation in accelerating sustainable development in emerging EU economies.

Originality/value – This study provides novel insights into the differentiated role of digitalization and innovation in promoting sustainability across various stages of development. Unlike previous research that primarily focused on advanced economies, this paper emphasizes the importance of tailored digital investment strategies in newer EU member states, offering practical implications for policymakers seeking to close the SDG performance gap within the European Union.

Keywords Digitalization, Technological innovation, SDG, Sustainable development goals, Quantile regression

Paper type Research article

1. Introduction

The Sustainable Development Goals (SDGs) are a development agenda adopted by the United Nations in 2015 that comprehensively addresses goals such as eliminating poverty, reducing inequalities, ensuring environmental sustainability and increasing social welfare on a global scale by 2030. These goals provide a common roadmap for both developed and developing countries and address sustainability with a holistic approach not only with environmental but also social and economic dimensions (Berrone *et al.*, 2023; Fallah Shayan *et al.*, 2022). The applicability of sustainable development goals is monitored and evaluated not only at the policy level but also in a wide range of areas such as corporate responsibility, urbanization planning, energy efficiency and technological developments. In particular, the traceability of SDGs at the corporate level should be supported by transparent reporting systems and a stakeholder-based management approach (Erin *et al.*, 2022). In addition, integrating SDGs into planning processes in the context of urbanisation and smart cities is also critical for

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sustainable urban management and reducing social inequalities (Sharifi *et al.*, 2024; Kalfas *et al.*, 2023). The impacts of the COVID-19 pandemic have made the need for global resilience and flexible strategies more visible in the SDG implementation process (Shulla *et al.*, 2021).

Digitalization has a transformative impact on the achievement of sustainable development goals, and this impact is manifested in multidimensional ways. Firstly, the proliferation of information and communication technologies increases transparency and traceability by enabling data-driven management in decision-making processes, which in turn contributes to governance-oriented goals such as SDG 16 (Peace, Justice and Strong Institutions) and SDG 17 (Partnerships for the Goals) (Awuah *et al.*, 2024; Onyango and Ondiek, 2021). At the same time, digital solutions facilitate access to services and increase inclusiveness in social dimension goals such as SDG 3 (Health), SDG 4 (Education) and SDG 6 (Water and Sanitation) (Mujtaba *et al.*, 2024; Gupta and Kumar, 2024). While digital platforms can foster collaboration among different stakeholders, these systems also facilitate the alignment of local and national policies with the SDGs (ElMassah and Mohieldin, 2020; Mburu and Munene, 2024). However, digitalization not only enhances managerial capacity but also supports environmental and economic sustainability through increased efficiency in production systems and resource management optimization. For example, digital technologies contribute to SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action) targets by enabling energy systems to operate more efficiently, while also overlapping with SDG 12 (Responsible Consumption and Production) targets such as waste management and carbon footprint reduction (Çelik *et al.*, 2022; Miskiewicz, 2022). The integration of digital technologies in different sectors such as ports (Almeida and Okon, 2024), agri-food systems (Sridhar *et al.*, 2023) and public administration (Mondejar *et al.*, 2021) makes it possible to implement sustainable development goals more effectively in cross-sectoral interaction.

Digitalization stands out as a facilitating tool in many areas from data management to public services in the realization of sustainable development goals (SDGs), especially strengthening transparency, monitoring and participation processes. However, when these opportunities offered by digital transformation are supported by technological innovation in terms of wider and more inclusive effects, the applicability of SDGs at sectoral and structural level increases significantly. In this context, technological innovation stands out as a fundamental building block that goes beyond digitalization and transforms sustainable development into concrete outputs. Innovative practices developed in areas such as renewable energy technologies, sustainable production systems, clean transport solutions and waste management strongly overlap with environmental and economic sustainability goals (Sinha *et al.*, 2020; Xing *et al.*, 2023). Technological innovation is not only limited to the process of developing new products or services, but also enables efficient use of resources, reduction of carbon footprint and sectoral transformation. Cost-effective solutions such as frugal innovation (Ebolor *et al.*, 2022) facilitate the achievement of the SDGs in key areas such as health, energy and food, especially in developing countries. Moreover, innovation ecosystems strengthened by collaborative innovation models, multi-stakeholder R&D processes and public-private sector coordination increase the feasibility of SDGs and support social inclusion (Guo *et al.*, 2022; Mariani *et al.*, 2022). In this respect, technological innovation is a holistic development tool that contributes not only to economic growth but also to social justice and environmental protection simultaneously.

This study aims to address the gap in understanding how digitalization and technological innovation jointly influence the achievement of Sustainable Development Goals (SDGs), particularly within the context of EU member states that joined after 2004. Despite increasing attention to these factors individually, their combined and heterogeneous effects across countries with diverse institutional and economic backgrounds remain insufficiently explored. Specifically, this research investigates the mechanisms through which digitalization and technological innovation impact SDG performance, taking into account varying development stages and structural characteristics of transition economies. The study employs an empirical approach, using panel data from 2000 to 2023 for 11 post-2004 EU member states (Bulgaria, Czechia, Estonia, Croatia, Hungary, Lithuania, Malta, Poland, Romania, Slovakia, and Slovenia), which have undergone significant institutional harmonization, digital transformation, and sustainability policy reforms following EU accession. By examining both distributional effects across different quantiles and causal relationships, the study seeks to uncover nuanced patterns in how these technological dynamics shape sustainable development outcomes. This approach not only clarifies the differential impacts across countries but also contributes to a more integrated understanding of the role of digital and technological factors in advancing the SDGs within transitioning economies.

In this study, 11 countries that joined the European Union (EU) after 2004 were selected as the sample. The primary reason for choosing these countries is that they have undergone significant structural changes in digital transformation, institutional harmonization processes, and sustainability policies following their EU membership. The EU accession process has encouraged both the strengthening of digital infrastructure and the alignment of environmental and social policies with EU norms in these countries. This situation makes these countries a meaningful laboratory for analysing the relationship between digitalization and the Sustainable Development Goals (SDGs). Moreover, the fact that these countries are “transition economies” aligns well with the objectives of the study. These countries, which are in the process of shifting from planned economies to market economies, are experiencing the effects of structural transformation simultaneously in the fields of digitalization and sustainability. Compared to more developed EU countries, higher heterogeneity is observed in these countries regarding digitalization levels, innovation capacity, and sustainable development performance. These differences provide the opportunity to analyse how the effects of digitalization and innovation on SDGs vary not only at the level but also depending on structural conditions. Therefore, selecting this group of countries enables the study to produce results that have high comparative and policy-relevant significance.

This study contributes to the literature in various aspects. First of all, this study is important in terms of being one of the first empirical applications of the effects of digitalization and technological innovation on sustainable development performance. In addition, the selection of 11 countries that joined the European Union after 2004 as the sample further increases the originality and application value of the study. This group of countries provides a highly meaningful framework for analysis, as they have both made significant progress in the digitalization process and have undergone structural transformation with sustainable development policies after EU membership. Moreover, the findings can be useful for various stakeholders at different levels. For example, public institutions and policymakers responsible for the design and implementation of sustainable development policies can benefit from the findings showing the impact of digitalization on sustainable development, review their existing strategies and evaluate the contribution of digital transformation to development processes more concretely. In addition, funding and programme development stakeholders such as international development organizations, European Union institutions and regional development agencies can also benefit from the results of the study. These findings, which reveal the contribution levels of digitalization and technological innovation to sustainable development, can also contribute to data-based decision-making processes in resource allocation and prioritisation processes.

This study consists of five chapters. In the first section, the subject, purpose and importance of the study are explained and a general framework is drawn. In the second section, previous research in the literature on the relationship between sustainable development goals (SDGs) and digitalization and technological innovation is summarized, and relevant theoretical and empirical findings are presented. In the third section, the data set and empirical methodology used in the study are introduced in detail. In the fourth section, empirical findings based on quantile regression analysis are presented and interpreted. Finally, in the fifth section, general evaluations are made in line with the findings and policy recommendations are developed for different stakeholders.

2. Literature review

2.1 Digitalization and innovation

Digitalization and innovation are increasingly recognized as two interdependent concepts that shape the sustainable competitiveness of firms. Digitalization refers to the diffusion and application of information and communication technologies (ICTs) into organizational processes, while innovation focuses on generating value through the development of new products, processes, or technologies (Sehlin *et al.*, 2019). Clarifying the conceptual boundaries between these notions is essential: digitalization provides the technological foundation and infrastructure, whereas innovation represents the transformative activities that build upon this foundation (Liu *et al.*, 2018).

Digitalization acts as a catalyst that enhances the speed and effectiveness of innovation. For instance, digital tools such as big data, artificial intelligence, and cloud computing accelerate R&D processes and strengthen innovation capacity (Heiden *et al.*, 2021; Wang *et al.*, 2025). In turn, innovation contributes to the advancement of digitalization by upgrading its quality and scope, thereby broadening the impact of digital services. This complementary relationship is particularly evident in the case of SMEs, where digital entrepreneurship benefits are reinforced, and the economic value of digital transformation is amplified (Rodrigues *et al.*, 2022; Łobacz and Szanter, 2022).

The literature also highlights that the intersection of digitalization and innovation is not limited to technological progress but extends to managerial practices. The integration of digitalization into business processes directly influences the maturity of innovation management practices, transforming strategic decision-making processes (Łobacz and Tylżanowski, 2022). In sectors such as family businesses and services, the alignment between digitalization and innovation creates both opportunities and challenges; from a managerial perspective, the lack of technology adoption can constitute significant barriers to competitiveness (Ullah *et al.*, 2021; Galeone *et al.*, 2023).

In conclusion, digitalization and innovation are not mutually exclusive but rather complementary processes. While digitalization provides the technological and organizational infrastructure for innovation to take place, innovation ensures that digitalization evolves into a sustainable and value-creating transformation. This reciprocal relationship represents a critical strategic dimension that determines both the short-term efficiency and long-term sustainability of firms.

2.2 The relationship between SDGs and digitalization

Digitalization constitutes a pivotal component of the sustainable development paradigm, underpinned by rapid advancements in information and communication technologies, artificial intelligence, big data analytics, and emergent applications such as blockchain. These innovations are instrumental not only in enhancing economic productivity but also in fostering social inclusion and environmental stewardship (Del Río Castro *et al.*, 2021; Mondejar *et al.*, 2021). Consequently, the nexus between digital technologies and the achievement of Sustainable Development Goals (SDGs) has become a prominent focus within contemporary academic discourse.

The transformative potential of digitalization is particularly evident in sector-specific sustainability challenges. For instance, Vărzaru (2024) elucidates the role of digital instruments in fortifying food security and mitigating inefficiencies within the European Union’s agricultural supply chains through improved traceability, monitoring, and decision-support systems, thereby advancing SDG 2 (Zero Hunger) and SDG 12 (Responsible Consumption and Production). This sectoral application exemplifies the broader capacity of digital infrastructures to enhance economic inclusivity while concurrently reducing systemic vulnerabilities.

In the domain of sustainable development monitoring, Bobylev *et al.* (2018) identify digital indicators as critical data sources for assessing SDGs related to climate action, environmental preservation, and public health-namely SDG 13 (Climate Action) and SDG 3 (Good Health and Well-Being). Furthermore, the industrial sector benefits significantly from digital interventions, as evidenced by Almeida and Okon (2024), who demonstrate that digital solutions optimize operational efficiencies and reduce carbon footprints within port enterprises, thereby contributing substantively to SDG 9 (Industry, Innovation, and Infrastructure). Sridhar *et al.* (2023) corroborate these findings by illustrating how digital technologies in the agri-food sector enhance resource use efficiency and productivity, reinforcing SDG 2 and SDG 12 targets.

Notwithstanding these benefits, the digitalization trajectory is accompanied by substantive challenges. In the energy sector, infrastructure inadequacies and human capital deficits hinder digital transformation, constraining progress towards SDG 7 (Affordable and Clean Energy) (Çelik *et al.*, 2022). However, Miskiewicz (2022) posits that the adoption of digital governance mechanisms could alleviate such impediments. Digitalization further augments educational (SDG 4) and healthcare services (SDG 3), improving accessibility and ameliorating spatial disparities, particularly within developing contexts (Gupta and Kumar, 2024; Zhou *et al.*, 2024).

Within public administration, digital technologies contribute to enhancing institutional effectiveness, fostering transparency, and strengthening cooperation, thus advancing SDG 16 (Peace, Justice, and Strong Institutions) and SDG 17 (Partnerships for the Goals) (Mburu and Munene, 2024; Onyango and Ondiek, 2021). Concurrently, the corporate sector increasingly employs digital reporting frameworks to improve the transparency and traceability of SDG-related performance, thereby bolstering investor confidence and facilitating sustainable finance and ESG initiatives (Awuah *et al.*, 2024).

Nonetheless, the literature also acknowledges the adverse implications of digitalization. Sparviero and Ragnedda (2021) caution that persistent digital divides exacerbate inequalities in access, skills, and infrastructure, undermining efforts to achieve SDG 10 (Reduced Inequalities). Moreover, Meskic *et al.* (2022) emphasize that effective digital transformation necessitates coordinated efforts across technological, legal, and administrative domains. Tlemsani *et al.* (2025) further highlight the salience of cultural and institutional contexts, particularly within Islamic economies, in shaping the alignment between digital transformation and sustainable development objectives. Collectively, these studies reveal that digitalization is a heterogeneous phenomenon, contingent upon local institutional and socio-economic conditions.

Mondejar *et al.* (2021) advance the discourse by advocating for a comprehensive and ethically grounded approach to digital transformation, integrating technical innovation with environmental and governance principles to foster the emergence of a "smart green planet." This underscores the imperative for strategic foresight in aligning digitalization with sustainability imperatives.

In sum, the interplay between digitalization and sustainable development is characterized by complexity and multidimensionality, encompassing both significant opportunities and emergent challenges related to inequality and governance. This necessitates the formulation of inclusive, context-sensitive, and ethically informed digital policies, alongside rigorous empirical and comparative research addressing long-term environmental impacts, governance integration, and social equity concerns.

2.3 The relationship between SDG and technological innovation

Technological innovation is widely recognized as a fundamental driver for achieving Sustainable Development Goals (SDGs), which holistically encompass environmental protection, economic growth, and social inclusion (Gupta and Vegelin, 2016). Advances in science and technology not only enhance productivity but also exert direct effects on critical sustainability dimensions, including resource efficiency, the transition to renewable energy sources, and the mitigation of environmental impacts.

The convergence of technological innovation and digital transformation has emerged as a crucial catalyst for the realization of the United Nations SDGs. Varriale *et al.* (2024) highlight the integral role of digital technologies within production systems in promoting sustainable industrial practices. Their findings demonstrate that digital innovation improves operational efficiency and reduces resource consumption, thereby aligning industrial growth with environmental sustainability objectives. Smart Technologies-such as automation and data-driven decision-making-are shown to contribute substantively to goals related to responsible consumption, climate action, and economic advancement.

In the context of small and medium-sized enterprises (SMEs), Wang and Zhang (2025) reveal how generative artificial intelligence (AI) can enhance sustainability performance within the Chinese tourism sector. Their research indicates that AI integration fosters improved environmental monitoring, optimized resource allocation, and enhanced customer experiences, supporting SDG 8 (Decent Work and Economic Growth) and SDG 9 (Industry, Innovation, and Infrastructure). These findings underscore the expanding recognition of emerging technologies as drivers of sustainability at both micro and macro levels.

Furthermore, the intersection of green finance, sustainable infrastructure, and digital innovation plays a vital role in advancing SDGs along the Belt and Road Initiative. Mahmood *et al.* (2024) argue that green technological advancements, bolstered by infrastructure investments, accelerate progress toward multiple sustainability targets. Similarly, Arzo and Hong (2024) contend that technological progress coupled with inclusive infrastructure fosters social mobility and equitable service access, key elements of SDG 10 (Reduced Inequalities) and SDG 11 (Sustainable Cities and Communities). Harfouche *et al.* (2024) further emphasize how data analytics and digital platforms facilitate evidence-based policymaking and enhance performance tracking toward SDG objectives.

Collectively, these studies position technological innovation not merely as a supporting instrument but as a strategic driver integral to sustainable development. However, the effectiveness of such innovations is contingent upon context-specific factors including institutional capacity, financial accessibility, and regional infrastructure disparities. Accordingly, leveraging the digital-SDG interface necessitates an integrated, cross-sectoral approach attuned to local development dynamics.

Xing *et al.* (2023) examined the combined effects of renewable energy policies and technological innovation on climate targets and sustainable development, revealing significant synergies in achieving SDG 7 (Affordable and Clean Energy), SDG 9, and SDG 13 (Climate Action). In parallel, Sinha *et al.* (2020) highlighted the importance of innovation-focused SDG policies tailored to Next-11 countries to enhance environmental quality. Hajikhani and Suominen (2022) employed machine learning techniques to systematically map scientific publications related to SDGs, demonstrating particularly strong linkages between technological innovation outputs and SDG 3 (Health), SDG 7, SDG 9, and SDG 13. This suggests that innovation is more intensively associated with certain sustainability goals.

Regarding the origin of green innovations, Walz *et al.* (2017) emphasize the critical role of public-private partnerships supported by R&D incentives in generating sustainable development-oriented technologies. Such innovations are essential for achieving SDG 12 (Responsible Consumption and Production) and SDG 13. In developing economies, Surana *et al.* (2020) highlight technology-based incubation centres in India as key facilitators of entrepreneurship and innovation, contributing positively to SDG 8, SDG 9, and SDG 17 (Partnerships for the Goals).

Dzhunushalieva and Teuber (2024) classified predominant SDG-related innovation themes via bibliometric analysis, identifying “clean energy technologies,” “waste management innovations,” and “financial technologies” as major focal points within sustainable innovation literature. Saha and Sinha (2020) investigated the relationship between technology policies and environmental quality across Asia-Pacific countries, demonstrating that the impact of green innovations on SDG 6 (Clean Water and Sanitation) and SDG 13 depends on the alignment of national policy frameworks. This highlights that both the presence of innovation and its policy integration are critical.

Van der Waal *et al.* (2021) examined multinational corporations' sustainable innovation outputs, advocating that corporate innovation strategies encompass environmentally friendly production alongside social responsibility and inclusion, thereby addressing SDG 10 and SDG 5 (Gender Equality). Additionally, frugal innovation-characterized by simple, low-cost technological solutions-has been shown to advance SDGs in developing contexts, particularly in health, water, and agriculture sectors (Ebolor *et al.*, 2022). Lekan *et al.* (2022) analysed Industry 4.0 technologies in construction, revealing applications such as smart construction sites, automation, IoT, and big data analytics that improve infrastructure quality and contribute directly to sustainable urbanization under SDG 9.

At the policy level, Kastrinos and Weber (2020) assessed the European Union's research and innovation policies, noting strong integration of the Green Deal and digital transformation agendas with SDGs. This underscores technological innovation as a tool serving SDG realization across corporate, public policy, and international cooperation domains. Lastly, Mariani *et al.* (2022) explored partnership initiatives in Europe, illustrating how collaborative innovation models generate collective value critical for SDG 17, emphasizing the necessity of cooperation across policy, business, and research sectors.

3. Methodology

3.1 Data

The aim of this study is to analyse the impact of digitalization and technological innovation on sustainable development goals (SDGs). In the study, 11 countries that joined the European Union (EU) after 2004 (Bulgaria, Czechia, Estonia, Croatia, Hungary, Lithuania, Malta, Poland, Romania, Slovakia and Slovenia) were selected as a sample and the data of these countries for the years 2000–2023 were used. Sustainable development goals are global goals determined by the United Nations (UN) and include wide-ranging areas such as economic growth, environmental sustainability and social development.

The study used the scores published by the Sustainable Development Report 2024 as the basis for measuring sustainable development goals. These scores are internationally accepted indicators that comprehensively evaluate the performance of countries in achieving the SDGs. The study used the digitalization indicator and the first independent variable as "Individuals using the Internet, % of population". This indicator is an important criterion widely preferred in the literature in terms of reflecting the level of digitalization of countries. A similar method has been used in previous studies to assess the level of digitalization. For example, researchers such as Demirci *et al.* (2021), Jóźwik *et al.* (2023), Rida *et al.* (2024), and Suárez-Álvarez and Vicente (2025) also used the internet usage rate as the basis for measuring digitalization and examined its effects on different variables such as economic development, sustainability and social development. In this context, it can be said that the selected indicator is a measure of digitalization that is accepted and widely used in the literature.

In the study, technological innovation was considered as the second main variable and patent application numbers were used in measuring this concept in line with the literature. Patent data are considered as an important indicator reflecting the output of innovative activities and provide meaningful information about the technology production capacity of countries and the level of development of their knowledge-based economic structures. In this context, the patent number indicator used in the study was evaluated as a concrete and comparable measure of technological innovation. It is seen that patent data is used in the literature in a similar way to measure technological innovation. For example, in the studies of Ullah *et al.* (2023), Khan *et al.* (2024), Dogan *et al.* (2024), Saadaoui *et al.* (2024), Ullah *et al.* (2024), Jóźwik *et al.* (2024), Georgescu *et al.* (2025), Yıldırım *et al.* (2025) and Fan *et al.* (2025), patent application numbers are also used to determine the level of technological innovation. In this context, the measurement approach preferred in our study is based on solid foundations both theoretically and empirically and is consistent with previous academic studies. As a result, a summary of the variables used in the study is shown in Table 1 and the research model is shown in Equation (1).

$$SDG_{i,t} = \beta_0 + +\beta_1 DG_{i,t}\beta_2 TI_{i,t} + \varepsilon_{i,t} \tag{1}$$

Quantile regression and Kernel Regularized Least Squares (KRLS) were chosen for this study due to their complementary strengths in capturing complex relationships within the data. Quantile regression allows us to analyse the effects of explanatory variables not only on the mean but across the entire distribution of the dependent variable, revealing heterogeneous impacts at different points, which is particularly useful in understanding variations in Sustainable Development Goals (SDG) performance among countries. KRLS, on the other hand, is a flexible, nonparametric method that models potentially nonlinear and interactive effects without imposing strict functional form assumptions. This flexibility enables us to uncover nuanced patterns and complex relationships between digitalization, technological innovation, and SDGs that traditional linear models might overlook. Together, these methods provide a robust analytical framework that enhances the depth and reliability of our empirical findings.

3.2 Method

In the study, cross-sectional dependence analysis was performed first. In this context, the LM test developed by Breusch and Pagan (1980), the scaled LM test proposed by Pesaran *et al.* (2004) and the bias-corrected LM (LMadj) test developed by Pesaran *et al.* (2008) are used to determine the cross-sectional dependence, respectively. The calculation methods of the relevant tests used in the study are detailed in Equations (2)–(5).

$$LM = T \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \widehat{\rho}_{ij}^{\,2} \tag{2}$$

$$\mathrm{CD_{LM}} = \sqrt{\frac{1}{\mathrm{N(N\text{-}1)}}} \sum_{\mathrm{i=1}}^{\mathrm{N\text{-}1}} \sum_{\mathrm{j=i+1}}^{\mathrm{N}} \left(\mathrm{T}\widehat{\rho}_{\mathrm{ij}}^{2}\text{-}1\right) \tag{3}$$

$$CD = \sqrt{\frac{2T}{N(N-1)}} \left(\sum_{i=1}^{N-1} \sum_{j=1+1}^{N} \widehat{\rho}_{ij} \right) \tag{4}$$

Table 1. Summary of variables

Variables	Symbol	Measure	Source
Sustainable Development	SDG	SDG Index Score	Sustainable Development Report 2024
Digitalization	DIG	Individuals using the Internet (% of population)	WDI
Technological innovation	TIN	Patent applications, nonresidents	WDI

Source(s): Authors' own work

$$LM_{adj} = \left(\frac{2}{N(N-1)}\right)^{½} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \hat{\rho}_{ij}^{2}(T-K-1)\frac{\hat{\rho}_{ij} - \hat{\mu}_{Tij}}{v_{Tij}} \sim N(0,1) \tag{5}$$

Considering the horizontal cross-sectional dependence, the CADF (Cross-Sectionally Augmented Dickey-Fuller) unit root test developed by Pesaran (2007) was applied to test the stationarity properties of the panel data set. The calculation method of this test is summarised in Equations (6)–(9).

$$\Delta y_{it} = \alpha_i + \beta_i y_{i,t-1} + u_{it} \tag{6}$$

$$u_{it} = \gamma f_t + \varepsilon_{it} \tag{7}$$

$$\Delta y_{it} = \alpha_i + \rho_i y_{i,t-1} + d_0 \overline{y}_{t-1} + d_1 \Delta \overline{y}_t + \varepsilon_{it} \tag{8}$$

$$\Delta y_{i,t} = \alpha_i + \rho_i y_{i,t-1} + c_i \overline{y}_{t-1} + \sum\nolimits_{j=0}^{p} d_{i,j} \Delta \overline{y}_{t-j} + \sum\nolimits_{j=0}^{p} \beta_{i,j} \Delta y_{i,t-j} + \mu_{i,t} \tag{9}$$

Kernel-based Regularised Least Squares (KRLS) is a nonparametric machine learning technique that combines ridge regression and kernel methods to estimate nonlinear and heterogeneous effects. The mathematical structure and optimisation process of this method is presented in Equation (10).

$$\min{}_{\alpha} ||\mathrm{Y} - \mathrm{K}\alpha||^2 + \lambda\, \alpha^{\mathrm{T}} \mathrm{K}\alpha \tag{10}$$

In the KRLS framework, Y represents the outcome vector, K is the kernel matrix derived from the explanatory variables (typically via a Gaussian kernel), α denotes the vector of dual coefficients to be estimated, and λ is the regularization parameter controlling model complexity. The first term ensures data fit, while the second penalizes complexity to avoid overfitting. Predictions are computed as f(x) = K(x, X)α. KRLS is effective in modelling nonlinear, context-sensitive relationships, allowing marginal effects to vary across observations. Quantile Regression extends classical regression by estimating conditional quantiles instead of the mean, capturing how covariate effects differ across the outcome distribution. The corresponding optimization is presented in Equation (11).

$$\min{}_{\beta} \sum \left[\tau * \left|\mathrm{y_i} - \mathrm{x_i^T}\beta\right| \text{if } \mathrm{y_i} \geq \mathrm{x_i^T}\beta + (1-\tau) * \left|\mathrm{y_i} - \mathrm{x_i^T}\beta\right| \text{if } \mathrm{y_i} < \mathrm{x_i^T}\beta\right] \tag{11}$$

In quantile regression, y_i is the dependent variable, x_i is the vector of explanatory variables, β is the coefficient vector, and τ ∈ (0,1) denotes the quantile of interest. Unlike ordinary least squares (OLS), which minimizes the sum of squared residuals, quantile regression minimizes a weighted sum of absolute residuals. This approach enhances robustness to outliers and heteroskedasticity, making it suitable for analysing how covariate effects vary across the distribution of the outcome variable.

In the last part of the study, the panel causality test developed by Dumitrescu and Hurlin (2012) is used to assess the causality link between the variables. This test, which is specific to the panel data structure, is a generalization of the classical Granger causality approach and allows for more robust and reliable inferences by taking into account the heterogeneity in the slope coefficients of different units and possible horizontal cross-sectional dependence. The mathematical representation of this test is presented in Equation (12).

$$y_{i,t} = \alpha_i + \sum_{k=1}^{K} \beta_{ik} y_{i,t-k} + \sum_{k=1}^{K} \gamma_{i,k} X_{i,t-k} + \varepsilon_{it} \tag{12}$$

4. Findings

In this part of the research, empirical findings on the effects of digitalization and technological innovation on sustainable development goals are given for 11 countries that joined the European Union after 2004.

Table 2 analyses the average scores of the 11 countries that joined the European Union after 2004 on the Sustainable Development Goals (SDGs) over the 2000–2023 period. The data in Table 2 reveal the long-term sustainable development performances of the countries comparatively. According to the average SDG scores, the highest performing countries are Czechia (78.88), Slovenia (78.61) and Hungary (78.40), while the lowest average scores are observed in Romania (73.25), Malta (73.05) and Bulgaria (72.98). This shows that Central European countries such as the Czech Republic and Slovenia are pursuing more stable policies in terms of environmental and social sustainability, whereas some South-Eastern European countries need further improvement in these areas (see Table 3).

The standard deviation values for the dataset provide information on fluctuations in sustainable development indicators across countries. For example, while SDG scores vary more over the years in countries such as Croatia (std. dev. 3.32) and Romania (3.12), this variability is more limited in countries such as Hungary (1.48) and Slovakia (1.89). This shows that some countries adopt more stable and sustained strategies in their sustainable development policies, while in some countries the impact of the policies implemented

Table 2. Average SDG index scores of the countries

	Mean	Std_dev	Min	Max
Bulgaria	72.97676	2.230485	68.34276	75.53739
Croatia	77.60834	3.315345	73.6657	82.34675
Czechia	78.8818	2.21726	74.95115	82.2177
Estonia	76.267	3.065002	70.84694	80.51091
Hungary	78.3981	1.480022	75.52967	80.67944
Lithuania	75.26733	1.948447	71.31858	78.1171
Malta	73.04899	2.676176	69.47961	76.95196
Poland	77.79995	2.537243	73.90189	81.69258
Romania	73.24899	3.122319	68.3223	76.73204
Slovak Republic	77.07976	1.894723	73.86766	79.74113
Slovenia	78.60672	1.975152	75.08254	81.34277

Source(s): Authors' own work

Table 3. CDS test results of variables

	Breusch-pagan LM	Pesaran scaled LM	Bias-corrected scaled LM	Pesaran CD
SDG	1064.49*	3.11*	2.85*	6.95*
DG	1150.69*	3.23*	2.97*	7.23*
TI	740.63*	2.59*	3.33*	5.44*

Note(s): *denotes significance at %1 level
Source(s): Authors' own work

varies more over time. In general, the average scores of these countries are above 70, indicating a significant improvement in their sustainability policies after EU accession.

The correlation matrix in Figure 1 shows the linear relationships between SDG and Digitalization (DG) and Technological Innovation (TI) variables. Accordingly, a positive and strong correlation (0.75) is observed between SDG and DG. This situation reveals that increasing the level of digitalization may have a supportive effect on achieving sustainable development goals. In this context, strengthening digital infrastructures and implementing digital transformation policies may have the potential to improve countries' SDG performance. The fact that the correlation between SDG and TI is negative and very weak (−0.14) indicates that there is no significant relationship between the two variables. In this context, linking technological innovation with SDG performance has not produced meaningful results.

The results of the cross-section dependence test in Table 2 show that there is statistically significant cross-section dependence at the 1% significance level for all variables. Breusch-Pagan LM, Pesaran scaled LM, bias-corrected scaled LM and Pesaran CD tests each produced significant results for SDG, DG and TI variables. Particularly high test statistics indicate the presence of similar shocks or common dynamics across countries. This indicates that countries do not act independently in the panel data set, but there is a strong simultaneity or interaction between them. Therefore, it is critical to prefer methods that take this dependence into account in panel analyses both from a methodological point of view and in terms of the reliability of the findings.

According to the CADF unit root test results presented in Table 4, statistically significant stationarity is observed for all variables. The test statistics of SDG, DG and TI variables are negative and significant and have low p-values that are significant at the 1% level, respectively.

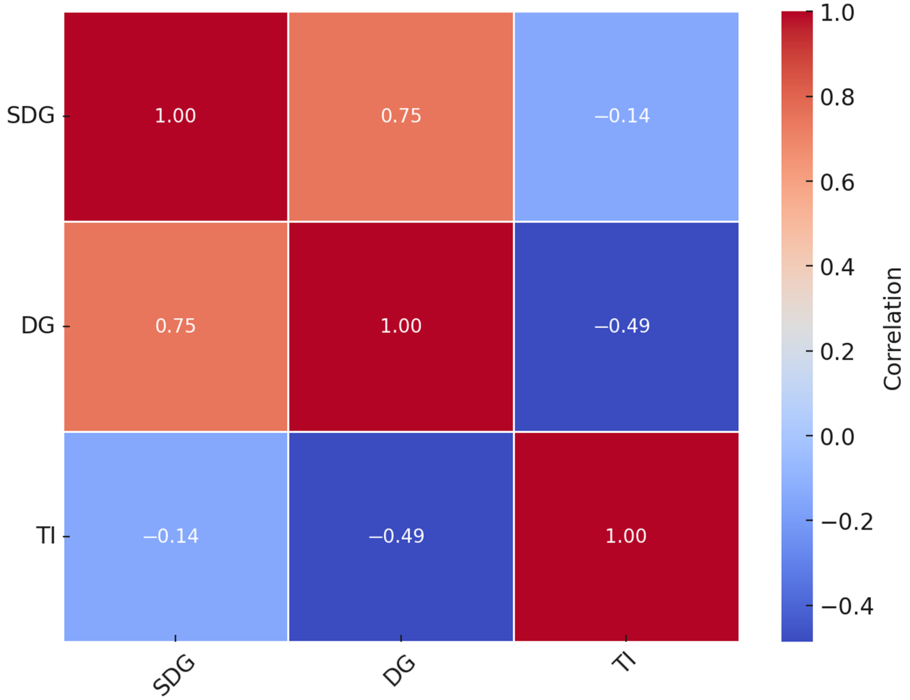

Figure 1. Correlation analysis. **Source(s):** Authors' own work

Table 4. CADF unit root test results

	I(0) stat.	I(0) prob.
SDG	−4.2430	0.0010
DG	−5.6110	0.0000
TI	−6.5670	0.0000

Source(s): Authors' own work

These findings indicate that the variables are stationary at their level values (I(0)) and these variables can be directly used in panel data analyses. Moreover, the fact that the CADF test takes into account the horizontal cross-section dependence increases the reliability of the stationarity results obtained. Therefore, it is possible to conduct analyses with their level values without any differencing at the modelling stage.

In Table 5, the Kernel Regularized Least Squares (KRLS) method applied in the study made it possible to evaluate the effects of digitalisation and technological innovation variables on sustainable development performance within the framework of non-linear structures and heterogeneous effects. The high R-square (R^2) value obtained from the model shows that digitalization and technological innovation have a strong predictive capacity in explaining SDG performance. The relatively low Leave-One-Out Loss value obtained from the KRLS model shows that the model has a high prediction success not only on the data but also on out-of-sample observations. This result shows that the generalization capacity of the model is strong.

Regarding the structural features of the model, the high Effective Degrees of Freedom value reveals that the KRLS model goes beyond the classical linear models and offers a very flexible structure in capturing complex relationships between variables. This flexibility is consistent with the findings that the effects of digitalisation and technological innovation are not fixed, but vary across countries, years or level of development. Moreover, while the sigma parameter (the spread width of the kernel function) reflects the extent to which the model is sensitive to local effects, the moderate value obtained indicates that the effects vary not only at the global level but also on the basis of certain subgroups (e.g. countries with low or high SDG scores).

Finally, the lambda value close to zero indicates that the model provides a high level of fit to the data. This finding indicates that the data structure allows the model to make free estimation and in this framework, potential non-linear interactions between variables are captured more accurately. In sum, the model fit tests reveal that the effects of digitalization and innovation on the SDGs are not static or unidirectional, but vary depending on the context, level and policy structure.

The quantile regression results presented in Table 6 reveal important findings on how the impact of digitalization (DG) and technological innovation (TI) on sustainable development performance (SDG) varies at different points of the distribution. The results show that the, e.g. and TI variables exhibit positive and statistically significant effects at all quantile levels. In particular, the digitalization variable has a strong and significant effect at all levels of the distribution, with a gradual decreasing trend between the lowest (10%) and the highest (90%) quantile.

The high coefficient observed in the 10% quantile of DG indicates that digitalization has a stronger impact on country-groups with relatively lower performance in terms of sustainable development. This suggests that the returns of digital infrastructure investments towards sustainable development are more pronounced in the early stages and that these countries benefit more from digitalization. However, as we move towards the upper quantiles of the

Table 5. KRLS estimation

Variable	Avg. effect	P10	P20	P30	P40	P50	P60	P70	P80	P90
DG	−0.756	0.000	1.127	0.000	0.000	16.223	0.000	0.000	−0.500	7.453
TI	0.165	0.000	−0.003	0.000	0.000	−0.848	0.000	0.000	9.002	3.400
Specification tests										
Lambda	: 0.000	Tolerance	: 0.011	Eff. df	: 242.00	R^2	: 0.785	Looloss	: 195.40	

Source(s): Authors' own work

Table 6. Quantile regression

Quantile	DG	TI	Pseudo R-squared
0.1	0.11411***	0.00092***	0.445221451
0.2	0.1114***	0.00093***	0.41874317
0.3	0.11814***	0.00100***	0.387364056
0.4	0.11982***	0.00098***	0.367397523
0.5	0.12680***	0.00106***	0.355631915
0.6	0.13194***	0.00099***	0.364175525
0.7	0.11845***	0.00077***	0.378364866
0.8	0.10514***	0.00058***	0.380082675
0.9	0.09693***	0.00033*	0.376560474

Source(s): Authors' own work

distribution, there is a noticeable decrease in the coefficient of DG, indicating that the impact of digitalization decreases after a certain level of saturation.

Similarly, the TI variable also presents positive and statistically significant effects at all quantile levels, but its impact is relatively lower and has much smaller coefficients compared to digitalization. This suggests that the impact of technological innovation on sustainable development is more limited and marginal, especially in groups with lower SDG performance levels. Moreover, the impact of TI tends to decrease as we move towards higher quantiles. This suggests that innovation may have an impact on SDGs through indirect channels rather than directly.

The gradual decline in the digitalization coefficient observed in the quantile regression analysis can be interpreted as reflecting diminishing marginal returns. This indicates that in countries with lower levels of digitalization, improvements in digital infrastructure and capabilities have a more pronounced and stronger impact on achieving sustainable development goals. However, as the level of digitalization increases, the additional gains tend to diminish due to reaching a saturation point in the benefits to sustainability performance. On the other hand, the weaker effects of technological innovation at higher quantiles may suggest that in more developed economies, the contribution of innovation to sustainable development is constrained by structural and institutional factors, technology transfer challenges, and the quality of innovation. Furthermore, it implies that in these countries, the focus should shift from the quantity of innovation, such as patent counts, to its quality and effective implementation, as mere patent numbers may not fully capture the true contribution to sustainable development. These findings highlight that the heterogeneous nature and varying development levels of the 11 countries play a crucial role in shaping the impact of digitalization and innovation on sustainable development outcomes.

The declining coefficients of digitalization (DG) across quantiles can be interpreted in economic terms as diminishing marginal returns. While the contribution of digitalization to SDG scores is stronger in countries at the lower quantiles, the effect becomes more limited at higher quantiles. This suggests that after a certain threshold of digitalization is reached, additional gains tend to diminish. Furthermore, the observed heterogeneity is closely linked to the structural characteristics of the new EU member states. In these countries, where digital infrastructure is still developing and innovation capacity varies significantly, the effects differ across quantiles. Overall, the findings indicate that the impacts of digitalization and innovation on SDGs are unidirectional but vary according to context, level of development, and policy structures.

When the Pseudo R-squared values for the model performance are analysed, it is seen that the level of explanatory power is higher in the lower quantiles (especially between 10-30%). This indicates that the impact of digitalization and innovation on sustainable development is more explanatory in low-performing groups; in other words, these factors are less effective in explaining the SDG variance in high-performing countries.

In conclusion, the quantile regression findings suggest that digitalization is an effective tool for achieving sustainable development goals, playing a more critical role, especially for low-development countries. Technological innovation has a more limited impact and needs to be integrated with institutional, infrastructural and strategic support to increase its impact. These findings suggest that policymakers need to prioritise investments in digitalization and align innovation policies with a more inclusive and sustainable development perspective.

Table 7 Dumitrescu-Hurlin panel causality test results reveal the direction of the relationship between digitalization (DG) and sustainable development goals (SDG). According to the findings, there is a significant and unidirectional causality relationship from digitalization to sustainable development (Z-bar = 6.964, $p < 0.01$). This result shows that strengthening digital infrastructure, expanding internet access and investments in information technologies play an important role in increasing sustainable development performance. On the other hand, there is no causality relationship from sustainable development indicators to digitalization ($p = 0.682$), suggesting that sustainability policies do not directly trigger digital transformation.

Similarly, when the relationship between technological innovation (TI) and SDGs is analysed, there is a significant causality from technological innovation to sustainable development (Z-bar = 2.39, $p = 0.044$). This shows that R&D activities, patent generation and technology development initiatives make significant contributions to achieving sustainable development goals. On the other hand, the impact of SDGs on innovation is not significant ($p = 0.889$). Overall, the results reveal that digitalization and innovation are supportive elements of sustainable development, but these two factors are not directly affected by sustainability.

5. Discussion and suggestions

The main purpose of the study is to evaluate the effects of digitalization and technological innovation on sustainable development in 11 countries that joined the European Union after 2004. The analyses conducted in light of the panel data for the period 2000–2023 reveal the contribution of digitalization and innovation to sustainable development in these countries from different perspectives. The findings show that digitalization significantly increases sustainable development performance, while innovation plays a more limited but supportive role. The results obtained show that the effect of digitalization on sustainable development varies according to the development level of country groups. While the effect of digitalization is much more pronounced in countries with relatively lower sustainable development scores, it is observed that this effect decreases over time in countries with high performance. This situation shows that digital infrastructure investments provide higher benefits in countries with low initial levels, but the returns decrease marginally after a certain threshold level is reached.

Table 7. Causality test results

	W-bar	Z-bar	p
SDG↛DG	0.651	0.782	0.682
DG↛SDG	3.951	6.964	0.000
SDG↛TI	0.492	0.609	0.889
TI↛SDG	2.01	2.39	0.044

Note(s): The maximum lag length is taken as 1
Source(s): Authors' own work

The effect of technological innovation, on the other hand, remained at a lower level compared to digitalization. Although innovation also produces positive effects on sustainable development, it is understood that this effect is more indirect and low-intensity. The impact of innovation is much lower than that of digitalization, especially in countries with low levels of development. This finding reveals that innovation alone may not be sufficient to achieve sustainability goals and must be supported by appropriate infrastructure, institutional capacity and governance mechanisms for effective results.

Another important finding obtained from the analysis is that digitalization has a one-way effect mechanism on sustainable development. In other words, while digitalization directly affects development goals, the level of sustainable development has not been found to have a significant effect on the digitalization process. This situation shows that digital transformation serves as a basic tool and leverage in terms of sustainability. However, in the opposite direction, sustainability policies do not have a strong function in accelerating digitalization. Similarly, it has been observed that technological innovation has a significant effect on sustainable development. The development of innovative technologies, especially environmentally friendly production processes, resource-efficient applications and green solutions strengthen this effect. However, this effect is not widespread and strong as in digitalization; it rather occurs in certain contexts and with supporting factors. Therefore, institutional reforms, directing R&D investments and implementing sustainability-focused innovation policies are necessary to increase the impact of innovation.

As a result, the findings of the study underscore that digitalization emerges as a pivotal driver of sustainable development, while technological innovation serves as a complementary enabler that amplifies this impact. Particularly for countries that joined the European Union after 2004 and are still navigating a transitional phase, the effective structuring of digital transformation policies is crucial-not merely as a lever for economic growth, but as a multifaceted tool to advance social inclusion, environmental sustainability, and institutional quality in governance. To harness the full potential of digitalization, it is imperative to move beyond infrastructure development and emphasize human capital and institutional capacity. This includes investing in digital literacy at all educational and demographic levels, promoting widespread and inclusive e-government services, and ensuring equitable access to digital technologies and platforms across regions and communities. From a policy perspective, the study highlights the need for digitalization strategies to be closely aligned with the United Nations Sustainable Development Goals (SDGs). Rather than pursuing digital transformation in isolation, these strategies should be embedded within a broader sustainability framework. In parallel, technological innovation policies should adopt a holistic perspective-one that not only enhances productivity and competitiveness, but also integrates environmental stewardship and social well-being as core objectives. Considering the European Union’s long-term strategic agendas, such as the European Green Deal and the Digital Compass, it becomes essential for post-2004 EU member states to synchronize their national policies with these overarching goals. A coherent and integrated policy alignment will not only enhance these countries’ contributions to the EU-wide sustainability transition but also strengthen their resilience, global competitiveness, and socio-economic cohesion in the long run.

The 11 post-2004 EU accession countries included in this study exhibit varying levels of development and digital infrastructure capacity in achieving the Sustainable Development Goals (SDGs). Therefore, it is crucial for policymakers to tailor sustainable development strategies by taking into account each country’s development stage, digitalization infrastructure, and innovation capacity. For countries with relatively low digital infrastructure and skills, priority should be given to investments that enhance digital inclusion. In this context, expanding e-government services, promoting digital literacy programs, and increasing broadband internet access emerge as critical factors for improving both economic growth and SDG performance. On the other hand, in countries where digitalization and technological innovation are more advanced, policy recommendations should focus on the adoption of innovative technologies, the promotion of green innovations, and the enhancement of sustainability-oriented institutional collaborations. Furthermore, alongside improving digital infrastructure quality and digital skills, these countries should aim to disseminate sustainable production and consumption models at the sectoral level. Ultimately, flexible and targeted policies developed with consideration of structural differences among countries will maximize the positive impacts of digitalization and technological innovation on SDGs.

This study has some limitations. First of all, the digitalization and technological innovation indicators used in the analysis were represented by a limited number of variables. While digitalization was measured only by the internet usage rate, innovation was expressed with a one-dimensional indicator such as patent applications. This situation may not fully reflect the multidimensional nature of digitalization and innovation. In addition, only 11 countries and a 24-year period were considered in the study, and different results may be obtained when the sample scope is expanded. Future research can increase the explanatory power of the model by considering more comprehensive digitalization and innovation indicators (e.g. e-government index, digital public services, private sector R&D expenditures, etc.). In addition, with more advanced models that integrate interactive factors such as structural breaks, institutional quality, and environmental regulations, the effects of digitalization and innovation on sustainable development can be assessed in a more holistic manner.

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