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From Innovation to Sustainable Competitiveness: Enhancing the Role of Education and the Green-Digital Transition in Central and Eastern Europe

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Abstract

Technological innovation and digital transformation are increasingly viewed as key drivers of competitiveness and environmental transformation in Central and Eastern Europe (CEE). Yet the extent to which innovation-driven performance also translates into broader sustainability improvements remains insufficiently understood. The current study focuses on determining the link between innovation capabilities, education system, digitization, and sustainable performance for CEE countries in the time frame of 2017 to 2024. Panel data were collected from a multivariate panel dataset created from the European Innovation Scoreboard, with sustainable performance evaluated by the environmental sustainability index, technology for the environment, and PM2.5 emissions. To guarantee the reliability of the results, several approaches for estimating the relationships between variables were used, such as random effects panel regression, pooled OLS estimation with Driscoll-Kraay and panel-corrected standard errors, and robust regression with Huber and biweight iterations. In addition, structural equation modeling (SEM) is employed to identify latent interdependencies among innovation, digitalization, education, and sustainability indicators. The results indicate that stronger innovation capacity and digitalization are associated with improvements in sustainability outcomes of CEE countries, with education playing a decisive role in enhancing this performance. Environmental improvements are even more noticeable in countries that have higher degrees of green and digital innovations. The present research makes a valuable contribution to existing literature in the field, as it presents a comprehensive examination of the innovation-greening-digitalization relationship in CEE countries by using an eclectic approach of multiple econometric and SEM analysis techniques.

Keywords: technological innovation, digitalization, environmental sustainability, education, econometric modeling

JEL: C21, O31, Q56, R12

Introduction

Technological innovation and digitalization have emerged as major pillars of economic change in the globalized digital economy, especially in response to increased levels of competitive pressures, green transition imperatives, and structural asymmetries between European economies. Innovation is a major asset in recent times, not only as a means of improving productivity and market dynamism but also as a strategic tool to improve environmental sustainability and resilience. This discussion has particular relevance with regard to Central and Eastern Europe (CEE), considering the fact that these countries face the challenge of striking the right balance between the pursuit of innovation and digitalization, on the one hand, and the need to meet the imperatives of sustainability which are part of the broader European policy agenda on the other hand. The relevance of this issue cannot be overemphasized, particularly with regard to the CEE economies, considering the fact that despite the higher levels of integration of these economies into the European and global value chains, significant disparities exist with regard to the levels of innovation, digitalization, institutional development, and market sophistication, among others. Thus, while the impact of innovation on development cannot be linear, with the former influencing the latter in many dimensions, such as capabilities, export performance, labor, and spillovers to neighboring countries, technological progress may impact development in many dimensions. At the same time, it is not evident that all economies benefit equally from such phenomena, as the benefits of innovation and digitalization may depend on the level of green, financial, and organizational capabilities accumulated in these economies.

From this existing literature, significant insights into these developments can be derived, although they remain fragmented in several respects. First, a significant amount of the literature confirms that digitalization and innovation are key drivers of enhanced sustainability in terms of cleaner production, green innovation, and environmental performance. Second, a series of contributions emphasizes their impact on competitiveness, renewal of firms, and performance enhancement in terms of digitalization, Industry 4.0, and innovation strategies. Yet, in most of these contributions, these dynamics are analyzed in isolation from each other, and environmental and economic effects are rarely analyzed in a unified manner. Moreover, whereas a large body of this literature is based on firm-level or cross-country analyses or broader international samples, there is a relatively limited amount of research on the specific case of CEE.

Finally, this literature still devotes relatively little attention to two key issues that are of significant concern to this particular region. First, the focus on spillovers and international border effects remains limited, especially in light of the strong interdependencies in terms of trade, policies, and geography, which define CEE. This points to the fact that, for instance, innovation and digitalization in one of the countries in the region will lead to noticeable effects in the neighboring countries. Second, the focus on distributional heterogeneity and the education dimension has been limited. This is surprising, considering that differences in skills development, endowments, and performance can have implications for the country's ability to leverage innovation and digitalization for enhanced market performance and sustainability.

In light of this context, the current research aims to explore the innovation-performance-sustainability link in CEE economies between 2017 and 2024. In particular, it aims to investigate whether innovation potential, digitalization, and education contribute to improving environmental performance. The timeframe from 2017 to 2024 is used because it represents an important phase of the development of the dual transition strategy of the European Union (EU) based on examples of policy milestones such as the European Green Deal, the European Climate Law, and the Digital Europe Programme (2021–2027). For this reason, the research period is especially relevant for studying how the relationships between innovation, digitalization, and education impact sustainability. In addition, the selection of CEE economies as the object of analysis is justified due to their experience of development after the socialist period, when there was a rapid integration into European and international production networks coupled with significant structural differences regarding innovation, digitalization, education, and sustainability.

The originality of this research is based on the incorporation of two analytical dimensions. First, this research applies panel data regression models Random Effects (RE), Pooled OLS, Panel-Corrected Standard Errors (PCSE), and Robust Regression (RREG) to analyze direct effects in the synergy between digitalization–innovation–education and environmental sustainability. Second, this research applies structural equation modeling (SEM) with latent variables to assess the overall impact on innovation's performance. From an analytical point of view, the current study is based on a complex panel of indicators that are derived from the European Innovation Scoreboard and include digital and innovation indicators, education-related indicators, and environmental data, in terms of environmental performance, environment-related technologies, and fine particulate air emissions.

The novelty of the paper resides in its contribution to the literature in several important ways. First, it develops an integrated analytical framework that jointly examines innovation capacity, digitalization, education, and environmental sustainability within the specific context of CEE countries. In this way, the study bridges the research gap that exists in the current literature, where these dimensions are commonly considered independently, not as interdependent factors that contribute to sustainable change. Additionally, the article extends the current literature by accounting for direct and total effects using latent variable modeling, which provides a deeper analysis of the links between innovation, digitalization, human resources, and sustainable performance. The article also contributes to the existing body of knowledge on CEE countries, providing insights for policymakers concerning the importance of education, digital readiness, and green innovation for sustainable development.

The remainder of the paper is structured as follows: Section 2 presents the theoretical framework and literature review related to innovation, digitalization, performance, and sustainability. Section 3 discusses the data, variables, and methodological approach. Finally, Section 4 presents the empirical results and direct and overall effects. Section 5 concludes the paper, providing a summary of the main results, as well as policy implications, research limitations, and future research avenues.

Theoretical Framework and Literature Review

The most recent literature increasingly treats technological innovation and digitalization as driving forces of competitiveness and sustainability. However, there is limited conclusive evidence of whether digitalization and innovation drive market performance, employment dynamics, and sustainability simultaneously. This is particularly relevant for CEE, which faces challenges in developing innovation potential, market performance, and sustainability, particularly in a context of uneven development. The literature generally suggests that digitalization and innovation potential affect productivity and sustainability in a conditional and heterogeneous way, but not in an integrated way that is particularly relevant to CEE. It is the unique developmental paths of the CEE countries that make it an important empirical setting for this study. Specifically, they experienced fast economic integration into international and European value chains, despite still holding certain differences concerning their innovativeness, digitalization, educational systems, institutional quality, and environmental management.

At the macro level, digitalization, green innovation, renewable energy, and financial development have been found to enhance environmental sustainability, while European evidence also links digitalization and e-governance to carbon neutrality and broader sustainability progress (Karlilar Pata, Balcilar, and Emir 2023; Wang et al. 2025a). Within the EU, digitalization, innovation, and environmental policy have been shown to reinforce sustainable production, suggesting that technological upgrading may support the ecological transition at the country level (Guaita Martínez et al. 2022; Mircea et al. 2023). The findings of these empirical studies converge to propose the following hypothesis: digital transformation can improve sustainability performance through the development of digital capabilities, organizational flexibility, and strategic alignment; simultaneously, industrial digitalization can improve environmental performance through the implementation of cleaner production technologies and structural upgrading (Wen, Lee, and Song 2021; Lu, Li, and Yuen 2023).

The findings of other empirical studies propose the following hypotheses: the digital economy can promote green innovation; digital capabilities can foster green collaborative innovation through learning and organizational orientation, thus supporting the argument for the sustainability benefits of innovation and digitalization (Chen et al. 2025; Xie and Wang 2025). The competitiveness dimension of the nexus is equally important for this study. Research on SMEs shows that digitalization can stimulate product and process innovation, although the magnitude of the effect depends on firm characteristics and internal R&D structures (Radicic and Petkovic 2023). AI readiness has also been associated with stronger international performance, suggesting that digital preparedness may improve firms' external competitiveness (Denicolai, Zucchella, and Magnani 2021). More strategic contributions argue that digital servitization, ecosystem orchestration, and Industry 4.0 strengthen value creation, knowledge integration, and capability development, thereby improving the foundations of long-term competitiveness and innovation-based renewal (Kohtamäki et al. 2019; Linde et al. 2021).

This argument is reinforced by work showing that Industry 4.0 functions as a roadmap to sustainable innovation in manufacturing (Ghobakhloo et al. 2021). Review-based studies further support the systemic relevance of digitalization, arguing that digital tools can support the transformation of sustainable business models and broader "digital sustainability," although only under appropriate organizational and strategic conditions (Guandalini 2022; Broccardo et al. 2023). Reviews focused on the SDGs, circular economy, and SMEs similarly suggest that digital technologies can contribute to a sustainable transition, but only when combined with governance quality, implementation capacity, and organizational readiness (Castro, Fernández, and Colsa 2021; Chauhan, Parida, and Dhir 2022). Related work suggests that organizational culture affects the link between sustainability and digitalization in small and medium-sized enterprises (SMEs), which supports the idea that the results of innovation activities are contingent on factors beyond the simple use of technology (Isensee et al. 2020).

To add to the narrative overview and provide a more structured overview of the field, Figure 1 presents a VOSviewer keyword co-occurrence map, which has been generated on the basis of articles in the Web of Science database with the Topic query "digitalization AND innovation AND sustainability".

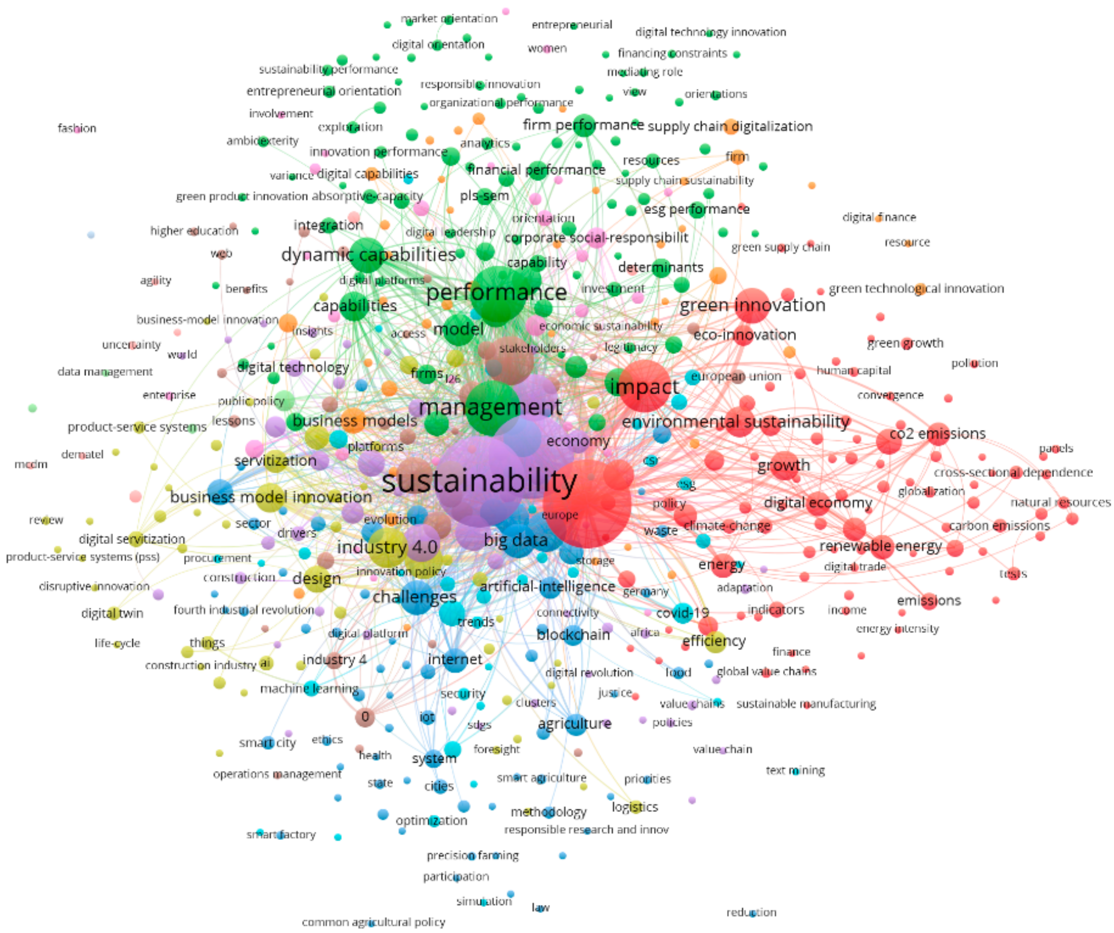


Figure 1. Keyword co-occurrence map of the literature on digitalization, innovation, and sustainability based on Web of Science records
Source: authors' elaboration in VOSviewer.

Beyond its descriptive role, the bibliometric map helps position the research within the broader literature and clarifies the contribution of the analysis. As shown in Figure 1 below, the existing literature focuses predominantly on a highly integrated set of topics related to sustainability, performance, the digital economy, green innovation, and growth. At the same time, the diagram reinforces the point that the academic discourse in this area is relatively disjointed, given that many scholars have written papers focusing on one or two aspects of the relationships between the three variables. This fact is particularly pertinent to this study, which attempts to integrate all these variables. While previous research has explored the connections between digitalization, innovation, and sustainability from an environmental, management, or competitive perspective, little effort has been made to determine how these interact with performance, employment, interdependencies, and regional differences. Thus, the bibliometric analysis supports the rationale of the research by showing both the growing importance of the topic and the need for a more integrated analytical framework.

For CEE countries, one of the key findings in the literature is that the effects of innovation and digitalization are not homogeneous. Quantile-based analysis has found that the effects of digitalization, green investment, and financial development on sustainability are not uniform, and the effects tend to be more pronounced in countries with more advanced complementary capabilities (Hung 2023; Wang et al. 2025b). Similarly, heterogeneous effects have been found in studies demonstrating that digitalization may increase emissions unless counteracted by green technological innovation or the use of renewable energy, suggesting that technological upgrade is effective only in certain structural conditions (Li et al. 2025; Rani et al. 2025). Country- and context-specific studies have found that digital infrastructure can have a synergistic effect on coordination, productivity, and sustainability, but these effects are highly contingent upon the structural and contextual conditions (Moshood et al. 2024; Manu and Asongu 2025).

Nonetheless, the literature maintains its fragmented focus on the innovation–performance–sustainability triad, with some research focusing on sustainability outcomes, others on green innovation and competitiveness, and the majority using non-spatial methods (Denicolai, Zucchella, and Magnani 2021; Chen et al. 2025). This is particularly limiting for CEE countries, where geographic proximity, trade, education differences, and EU policy spillovers are highly relevant, especially considering that the current literature does not test the capacity of innovation and digitalization in one country to enhance the market performance and sustainability of neighboring countries (Guaita Martínez et al. 2022; Wang et al. 2025a).

Data and Methodology

Data and Indicators Used in the Empirical Analysis

The empirical analysis is based on a country-level panel dataset provided by the European Innovation Scoreboard (EIS). The dataset covers ten Central and Eastern European countries: Bulgaria, Czechia, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, Slovakia, and Slovenia, analyzed over the period 2017 to 2024. The period from 2017 to 2024 was selected because it represents an important stage at which the EU's dual-transition strategy gradually became more established through initiatives such as the European Green Deal, the European Climate Law, and the Digital Europe Programme (2021–2027). It also enabled a systematic cross-country analysis based on recently published EIS data.

The EIS is designed to provide a harmonized and methodologically comparable framework for cross-country and cross-temporal analysis of innovation performance. In line with the proposed structural equation modeling (SEM), the indicators are grouped into three analytical domains: environmental sustainability, digital and innovation, and education-related indicators. The selection of these indicators is justified by their relevance to the key variables of the conceptual model of the study, namely linking environmental sustainability performance and pressures for pollution reduction with digital and innovative capacities, as well as with the education and knowledge inputs which enable the diffusion and adoption of sustainable innovations. These measures are based on the assumption that sustainable development and innovation performance are determined by the effects of ecological, technological, and human capital.

A list of the indicators employed in the empirical analysis and extracted from the EIS for the period 2017–2024 is presented below.

Environmental Sustainability Indicators:

- *Environmental Sustainability (ENV_SUS)*: Reflects the environmental performance dimension associated with national innovation systems and captures the extent to which countries combine innovation development with sustainability-oriented outcomes.
- *Environment-related Technologies (ENV_TECH)*: Measures the development and diffusion of environment-related technologies and reflects the capacity of the economy to generate technological solutions addressing environmental challenges and green transition objectives.
- *Emissions of Fine Particulates (PM25)*: Captures the level of emissions of fine particulate matter generated in economic activity and is used as an indicator of environmental pressure and pollution intensity. Lower values are associated with better environmental performance and a more sustainable production structure.

Digital and Innovation Indicators:

- *Direct and Indirect Government Support of Business R&D (GOV_RD)*: Measures the public support provided to business research and development through direct funding and indirect fiscal instruments. It reflects the institutional commitment to stimulating private-sector innovation activity.
- *Employed ICT Specialists (ICT_EMP)*: Indicates the share of ICT specialists in total employment and captures the availability of advanced digital human resources required for technology adoption, digital transformation, and innovation diffusion.
- *Individuals with Above Basic Overall Digital Skills (DIG_SKL)*: Reflects the proportion of the population possessing advanced digital competences, thus capturing the general digital readiness of society and its capacity to engage with knowledge-intensive and technology-driven activities.
- *Innovation Expenditures per Person Employed (INN_EXP)*: Measures the level of innovation-related expenditures relative to employment and serves as a proxy for firm-level and economy-level commitment to innovation investment.
- *Knowledge-intensive Services Exports (KIS_EXP)*: *Captures* the export performance of knowledge-intensive services and reflects the international competitiveness of economies in sectors characterized by high value added, knowledge content, and innovation intensity.
- *PCT Patent Applications (PCT_PAT)*: Measures the number of patent applications filed under the Patent Cooperation Treaty and is employed as an indicator of technological output, inventive activity, and internationally relevant innovation capacity.

Education-Related Indicators:

- *Population Involved in Lifelong Learning (LLL)*: Measures the participation of the adult population in education and training activities and reflects the degree to which countries support the continuous upgrading of skills and competences over the life course.

- *Population with Tertiary Education (TER_EDU)*: Captures the share of the population having completed tertiary education and serves as a core indicator of advanced human capital formation and knowledge potential.
- *International Co-authored Articles (CO_AUT)*: Reflects the extent of international academic collaboration through co-authored research articles and is used as an indicator of research openness, academic connectivity, and knowledge integration into global networks.
- *Job-to-job Mobility of HRST (HRST_MOB)*: Measures the mobility of human resources in science and technology across jobs and sectors and captures the circulation of highly skilled labor, which contributes to knowledge diffusion and innovation spillovers.
- *Intellectual Assets (INT_AST)*: Reflects the creation of codified knowledge assets and innovation-related intangible outputs, such as patents, trademarks, or designs, and captures the extent to which knowledge generation is transformed into formalized intellectual property.

Although the indicators are grouped under three major analytical categories, it is apparent that their role is complementary rather than segmented. The environmental sustainability indicators encompass ecological success and the green nature of national development paths. The digital and innovation indicators embrace inputs and outputs of technology-based competitiveness, including support from the public sector, digital workforces, innovation spending, and patenting. Education-related indicators provide an understanding of the human and knowledge base of national innovation success over time, with a focus on formal education, lifelong learning, academic collaboration, and the creation of intellectual property.

The data provided offer an integrated empirical basis for investigating relationships between sustainability, digitalization, innovation, and education in selected CEE countries. The combination of environmental, technological, and human factors into the panel data model allows the capture of country-level and time-related aspects between 2017 and 2024. This approach is especially important for investigating the evolution of new European innovation systems and the drivers behind sustainable and knowledge-intensive growth.

Table 1. Descriptive statistics

Variables	Mean	Std. Dev.	Min	Max	Skew.	Kurt.
PM25	79.041	25.708	25.6	115.9	– .537	2.141
DIG	82.523	18.473	43.8	121.5	– .008	2.94
GOV RD	56.073	54.709	2.7	223.9	1.088	3.326
ICT EMP	90.225	29.347	38.7	171	.784	4.126
EMP IMP	68.516	34.789	10.3	151.2	.293	2.404
ICT TRN	66.831	41.435	0	152.2	.357	2.325
ENV SUS	77.95	17.505	32.9	109.9	– .323	2.695
ENV TECH	94.965	38.229	0	188.7	.261	3.077

Variables	Mean	Std. Dev.	Min	Max	Skew.	Kurt.
MHT EXP	78.404	27.699	35.6	118	– .024	1.41
FIN SUP	65.859	25.867	23.6	118.8	.026	1.98
FIRM INV	64.472	25.067	15	122.4	– .132	2.302
HR	74.078	33.44	18.3	151.8	.138	2.087
DIG SKL	71.386	29.613	16.6	140.2	– .621	2.928
INN EXP	44.875	24.442	2.7	119.9	.194	2.89
INT AST	63.998	21.253	27.6	116.7	.426	2.605
CO AUT	89.343	59.874	18.6	239.8	.991	2.932
HRST MOB	96.76	69.005	0	267.6	.698	2.946
KIS EXP	53.356	15.594	13.7	87.7	– .414	3.19
PCT PAT	45.802	14.807	19.2	94.6	.855	4.028
LLL	87.708	59.221	4.2	226.4	.732	2.468
TER EDU	88.575	50.856	0	200.6	.39	3.178
RES PROD	55.365	30.105	2.9	110.2	– .149	1.868
SAL IMP	68.831	16.7	39.3	101.7	.155	1.934
SII	71.814	20.97	35.5	118.2	.128	2.349

Source: authors' elaboration in Stata 16.

Table 1 indicates significant variation across the variables, evidencing significant cross-country and intertemporal heterogeneity within the selected sample. The highest variations are observed for the HRST_MOB, CO_AUT, LLL, GOV_RD, and TER_EDU variables. These findings imply significant differences for human capital mobility, academic collaboration, lifelong learning, government support for business research and development, and educational attainment at the tertiary level among the ten countries. In contrast, variables such as KIS_EXP, PCT_PAT, ENV_SUS, and DIG appear to have relatively smaller variations, as indicated by their standard deviations. The descriptive statistics for the variables suggest that the dataset is sufficiently heterogeneous for comparative panel analysis and statistically well-behaved for subsequent econometric analysis.

To support the descriptive statistics provided above and to better visualize the dynamics of the countries considered, Figures 2–4 illustrate the panel evolution of the main indicators grouped by the three analytical dimensions considered in this study: environmental sustainability, digitalization/innovation, and education.

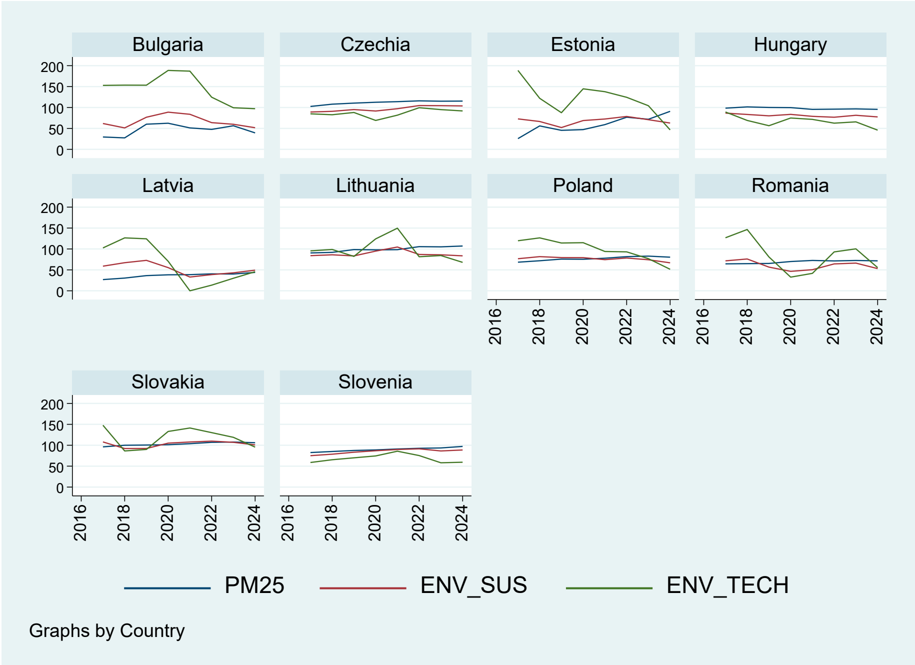


Figure 2. Panel evolution of environmental sustainability indicators
Source: authors' elaboration in Stata 16.

Figure 2 indicates that the environmental sustainability indicators vary somewhat unevenly across countries over the period. While PM25 and ENV_SUS appear to be relatively stable in some cases, ENV_TECH fluctuates more significantly, suggesting large variations in the dynamics of green technologies.

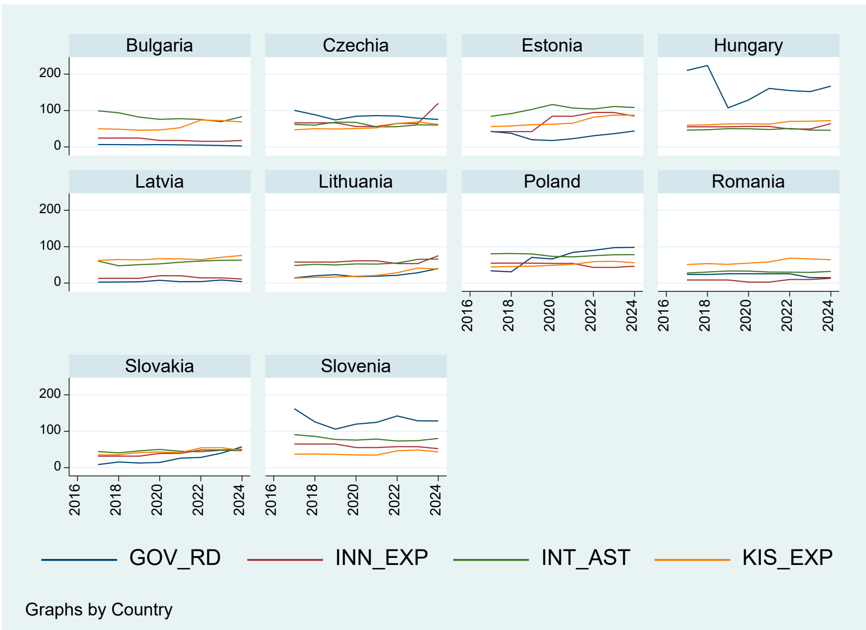


Figure 3. Panel evolution of digitalization and innovation indicators
Source: authors' elaboration in Stata 16.

Figure 3 indicates that the digitalization and innovation indicators vary somewhat heterogeneously across countries, with noticeable variations in terms of both level and dynamics. For instance, GOV_RD and INT_AST differ more significantly across countries, while INN_EXP and KIS_EXP vary somewhat more smoothly.

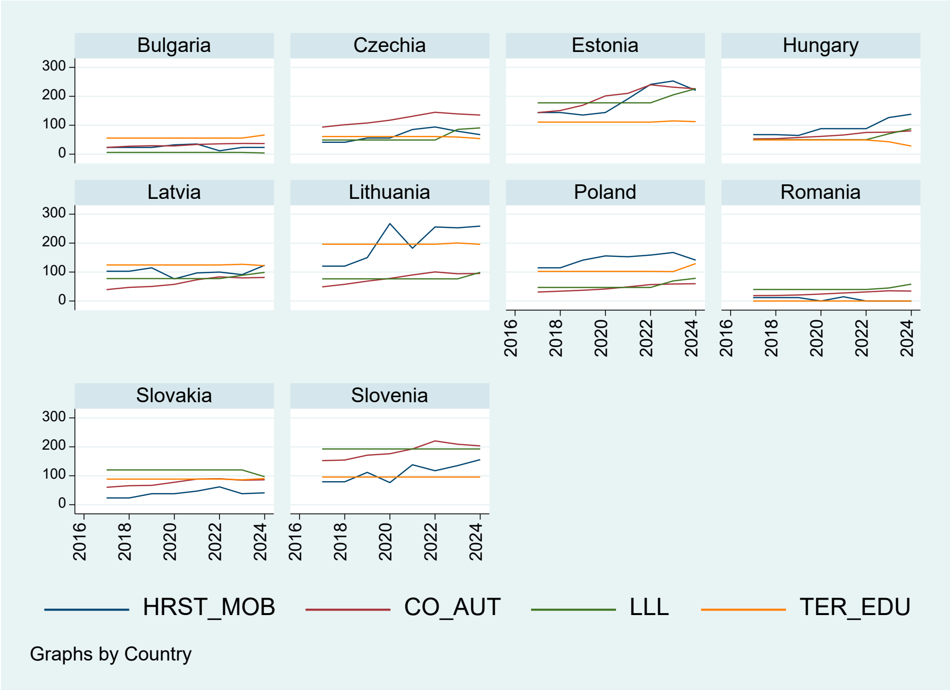


Figure 4. Panel evolution of education indicators
Source: authors' elaboration in Stata 16.

Figure 4 indicates that there is an evident upward trend in education-related indicators, especially HRST_MOB, CO_AUT, and LLL over time, although with varying degrees of change across countries. At the same time, Figure 4 also confirms that there are large variations in human capital and knowledge performance across the countries included in the panel sample.

Methodology

To examine the determinants of the variables across countries and over time, the empirical analysis is based on a complex set of modern econometric techniques, embedding correlation analysis, panel data regression models, and structural equation modeling (SEM).

To obtain a preliminary understanding of the relationships between the variables included in the analysis, a correlation analysis was first conducted. This method identifies the direction and strength of linear relationships between variables and provides an initial indication of possible associations among the studied indicators. At the same time, correlation analysis serves as a diagnostic step for identifying potential multicollinearity issues that may influence the estimation of econometric models (Porter and Gujarati 2009).

Moreover, several panel data regression model specifications were developed and estimated through several alternative strategies. The main specification is based on a Random Effects model that is estimated via a Generalized Least Squares method. In this model specification, the effects that are specific to a country are treated as randomly distributed and independent of the other independent variables. Baltagi (2021) describes this model in detail. Random effects were chosen based on several methodological aspects.

First, in contrast to the fixed effects approach, it considers variability within and between countries, potentially yielding more efficient estimates. In addition, the random-effects estimator preserves degrees of freedom in relatively small panel samples and allows the inclusion of time-invariant characteristics that can help explain cross-country differences. Furthermore, by treating sampled countries as representative of a broader population, the random-effects framework supports more generalizable inference. The alternative model specification that was developed and estimated is an Ordinary Least Squares model that is based on a pooling procedure and Driscoll-Kraay standard errors. The Driscoll-Kraay procedure adjusts the covariance matrix in such a way that the standard errors that are obtained remain consistent in the presence of such forms of dependence. Driscoll and Kraay (1998) describe this procedure in detail.

In addition to these model specifications and estimators, the analysis also employs a Panel-Corrected Standard Errors procedure. The PCSE procedure adjusts the estimated covariance matrix so that the resulting standard errors remain reliable. The procedure does not affect the coefficient estimates, as detailed by Beck and Katz (1995).

Finally, to mitigate the effects of extreme values and possible violations of classical regression analysis assumptions, this study also incorporates robust regression analysis (RREG) estimations. The robust regression analysis reduces the impact of influential observations, thus limiting the effects of possible outliers on the estimated parameters. In this way, the estimated parameters remain stable even when the distribution of residuals differs from the assumptions of classical regression analysis (Huber 1981; Rousseeuw and Leroy 1987).

Aside from these econometric analyses, this study also employed a Structural Equation Modeling (SEM) approach in order to examine the structural relationships between the primary dimensions of analysis. The SEM approach allows for the simultaneous estimation of relationships between multiple observed variables, including latent variables that represent broader theoretical constructs (Bollen 1989; Kline 2016). This is particularly useful when multiple underlying processes are present simultaneously, where some variables are not directly measurable. One of the principal benefits of using SEM is the ability to combine measurement models with structural paths in a single type of analytical structure. This allows for the evaluation of the validity of the constructs as well as the strength of the relationships that exist between the constructs. This is essentially a more holistic approach to the conceptual model on which the analysis is based.

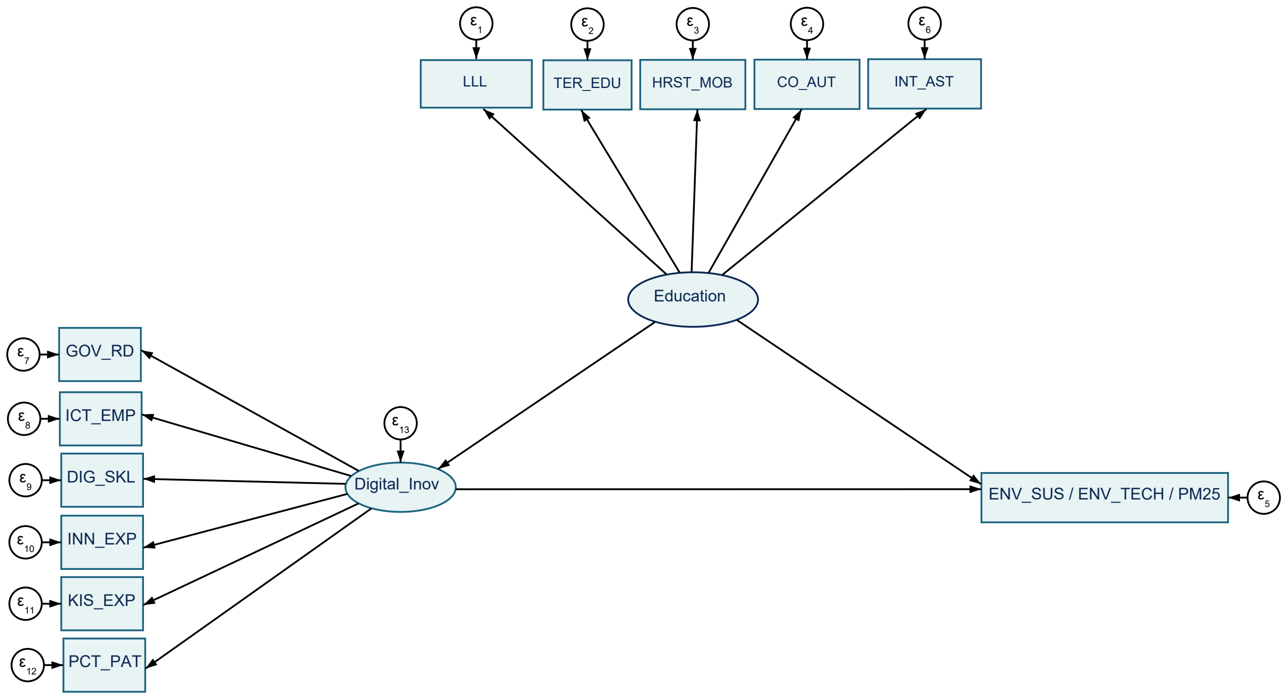


Figure 5. General configuration of the SEM model
Source: authors' elaboration in Stata 16.

As can be seen in Figure 5 above, the SEM model comprises three key dimensions of analysis. The first is the first latent construct Digital_Inov, which is measured by several indicators that represent different aspects of technological capacity and innovation: GOV_RD, ICT_EMP, DIG_SKL, INN_EXP, KIS_EXP, and PCT_PAT. These indicators collectively represent the general dynamics of digital development. The second construct is Education, which is measured by the indicators LLL, TER_EDU, HRST_MOB, CO_AUT, and INT_AST. These indicators represent different aspects of the education system, thereby reflecting its multidimensionality. The environmental dimension is based on the indicators ENV_SUS, ENV_TECH, and PM25.

Overall, the incorporation of these approaches provides a more comprehensive framework for analyzing these relationships.

The research hypotheses are:

- *H1: Digitalization, innovation, and education positively influence environmental performance sustainability in CEE countries;*
- *H2: Digitalization, innovation, and education positively influence environment-related technologies in CEE countries;*
- *H3: Digitalization, innovation, and education positively influence the reduction of emissions by fine particulates in CEE countries.*

Results and Discussion

Correlation Analysis

The pairwise correlations between the variables included in the analysis are reported in Table 2 and Figure 6, providing an initial overview of the relationships linking environmental sustainability, digitalization, innovation, and education indicators. Examining these associations identifies preliminary patterns before proceeding to more complex econometric modeling.

Table 2. Pairwise correlations

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
(1) ENV_SUS	1.000													
(2) ENV_TECH	0.349	1.000												
(3) PM25	0.787	−0.213	1.000											
(4) GOV_RD	0.303	−0.376	0.514	1.000										
(5) ICT_EMP	0.140	0.090	0.040	0.102	1.000									
(6) DIG_SKL	0.295	−0.201	0.326	0.249	0.665	1.000								
(7) INN_EXP	0.522	−0.031	0.575	0.453	0.632	0.729	1.000							
(8) INT_AST	−0.149	0.207	−0.296	−0.002	0.728	0.266	0.442	1.000						
(9) CO_AUT	0.223	−0.136	0.241	0.288	0.813	0.589	0.673	0.569	1.000					
(10) HRST_MOB	0.081	−0.086	0.127	0.095	0.511	0.631	0.577	0.453	0.512	1.000				
(11) KIS_EXP	−0.460	−0.194	−0.341	0.036	0.185	0.037	−0.106	0.155	0.094	−0.080	1.000			
(12) PCT_PAT	0.142	−0.210	0.145	0.618	0.594	0.446	0.540	0.493	0.691	0.292	−0.012	1.000		
(13) LLL	0.155	−0.138	0.128	0.192	0.716	0.550	0.482	0.428	0.862	0.451	−0.045	0.650	1.000	
(14) TER_EDU	0.134	0.012	0.033	−0.216	0.367	0.531	0.340	0.299	0.264	0.742	−0.455	0.156	0.336	1.000

Source: authors' elaboration in Stata 16.

As shown in Table 2, several moderate to strong correlations emerge across the analyzed variables.

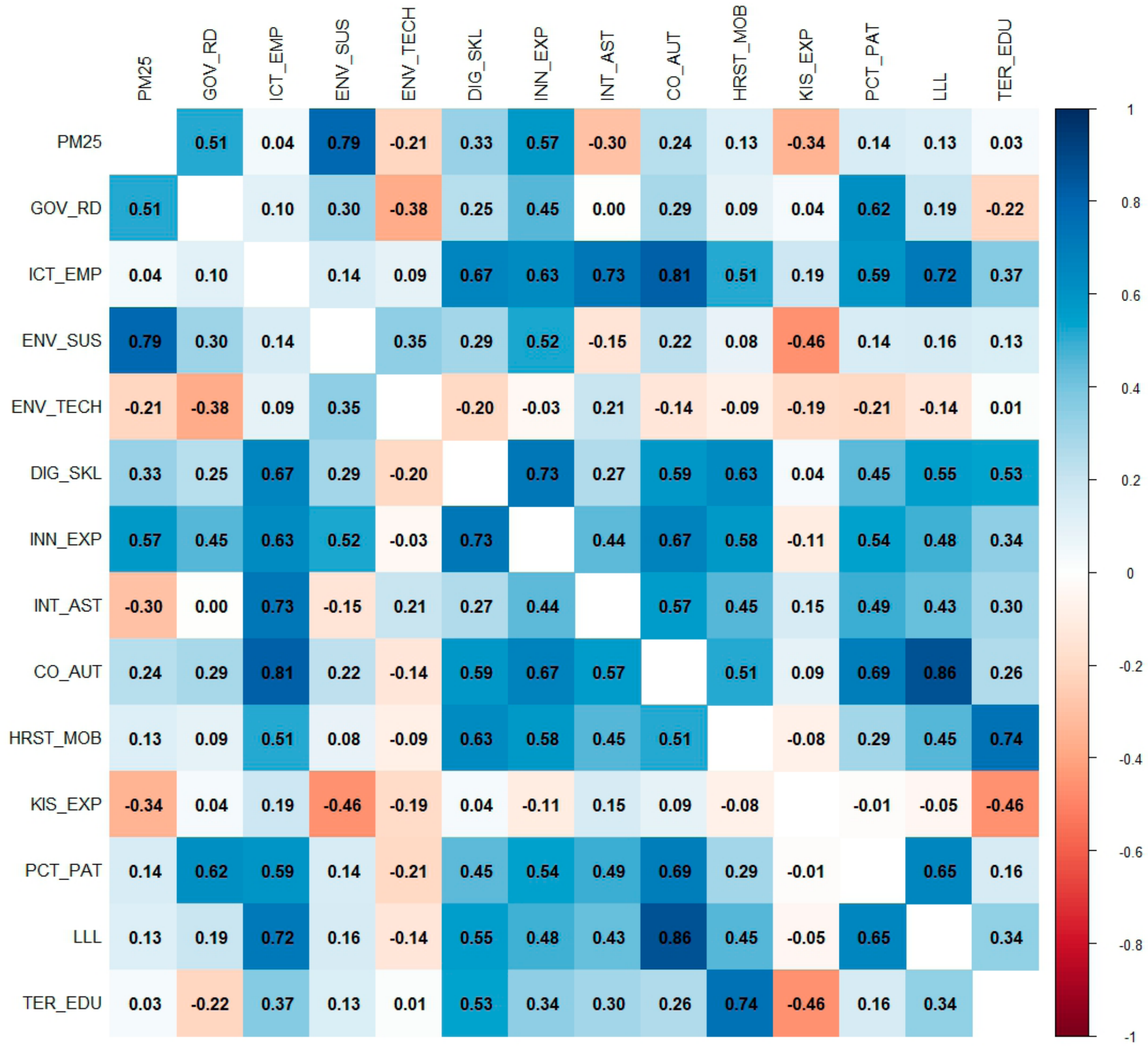


Figure 6. Heatmap of correlation coefficients for all variables
Source: authors' elaboration in RStudio.

A complementary perspective is offered by the multidimensional representation shown in Figure 7, which depicts the dual-layer relationships between the digital, educational, innovation, and sustainability indicators.

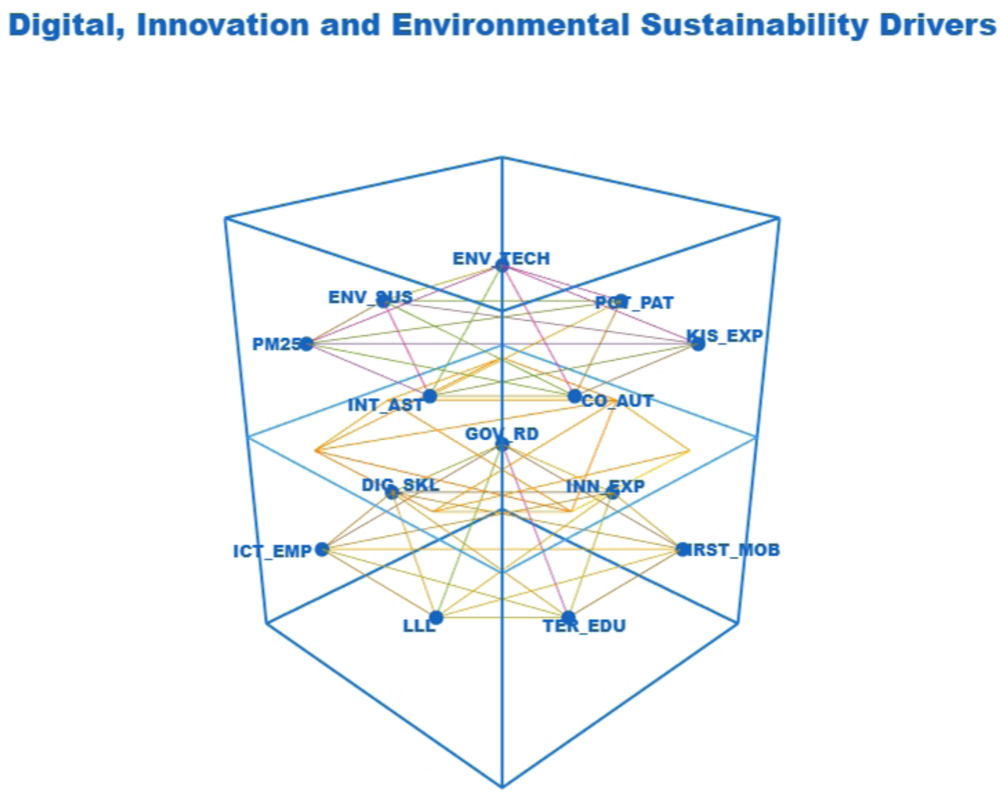


Figure 7. Multidimensional links (dual-layer cube) between digital, innovation, education and sustainability indicators
Source: authors' elaboration in RStudio.

Figure 7 illustrates the simultaneous interaction among all dimensions, which highlights the importance of knowledge-based factors like digital literacy, research cooperation, and spending on innovation within the larger context of the system. Before proceeding to the econometric estimations, potential multicollinearity among the explanatory variables was assessed using the Variance Inflation Factor (VIF) and the corresponding tolerance values. The results indicate that CO_AUT records the highest VIF value of 8.79, followed by TER_EDU and ICT_EMP, both with VIF values of 7.51, respectively. DIG_SKL presents a VIF of 6.00, while LLL and INN_EXP show VIF values of 5.93 and 5.63. Slightly lower values are observed for HRST_MOB (VIF = 5.39) and PCT_PAT (VIF = 5.31). The remaining variables display more moderate levels, with INT_AST recording a VIF of 4.32, GOV_RD a VIF of 4.13, and KIS_EXP the lowest VIF value of 3.08. Overall, the mean VIF is 5.78, indicating moderate levels of multicollinearity within the model, while all tolerance values remain above the commonly accepted threshold, suggesting that multicollinearity does not pose a critical concern for the subsequent econometric estimations.

Results of the Panel Data Modeling

To estimate the direct impact of the dimensions of digitalization, innovation, and education on the three coordinates representing the dependent variables, namely environmental performance oriented towards innovation and sustainability (ENV_SUS), the development and diffusion of environment-related technologies (ENV_TECH), and the level of emissions of fine particulate matter generated in economic activity (PM25), we have applied four panel regression specifications, namely Random Effects (RE), Pooled OLS, Panel-Corrected Standard Errors (PCSE), and Robust Regression (RREG).

The results estimated for the environmental performance oriented towards innovation and sustainability (ENV_SUS) are presented in Table 3. The share of ICT specialists in total employment (ICT_EMP) and the level of innovation-related expenditures relative to employment (INN_EXP) had a positive and statistically significant influence on environmental performance oriented towards innovation and sustainability (ENV_SUS), with the effect being more pronounced in the case of innovation-related expenditures per employee (INN_EXP). In contrast, intellectual assets (INT_AST) and the export performance of knowledge-intensive services (KIS_EXP) had a negative and statistically significant influence on this dimension (ENV_SUS). These findings are similar to those obtained by Wen, Lee, and Song (2021), Lu, Li, and Yuen (2023), Chen et al. (2025), and Xie and Wang (2025), who revealed that digital capabilities can improve environmental performance through green collaborative innovation through learning and organizational orientation.

Therefore, the first hypothesis (H1), which proposed that digitalization, innovation, and education positively influence environmental performance sustainability in CEE countries, is supported only for the share of ICT specialists in total employment and the innovation expenditures per person employed.

Table 3. Results of the panel regression models (dependent variable: ENV_SUS)

	(1)	(2)	(3)	(4)
	ENV_SUS	ENV_SUS	ENV_SUS	ENV_SUS
	RE	Pooled OLS	PCSE	RREG
GOV_RD	0.0633 (0.0467)	0.0633 (0.0551)	0.0633 (0.0347)	0.0608 (0.0517)
ICT_EMP	0.301* (0.117)	0.301 (0.180)	0.301** (0.107)	0.261* (0.130)
DIG_SKL	−0.111 (0.104)	−0.111 (0.148)	−0.111 (0.0981)	−0.0889 (0.115)
INN_EXP	0.459*** (0.122)	0.459** (0.127)	0.459*** (0.0991)	0.427** (0.135)
INT_AST	−0.407*** (0.123)	−0.407** (0.0961)	−0.407*** (0.0960)	−0.386** (0.136)
CO_AUT	0.0518 (0.0622)	0.0518 (0.0724)	0.0518 (0.0399)	0.0676 (0.0688)
HRST_MOB	−0.0596 (0.0423)	−0.0596 (0.0373)	−0.0596 (0.0488)	−0.0491 (0.0468)
KIS_EXP	−0.489*** (0.141)	−0.489** (0.0921)	−0.489*** (0.136)	−0.508** (0.156)
PCT_PAT	−0.321 (0.195)	−0.321 (0.246)	−0.321 (0.167)	−0.319 (0.216)

	(1)	(2)	(3)	(4)
	ENV_SUS	ENV_SUS	ENV_SUS	ENV_SUS
	RE	Pooled OLS	PCSE	RREG
LLL	− 0.0 417 (0.0 516)	− 0.0 417 (0.0 314)	− 0.0 417 (0.0 398)	− 0.0 518 (0.0 572)
TER_EDU	0.0 137 (0.0 677)	0.0 137 (0.0 603)	0.0 137 (0.0 642)	0.00 209 (0.0 749)
_cons	105.0*** (9.133)	105.0*** (5.820)	105.0*** (8.496)	107.6*** (10.11)
N	80	80	80	80
R^2	0.8 567	0.650	0.650	0.592

Note: Standard errors are in parentheses. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Source: authors' elaboration in Stata 16.

Regarding the development and diffusion of environment-related technologies (ENV_TECH), the results in Table 4 show a direct and statistically significant positive impact only from the share of ICT specialists in total employment (ICT_EMP). In the CEE region, environment-related technologies (ENV_TECH) were negatively and statistically significantly influenced by the public support provided to business R&D through direct funding and indirect fiscal instruments (GOV_RD), international co-authored articles (CO_AUT), the export performance of knowledge-intensive services (KIS_EXP), and the population with tertiary education (TER_EDU).

From an economic perspective, these results suggest that improvements in these areas are not automatically reflected in stronger environmental technological performance across the region. Although these findings may seem unexpected, they can be explained by several structural features unique to CEE economies. For GOV_RD, the negative coefficient may indicate that public support for R&D is still directed mainly towards general innovation or competitiveness objectives, without a strong focus on green technologies. Similarly, the expansion of knowledge-intensive service exports (KIS_EXP) does not necessarily imply a stronger environmental orientation, as many of these activities may be concentrated in business, financial, or IT services with only indirect links to sustainability outcomes.

The negative relationship identified for tertiary education (TER_EDU) and international academic collaboration (CO_AUT) should also be interpreted carefully. A larger share of tertiary educated population or a higher level of academic cooperation does not automatically translate into environmental innovation if research activities and educational specializations are not sufficiently connected to green sectors. This result may also reflect the persistence of skilled labor migration in several CEE countries, where highly educated individuals contribute increasingly to innovation systems abroad rather than to domestic environmental technological development (Noja et al. 2018).

Thus, the second hypothesis (H2), which proposed that digitalization, innovation, and education positively influence environment-related technologies in CEE countries, is only partially supported, specifically for the share of ICT specialists in total employment.

Table 4. Results of the panel regression models (dependent variable: ENV_TECH)

	(1)	(2)	(3)	(4)
	ENV_TECH	ENV_TECH	ENV_TECH	ENV_TECH
	RE	Pooled OLS	PCSE	RREG
GOV_RD	− 0.324* (0.126)	− 0.324** (0.0718)	− 0.324*** (0.0970)	− 0.324* (0.136)
ICT_EMP	1.037** (0.317)	1.037 (0.488)	1.037** (0.388)	0.901* (0.342)
DIG_SKL	− 0.391 (0.281)	− 0.391 (0.519)	− 0.391 (0.326)	− 0.452 (0.303)
INN_EXP	0.438 (0.330)	0.438 (0.604)	0.438 (0.330)	0.561 (0.355)
INT_AST	0.121 (0.332)	0.121 (0.240)	0.121 (0.283)	0.151 (0.358)
CO_AUT	− 0.374* (0.168)	− 0.374 (0.207)	− 0.374** (0.128)	− 0.343 (0.181)
HRST_MOB	0.146 (0.114)	0.146 (0.129)	0.146 (0.0986)	0.138 (0.123)
KIS_EXP	− 1.182** (0.382)	− 1.182* (0.461)	− 1.182** (0.436)	− 1.111** (0.412)
PCT_PAT	0.0225 (0.529)	0.0225 (0.401)	0.0225 (0.430)	− 0.0762 (0.570)
LLL	− 0.0417 (0.140)	− 0.0417 (0.0757)	− 0.0417 (0.0821)	− 0.0224 (0.151)
TER_EDU	− 0.432* (0.183)	− 0.432 (0.220)	− 0.432** (0.167)	− 0.435* (0.197)
_cons	143.4*** (24.71)	143.4** (32.10)	143.4*** (25.07)	149.3*** (26.63)
N	80	80	80	80
R^2	0.9317	0.463	0.463	0.422

Note: Standard errors in parentheses. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Source: authors' elaboration in Stata 16.

The empirical results for emissions of fine particulate matter generated in economic activity (PM25) are reported in Table 5. Favorable influences (as indicated by the negative coefficients obtained, which reflect a decrease in the level of fine particulate matter emissions generated) that are statistically significant were observed for the following variables: the proportion of the population possessing advanced digital competences (DIG_SKL), the export performance of knowledge-intensive services (KIS_EXP), patent applications filed under the Patent Cooperation Treaty (PCT) (PCT_PAT) and intellectual assets (INT_AST). Thus, a higher proportion of the population with advanced digital skills, intellectual assets, more patent applications, and a higher level of exports of knowledge-based services reduces emissions of fine particles. This may be explained by the fact that digitalization optimizes processes in SMEs (Chen et al. 2025; Xie and Wang 2025) and facilitates the adoption of more energy-efficient and pollution-reducing technologies, as smart technologies help reduce pollution (Marcu et al. 2016; Drăcea et al. 2026).

In contrast, direct and indirect government support of business R&D (GOV_RD), the share of ICT specialists in total employment (ICT_EMP), the level of innovation-related expenditures relative to employment (INN_EXP), and international co-authored articles (CO_AUT) are associated with an increase in PM25 emissions generated in economic activity, as indicated by the positive and statistically significant coefficients obtained. These results may reflect the structure of CEE economies, where industrialization and technological development may initially have environmental costs, with positive environmental effects emerging only after a longer time horizon (Lazăr, Minea, and Purcel 2016).

Table 5. Results of the panel regression models (dependent variable: PM25)

	(1)	(2)	(3)	(4)
	PM25	PM25	PM25	PM25
	RE	Pooled OLS	PCSE	RREG
GOV_RD	0.199*** (0.0474)	0.199** (0.0562)	0.199*** (0.0433)	0.200*** (0.0482)
ICT_EMP	0.250* (0.119)	0.250 (0.159)	0.250* (0.103)	0.370** (0.121)
DIG_SKL	−0.215* (0.106)	−0.215*** (0.0353)	−0.215** (0.0779)	−0.187 (0.107)
INN_EXP	0.740*** (0.124)	0.740** (0.154)	0.740*** (0.116)	0.654*** (0.126)
INT_AST	−0.786*** (0.125)	−0.786*** (0.0863)	−0.786*** (0.0941)	−0.807*** (0.127)
CO_AUT	0.166** (0.0632)	0.166** (0.0342)	0.166*** (0.0470)	0.139* (0.0642)
HRST_MOB	−0.0455 (0.0429)	−0.0455 (0.0270)	−0.0455 (0.0454)	−0.0267 (0.0436)
KIS_EXP	−0.392** (0.144)	−0.392* (0.157)	−0.392** (0.125)	−0.482** (0.146)
PCT_PAT	−0.669*** (0.199)	−0.669* (0.200)	−0.669*** (0.185)	−0.655** (0.202)

	(1)	(2)	(3)	(4)
	PM25	PM25	PM25	PM25
	RE	Pooled OLS	PCSE	RREG
LLL	− 0.0669 (0.0525)	− 0.0669 (0.0383)	− 0.0669 (0.0465)	− 0.0674 (0.0533)
TER_EDU	0.0499 (0.0688)	0.0499 (0.0786)	0.0499 (0.0506)	0.0126 (0.0699)
_cons	120.3*** (9.279)	120.3*** (8.167)	120.3*** (6.865)	121.1*** (9.430)
N	80	80	80	80
R^2	0.9612	0.8325	0.832	0.823

Note: Standard errors in parentheses. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Source: authors' elaboration in Stata 16.

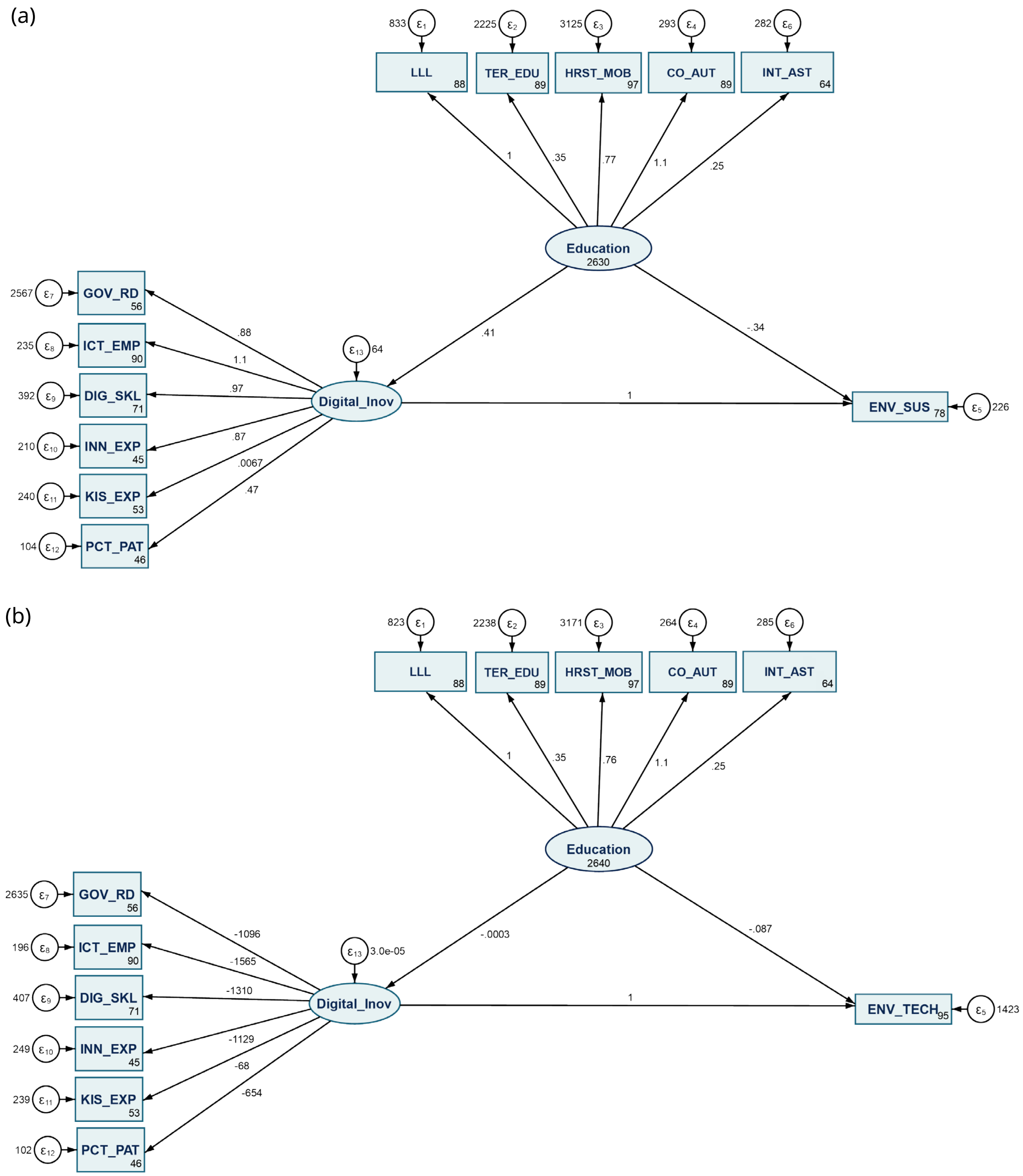
Therefore, the third hypothesis (H3), which proposed that digitalization, innovation, and education help reduce PM25 emissions in CEE countries, is partially supported, specifically for the proportion of the population with advanced digital skills, the export performance of knowledge-intensive services, patent applications, and intellectual assets.

Results of Structural Equations Models (SEM)

To further examine the relationships between the key dimensions identified in the previous analyses, a Structural Equation Modeling (SEM) framework using the Maximum Likelihood Estimator (MLE) was applied. This approach allows for the simultaneous assessment of the measurement relationships between the latent constructs and their observed indicators, as well as the structural links between the latent variables and the environmental outcomes. The main results for each dependent variable are presented in Figure 8.

The digital and innovation dimensions gathered within the latent variable (Digital_Inov) generated positive effects on sustainable environmental performance (ENV_SUS) (Figure 8(a)), as well as on environment-related technologies (ENV_TECH) (Figure 8(b)), mediated by the indirect impact of favorable influences from education (Education). However, the construct of education (Education) negatively influences both sustainable environmental performance (ENV_SUS) (Figure 8(a)) and environment-related technologies (ENV_TECH) (Figure 8(b)), although this arises from the positive influences of its subdimensions. The constructs of digitalization and innovation (Digital_Inov) encompass positive effects from all the sub-dimensions introduced in the case of environmental performance (ENV_SUS), while in the case of environment-related technologies (ENV_TECH), these effects are negative. Therefore, a higher share of the population with advanced digitalization and innovation skills (Digital_Inov), together with stronger education features, contributes to higher environmental performance (ENV_SUS). This can be explained by the role of digitalization and innovation in improving SME efficiency and supporting the adoption of cleaner, more energy-efficient technologies, including smart solutions that help reduce pollution (Marcu et al. 2016; Chen et al. 2025; Xie and Wang 2025; Drăcea et al. 2026).

Therefore, hypotheses H1 (which proposed that digitalization, innovation, and education positively influence environmental performance sustainability in CEE countries) and H2 (which proposed that digitalization, innovation, and education favorably influence environment-related technologies in CEE countries) are partially supported only in the case of digitalization and innovation, while education needs some reconsideration in the CEE countries.



(c)

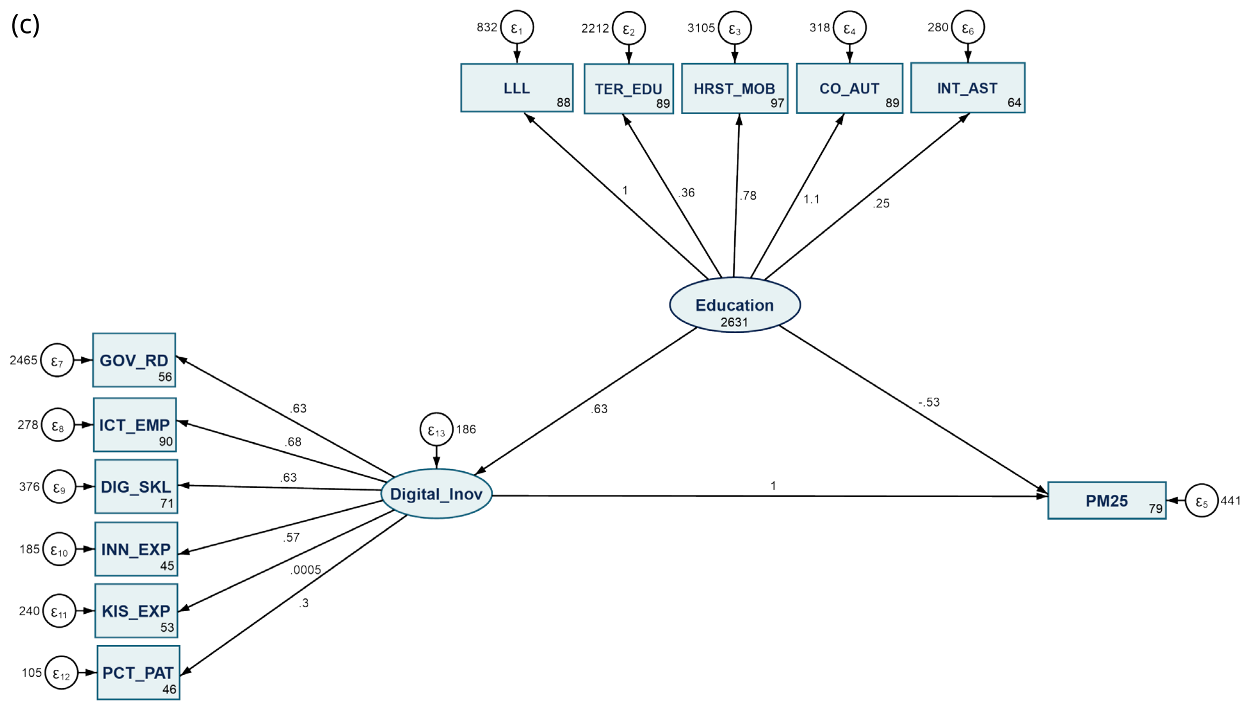


Figure 8. Results of structural equations models (SEM), on sustainable environmental performance (ENV_SUS) (a), environment-related technologies (ENV_TECH) (b), and PM25 emissions (c)
Source: authors' elaboration in Stata 16.

Regarding the implications for pollution, we observe that digitalization and innovation lead to increased PM25 emissions (Figure 8(c)), acting as a mediating factor for education, which enhances digitalization and innovation. However, the construct of education (Education) favorably influenced emissions of fine particulates (PM25) by reducing them. Thus, H3 (which posits that digitalization, innovation, and education help reduce PM25 emissions in CEE countries) is supported only for education, while digitalization and innovation require adaptation to reduce pollution.

Conclusion

This paper explored the relationships between innovation, digitalization, education, and the environment in CEE countries from 2017 to 2024. In particular, the environmental dimension was represented by environmental sustainability, environment-related technology, and fine particulate matter (PM2.5) emissions. Methodologically, the paper relied on a range of panel data regressions, including a random effects model, pooled ordinary least squares (OLS) estimates with Driscoll-Kraay standard errors, panel-corrected standard errors (PCSE), and robust regression. The paper also examined the general relationship between innovation, education, and the environment through the lens of structural equation modeling (SEM).

The main results indicated that the dimensions of digitalization and innovation, proxied by the share of ICT specialists in total employment and the innovation expenditures per person employed, positively and directly influenced environmental performance sustainability in CEE countries (H1) and environment-related technologies (H2). Meanwhile, PM25 emissions were reduced by digitalization and innovation, proxied by individuals with advanced digital skills, the export performance of knowledge-intensive services, and patent applications, as well as by education, proxied by intellectual assets (H3). Overall, the SEM findings revealed that digitalization and innovation act as a beneficial motor for the environment, while education needs to be aligned with green technology. Based on these results, these areas should be further supported and intensified.

Regarding the negative effects obtained, the following measures should be considered:

- Reorienting public support for R&D by introducing dedicated funding programs for green innovation and prioritizing projects towards renewable energy, circular economy, energy efficiency, and pollution reduction technologies;
- Orienting knowledge-intensive services towards the green sector;
- Capitalizing on intellectual assets, education, and research towards green technologies;
- Reducing the brain drain in CEE countries;
- Integrating innovation with pollution reduction objectives;
- Supporting the development of competencies for green and digital transformation by introducing new curriculum reforms and promoting lifelong learning;
- Fostering cooperation between universities, businesses, and government bodies;
- Adjusting higher education and vocational education programs to meet the needs of green technologies, circular economy projects, and digital innovations.

The implementation of these policies is likely to boost the ability of CEE countries to adopt sustainable technologies, address skills gaps, and transform human capital into a competitive advantage for green growth.

The study has several limitations that should be acknowledged. First, it is constrained by the availability and comparability of data across CEE countries. Even though European databases provide a high degree of harmonization, some indicators might still have national peculiarities, and some dimensions of green innovation might be only indirectly accounted for using proxies. Second, there is a risk of a time lag the effects of innovations, digitalization, and R&D on environmental performance are often delayed. Therefore, due to the relatively limited time horizon of our analysis, the full impact of these factors on the environment might not be captured. Additionally, endogeneity issues cannot be totally ruled out because there can be a two-way relationship between innovation and environmental performance, and other omitted factors may have influenced the analysis. Lastly, the limited time period precludes a proper analysis of the structural transformation pathways in CEE economies. Further studies could improve our understanding of the issue by using more extended time series and even firm- or regional-level data. Furthermore, it would be beneficial to consider more developed EU economies when conducting a comparative analysis and employing a spatial econometric framework.

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