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Digital Transformation and Its Implications on Educational Quality: An Empirical Analysis Within the European Union Context

Mirela Cristea[1], Grațiela Georgiana Noja[2*], Teodora Andreea Găinaru[3], Catrinel Delia Tălăban[3*]

[1] Department of Finance, Banking and Economic Analysis, Faculty of Economics and Business Administration, University of Craiova, 200585 Craiova, Romania
[2] Department of Marketing and International Economic Relations, Faculty of Economics and Business Administration, West University of Timisoara, 300115 Timisoara, Romania
[3] Faculty of Economics and Business Administration, Doctoral School of Economics, University of Craiova, 200585 Craiova, Romania

[*] Correspondence: Grațiela Georgiana Noja (gratiela.noja@e-uvt.ro); Catrinel Delia Tălăban (talaban.catrinel.c2a@student.ucv.ro)

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Abstract: In the face of profound digital transformations, the societal and economic landscape has undergone significant shifts, notably impacting the educational sector across European Union (EU) member states. Through the employment of robust regression models, employing both Huber and biweight iterations, data spanning 1995-2021 were analyzed. The focus was on the relationship between the Education Index (EI) (a component of the Human Development Index (HDI)) and the Global Innovation Index (GINNOV). Results from this analysis suggest that an increase in internet usage, global innovation levels, and poverty alleviation measures have been found to positively influence the EI. Concurrently, positive correlations between internet usage, the contribution of the Information and Communication Technology (ICT) sector to GDP, employment rates, and the EI on global innovation levels were observed. Interestingly, adverse correlations were detected between household internet access and the ICT sector's GDP contribution to the EI, and between internet access and high-speed internet coverage with global innovation. Such findings underline the need for strategic interventions within the education sector, which are elaborated upon in the article.

Keywords: Education Index; Digital transformation; Innovation; Poverty alleviation; Employment; Econometric modelling; European Union member states

1. Introduction

In recent times, profound shifts have been observed in societal and economic landscapes, largely attributed to digital transformation (Małkowska et al., 2021; Morze & Strutynska, 2021; Pappas et al., 2023). The indispensable role of education and professional training systems tailored for the digital era was underscored by the pandemic (Zancajo et al., 2022). Prior to the COVID-19 disruption, technological innovation had already intensified the demand for novel skills, largely due to the rising incorporation of digital technology in education and training (Núñez-Canal et al., 2022). In connection with this trend, radical innovations related to the digitalization of education and training, like those offering entrepreneurial skills suited for the digital labor market, have emerged (Pirtea et al., 2019; Sá et al., 2021; Apostu et al., 2022; Trif et al., 2022). Additionally, advancements in technology have been found to reshape educator interactions, facilitating digital platforms that synchronize classroom training, thus paving the way for blended learning modalities and novel online social learning methods (Camilleri & Camilleri, 2017; Safapour et al., 2019). For those engaged in student interactions, acquiring the requisite skills and adopting an innovative mindset has been deemed essential (Vasilescu et al., 2020; Dimian et al., 2023).

Furthermore, intensive studies have documented the repercussions of digitalization on economic growth (Arsić, 2020; Son et al., 2013; Stroiko et al., 2021) and living standards (Noja et al., 2022; Petropoulos et al., 2019). Technological assimilation has also been observed to catalyze shifts within labor market dynamics and human resources. Such shifts often necessitate employee adaptation to digital transformations, encompassing the creation of novel job roles, fostering staff flexibility, honing soft skills, and cultivating digital dexterity (Erro-Garcés & Aramendia-Muneta, 2023).

Within this context, the objective of this study is elucidated: the emphasis lies on emphasizing the urgent need to restructure education systems in alignment with the digital age and its emerging skill set, particularly within the EU member states. The primary research goal revolves around appraising the influence of digitalization and innovation on education quality, as well as the mutual impact between education and digitalization on innovation metrics. The study's pivotal dependent variables are identified as the EI (a facet of the HDI) and the GINNOV. An analysis spanning the years 1995-2021 is conducted, with the methodology centered on robust regression modeling (RREG) implemented through Huber and biweight iterations (UCLA: Statistical Consulting Group, 2023). It should be noted that despite numerous discussions on this theme, the scrutiny of the educational facet of the HDI, particularly in the context of the EU and in correlation with factors like internet accessibility, innovation degrees, employment metrics, and living standards, has been relatively scarce.

Following this introduction, Section 2 delves into a literature review, shedding light on the multifaceted benefits of digitalization, its innovative imprints on education, the marked impacts of the COVID-19 pandemic, and the inherent challenges posed by rapid digital transformation. Section 3 details the data and methodology, concentrating on RREG-based modeling that gauges the influence of digitalization and innovation on education metrics and vice versa, within the EU precincts. Thereafter, Section 4 unveils the analysis and discussion, rigorously evaluating eight hypotheses that resonate with the research objectives. A concise overview of the discerned findings concludes this section. The study culminates in Section 5, proffering strategic recommendations to foster synergy between education, digitalization, and innovation.

2. Literature Review

2.1 Benefits of Digitalization in Education

In extant literature, a significant emphasis has been placed on delineating the merits of digitalization by various scholars. Among the myriad benefits identified, it has been posited that the synergy of digitalization and innovation holds the potential to usher countries towards sustainable and high-caliber education (Grima et al., 2022; Zancajo et al., 2022; Cvahte Ojsteršek et al., 2023).

A prevailing trend has been discerned towards embracing innovative educational modalities, with particular attention to digital resources for online pedagogy. Such an inclination is perceived to democratize learning access, obliterating redundant barriers, and thereby offering learners an enhanced likelihood of success across multifarious academic domains (Camilleri & Camilleri, 2017; Kahramonovna, 2021; Safapour et al., 2019; Sá et al., 2021). The proliferation of digital technologies, epitomized by widespread internet accessibility, is deemed to augment pedagogical experiences. As substantiated by Mello et al. (2019) in the context of the BRICS nations, the democratization of information accessibility has transformed pedagogical structures, rendering them less tethered to conventional educational infrastructures.

Nevertheless, challenges loom in the horizon of this digital transformation. It has been highlighted that several nations, inclusive of the EU-27 member states (Crăciun et al., 2023) and others like India (Dubey & Pandey, 2020), Peru (Martinez Puma et al., 2022), Indonesia (Aditya, 2021), and Russia (Afonasova et al., 2019), are yet to provide ubiquitous high-speed internet connectivity to their populace. This lacuna, thus, presents a significant impediment to the full realization of the advantages inherent in digital education.

In light of the above, it becomes imperative to delve deeper into the multifaceted dynamics of digitalization in education, understanding both its transformative potential and the challenges that need navigation.

2.2 The Dynamics of Innovation in Education

Innovative measures within educational systems, encompassing the introduction of novel services, technologies, and proficiencies by educational entities, have been posited to enhance learning outcomes and foster both equity and efficiency (Kahramonovna, 2021; Serdyukov, 2017). However, while a close interrelation between digitalization and innovation is acknowledged, it has been emphasized that not every digital initiative precipitates innovation. Similarly, not all innovative measures are predicated on digital foundations (Afonasova et al., 2019).

For clarity in understanding the impact of digital advancements in a social and temporal context, distinctions between several terminologies related to digitalization have been drawn (Bloomberg, 2018; Brennen & Kreiss, 2016):

(i) Digitization is elucidated as the process whereby tangible information, encompassing a range from documents to photographs, is converted into electronic formats, accessible via various digital devices.

(ii) Digitalization, encompassing aspects of digitization, represents a broader transformation where manual procedures are automated.

(iii) Digital Transformation is perceived to delineate a profound, rapid overhaul of all undertakings, processes, competencies, and business models in alignment with the potentialities proffered by digital technologies.

Furthermore, innovation, distinct from concepts of progress and growth, remains closely tied to notions of improvement, especially when viewed beyond mere technological shifts (Downs Jr. & Mohr, 1976). A myriad of factors has been identified as influencing innovation, with salient examples being the quality of human capital, the contribution of research and development (R&D) to GDP, incentives for R&D, and revenue generated from innovation, or the "commercialization of innovation" (Ezell et al., 2016). In a comprehensive analysis covering 56 countries—accounting for almost 90 percent of the global economy-certain European nations, specifically Finland, Sweden, and the United Kingdom, were spotlighted for their robust innovation efforts. These efforts, it was asserted, emanated from a confluence of policies bolstering innovation and a dearth of policies detrimental to it. Conversely, countries in Asia and Latin America, notably India, Indonesia, and Argentina, were highlighted for their comparatively languid innovation trajectories (Ezell et al., 2016).

2.3 The Educational Shifts Stemming from the COVID-19 Crisis

The advent of the COVID-19 pandemic precipitated a marked transition toward online and distance education. Dependencies on advanced technologies, notably internet accessibility, online teaching platforms, and the imperativeness of high-speed internet coverage, became more pronounced (Mello et al., 2019). Concurrently, the crisis starkly exposed the vulnerabilities in the educational systems of many emerging countries (Aditya, 2021; Drăcea & Cristea, 2009). Distinct disparities were observed among student cohorts, with certain groups, especially those hailing from rural territories and nations like Pakistan and Romania, facing pronounced educational inequalities (Adnan & Anwar, 2020; Beaunoyer et al., 2020; Cristea et al., 2022).

In an evaluation of the efficacy of digital versus traditional educational materials, it was found that digital content, characterized by its interactive nature, was more readily retained and assimilated compared to conventional textbooks. Such findings suggest that digital educational paradigms enable learners to progress at an individualized pace, unencumbered by temporal constraints or the potential hindrances posed by peers (Cramarenco et al., 2023). In alignment with these insights, emergent learning technologies are increasingly recognized for their potential to customize the educational landscape.

2.4 Digitalization in Education: Opportunities and Challenges

Significant improvements in student outcomes through the application of information and communication technologies in education have been highlighted by global research endeavors (Goswami et al., 2020). The integration of traditional face-to-face learning with e-learning is posited to align educational methods with the anticipations of the digital generation (Agung et al., 2020; Hong et al., 2022). Notably, studies increasingly suggest that blended learning modalities, which incorporate both traditional and e-learning elements, tend to surpass the efficacy of either method when applied in isolation.

In the contemporary era, familiarity with digital devices such as computers, tablets, and mobile phones is observed from early childhood, primarily due to exposure to digital games and platforms. As such, the introduction of these technologies into educational settings can be viewed as bridging the gap between learners' experiences and institutional methodologies. Emphasis is thus placed on the deployment of genuine digital tools that not only complement, but also substantively enhance the learning process (Mello et al., 2019; Serdyukov, 2017). Yet, it is imperative that educators be both proficient in and convinced of the merits of such interactive pedagogies for these technologies to truly impact educational outcomes (Borisova et al., 2016; Hong et al., 2022).

In recent times, particularly underscored by the constraints of the COVID-19 pandemic, the significance of digital technologies, innovation, and ICT integration in education has been accentuated. The year 2020 marked a pivotal shift to entirely online educational paradigms for multiple EU nations. Despite the manifest urgency of such digital adaptations, several newly-inducted EU states (post-2004) grapple with inequalities in student access to digital infrastructure and resources. Disparities also persist in institutional provisions, educator training, and digital proficiencies. A lacuna in current research pertains to comprehensively analyzing the interplay between education quality-considered a key facet of the HDI-and levels of digitalization. This, in conjunction with labor market dynamics and living standards across EU member states, presents a critical avenue for further inquiry.

3. Data and Methodological Framework

In accordance with the stated research objectives and foundational literature, data compiled for analysis (as delineated in Table 1) were categorized into three distinct clusters of variables:

- *Digital and Innovation Metrics*: This encompasses variables such as "household level of internet access"

(H_IA); "individuals reporting internet use within the last 12 months" (I_IU); "contribution of the ICT sector to total GDP" (ICT_GDP); "extent of high-speed internet coverage" (ICHS); and the "GINNOV".

• *Educational Criterion*: This is represented by the "EI".

• *Control Variables*: Notable among these are the "rate of individuals at risk of poverty delineated by the poverty line" (Pvt) and "employment rate within the age bracket of 20-64 years" (ER).

A methodical and rigorous approach was employed in data procurement. Only data from official statistics, as disseminated by recognized national and international entities/organizations/institutes, were considered. Subsequently, each of these indicators was transposed into an aggregated dataset to facilitate its incorporation into Stata, enabling the commencement of data analysis and the corresponding econometric procedures.

The specifics pertaining to the chosen variables-including the unit of measurement, acronym, and data source-are meticulously cataloged in Table 1.

Table 1. Variables deployed in empirical analysis at the EU-27 scale, spanning 1995-2021

No.	Variables Explanation	Unit of Measure (UM)	Acronym	Source
1	"EI"	Score (index from 0 to 1)	EI	United Nations Development Programme (2023) (UNDP), Human Development Reports (HDRO)
2	"At-risk-of-poverty rate by poverty line"	%	Pvt	European Commission (2023), Eurostat [ILC_LI02]
3	"Employment rate, 20-64 years"	% of total population	ER	European Commission (2023), Eurostat [LFSI_EMP_A$DEFAULTVIEW]
4	"Households - level of internet access"	% of households	H_IA	European Commission (2023), Eurostat [ISOC_CI_IN_H__custom_6868205]
5	"Individuals - internet use, Last internet use in the last 12 months"	% of individuals	I_IU	European Commission (2023), Eurostat [ISOC_CI_IFP_IU__custom_6868969]
6	"Percentage of the ICT total sector on GDP"	% of GDP	ICT_GDP	European Commission (2023), Eurostat [TIN00074]
7	"High-speed internet coverage"	% of households	HSIC	European Commission (2023), Eurostat [SDG_17_60]
8	"GINNOV"	Score (scale from 0 - 100)	GINNOV	World Intellectual Property Organization (2022) (WIPO)

Source: Authors' contribution

The "***EI***" elucidating the level of "knowledge," is recognized as one of the three dimensions of the HDI. As delineated by the United Nations Development Programme (2023), the other two dimensions encompass "long and healthy life," quantified by the "life expectancy index," and "a decent standard of living," gauged through the Gross National Income (GNI) index. The methodological approach taken by the United Nations Development Programme (2023) for the computation of the EI encompasses the "mean years of schooling for adults aged 25 years and over" combined with the "expected years of schooling for children at the commencement of their educational journey."

Separately, the "***GINNOV***", an analytical tool introduced by Dutta in 2007, was operationalized in 2011 following a collaboration between INSEAD and its designated "knowledge partners," which notably included the World Intellectual Property Organization (2022) (WIPO) (Dutta, 2011). This index is computed as the mean of two primary sub-indices: the "Innovation Input" and the "Innovation Output." The former sub-index encompasses five economic pillars, namely: "Institutions," "Human Capital and Research," "Infrastructure," "Market Sophistication," and "Business Sophistication" (World Intellectual Property Organization, 2022). Conversely, the "Innovation Output Sub-Index" evaluates the tangible outcomes of innovative endeavors within the economic sphere. Despite consisting of only two pillars-"Knowledge and Technology Outputs" and "Creative Outputs"—it holds equivalent weight to the "Innovation Input Sub-Index" within the overarching GINNOV. It is pertinent to note that these pillars further branch out into sub-pillars, culminating in a total of 81 individual indicators as of 2022 (World Intellectual Property Organization, 2022).

The temporal progression of the EI, spanning from 1995 to 2021, for EU-27 member states is delineated in Figure 1. An upward trajectory is observed in the EI across the majority of these nations. However, a minor deceleration in recent years is discerned in Bulgaria, the Czech Republic, and Romania. Noteworthy peaks in the 2021 data are observed in Belgium, Finland, and Sweden (each at 0.96), followed closely by Denmark (0.95) and a trio comprising Germany, Greece, and the Netherlands (each at 0.94). Conversely, the nadirs for the same year are found in Romania and Bulgaria (both at 0.77) and Portugal (0.79).

The summarized statistics presented in Table 2 delineate the key indicators for the EU-27 member states over the period of 1995-2021. For the considered duration, the EI showcased a mean value of 0.7986. A minimum value of 0.56 was observed in Croatia in 1995, while a peak of 0.96 was noted in Belgium, Finland, and Sweden in 2021.

During this analysis, the poverty rate (Pvt) exhibited a mean of 23.78%. It reached its nadir at 10.8% in the Czech Republic in 2021 and its zenith at 61.3% in Bulgaria in 2003 (European Commission, 2023). On the employment front, an average rate (ER) of 69.17% was documented for the total population of the EU-27. The most diminished rate was 51.7% in 1995 in the Slovak Republic, with the apogee being 82.4% in 2018 in Slovenia (European Commission, 2023).

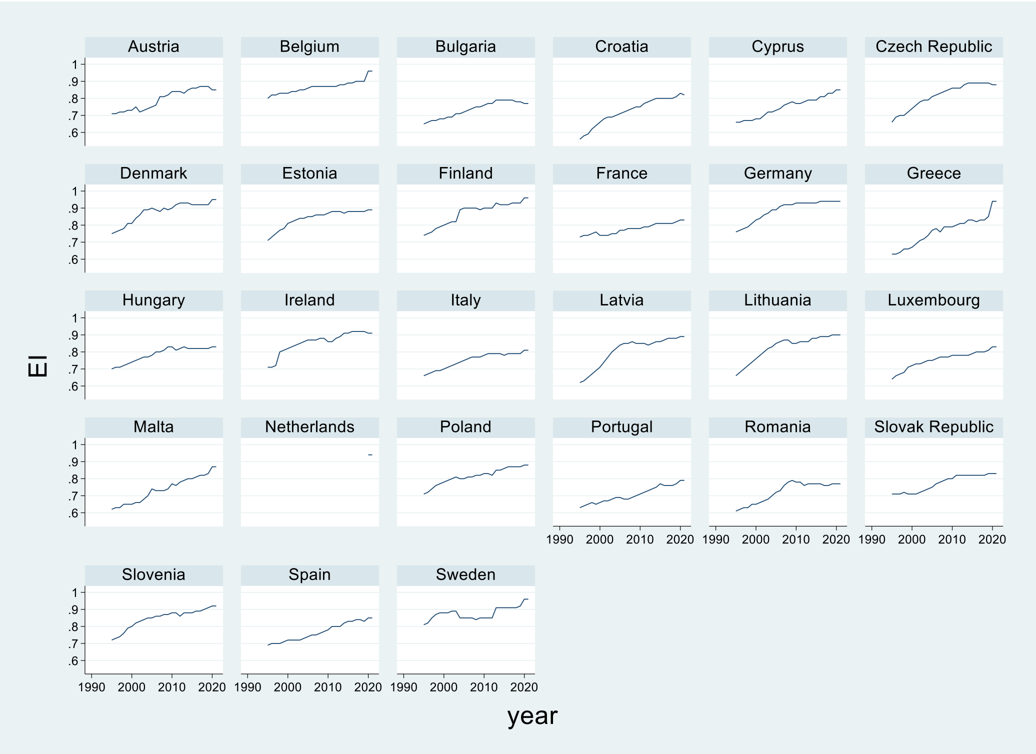

Figure 1. Temporal trajectory of the EI across EU member states, 1995-2021
Source: Authors' contribution in Stata 17

Digital metrics, as chronicled in Table 2, reveal that household internet access (H_IA) averaged at 68.02% of the total households. The upper extremity of this index was nearly absolute at 99.18% in Luxembourg in 2021, while its lower boundary was a mere 3% in Latvia in 2002 (European Commission, 2023). The proportion of individuals who utilized the internet in the previous year (I_IU) demonstrated a mean of 72.22%. Romania recorded the minimum usage at 14.5% in 2004, and Ireland witnessed a nearly ubiquitous rate at 99.23% in 2021 (European Commission, 2023). Moreover, the average contribution of the ICT sector to the GDP (ICT_GDP) was discerned to be 4.27%. Fluctuations ranged from a low of 1.99% in Greece in 2013 to a high of 8.89% in Malta in 2011 (European Commission, 2023). High-speed internet coverage (HSIC) had an average representation of 42.74% of households. Notably, no households in Cyprus had high-speed internet from 2013-2017, in contrast to Malta where the entirety of households had such access between 2019-2021 (European Commission, 2023).

Lastly, the GINNOV was evaluated for the EU-27 countries from 2013 to 2021. It was identified that the average score stood at 48.77. Romania recorded the lowest score of 35.6 in 2021, while Sweden peaked with a score of 63.8 in 2017 (World Intellectual Property Organization, 2022).

Table 2. Synopsis of statistical indicators, 1995-2021

Variables	Count	Mean	Standard Deviation (sd)	Minimum	Maximum
EI	704	0.798608	0.0801016	0.56	0.96
Pvt	473	23.78013	7.80253	10.8	61.3
ER	684	69.17383	6.301472	51.7	82.4
H_IA	506	68.01955	22.59116	3	99.18
I_IU	484	72.22194	18.61209	14.5	99.23
ICT_GDP	255	4.272902	1.20692	1.99	8.89
HSIC	243	42.74033	28.48874	0	100
GINNOV	243	48.76543	7.28586	35.6	63.8
N total	729				

Source: Authors' contribution in Stata 17

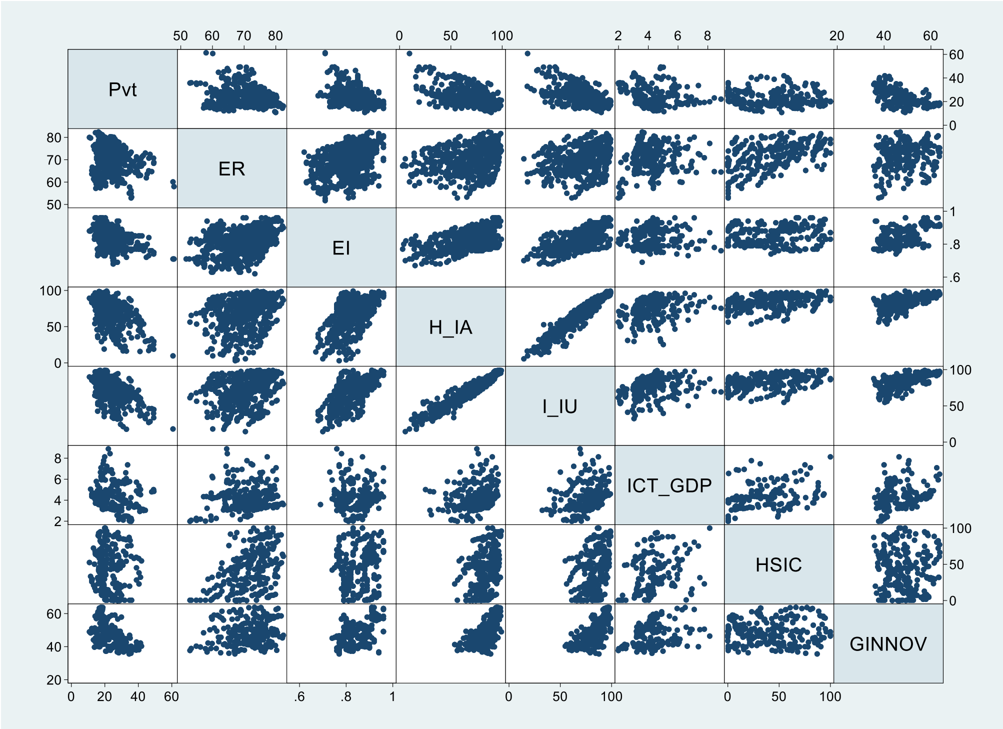

Figure 2. Scatterplot matrix of EU-27 indicators, 1995-2021
Source: Authors' contribution in Stata 17

The data for the aforementioned period, visualized comprehensively, can be found in the scatterplot matrix presented in Figure 2.

RREG were employed in this research, described as "a form of weighted and reweighted least squares regression" (UCLA: Statistical Consulting Group, 2023). Three central attributes of robust regression are efficiency, breakdown point, and bounded influence (Khan et al., 2021). The selection of robust regression was justified due to its capacity to detect influential outliers that might negatively affect regression models, subsequently offering consistent estimates that circumvent spurious regression (Noja et al., 2023).

To address potential outliers, two iterations of RREG, Huber and biweight, were implemented. The decision stemmed from the understanding that while Huber weights can struggle with extreme outliers, biweights might experience convergence issues or result in multiple solutions. Utilizing Huber weights initially was found to mitigate complications with biweights (UCLA: Statistical Consulting Group, 2023). Additionally, the robust regression procedure was beneficial in handling missing values by employing robust regression imputation in the presence of outliers (Rana et al., 2015). It was noted that robust regression differentially weights observations based on their behavior, addressing concerns of high leverage points which can engender multicollinearity problems (Bagheri & Midi, 2009).

Given the overarching aim to discern the reciprocal influence of education and digitalization on innovation levels, two RREG models were constructed. These models were based on alternative dependent variables: the EI for model (1) and the GINNOV for model (2). The underlying structure of the models can be elucidated through Eqs. (1) and (2):

Model (1):

$$EI_{it} = \beta_0 + \beta_1 Pvt_{it} + \beta_2 ER_{it} + \beta_3 H\_IA_{it} + \beta_4 I\_IU_{it} + \beta_5 ICT\_GDP_{it} + \beta_6 HSIC_{it} + \beta_7 GINNOV_{it} + \theta_i + \varepsilon \quad (1)$$

Model (2):

$$GINNOV_{it} = \beta_0 + \beta_1 Pvt_{it} + \beta_2 ER_{it} + \beta_3 H\_IA_{it} + \beta_4 I\_IU_{it} + \beta_5 ICT\_GDP_{it} + \beta_6 HSIC_{it} + \beta_7 \mathrm{EI}_{it} + \theta_i + \varepsilon \quad (2)$$

where, "i = 1,…,n; n denotes sample size; t represents the period of time; θ_i captures the country effects; and ε signifies the error term (residual variable)" (Rousseeuw & Leroy, 2003).

In light of the research objectives and the employed methodology, the following hypotheses were postulated:

- *H1. Digital technology dimensions exert a direct and positive influence on the education level in EU countries.*
- *H2. The innovation index holds a direct and positive impact on the education level in EU countries.*

• *H3. Poverty alleviation strategies have a direct and favorable effect on the education level in EU countries.*

• *H4. Labor market performance, as indicated by the employment rate, directly and positively impacts the education level in EU countries.*

• *H5. Digital technology dimensions directly and favorably influence the innovation level in EU countries.*

• *H6. Poverty alleviation tactics show a direct and positive impact on the innovation level in EU countries.*

• *H7. Labor market performance, as signified by the employment rate, exerts a direct and favorable influence on the innovation level in EU countries.*

• *H8. The EI has a direct and positive effect on the innovation level in EU countries.*

4. Results and Discussions

In evaluating the proposed hypotheses, two RREG models were constructed based on the respective dependent variables: the EI (model (1), presented in Table 3) and the GINNOV (model (2), also detailed in Table 3). The explanatory power of the models, as indicated by the R^2 values in Table 3, surpassed 60% for each dependent variable.

Table 3. Results derived from RREG models, focusing on dependent variables: EI (model 1) and GINNOV (model 2)

Variables	**Model (1)** EI	**Model (2)** GINNOV
Pvt	-0.00136^{*}	0.00418
	(0.000643)	(0.0836)
ER	0.000220	0.248^{***}
	(0.000577)	(0.0720)
H_IA	-0.00225^{*}	-0.241^{*}
	(0.000926)	(0.120)
I_IU	0.00414^{***}	0.553^{***}
	(0.000916)	(0.117)
ICT_GDP	-0.0115^{***}	1.144^{***}
	(0.00254)	(0.328)
HSIC	0.000258	-0.0976^{***}
	(0.000140)	(0.0164)
GINNOV	0.00246^{***}	
	(0.000643)	
EI		26.17^{*}
		(10.17)
_cons	0.647^{***}	-19.57
	(0.0585)	(9.941)
N	155	155
R^2	0.622	0.609

Note: "Standard errors in parentheses; * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$"
Source: Authors' contribution in Stata 17

Findings from model (1) revealed a notable influence of digital technology credentials. Specifically, the percentage of individuals who utilized the internet in the past year (I_IU) was found to exert a favorable and statistically significant influence on the EI at p<0.001. This correlation indicates that a 1% augmentation in internet users corresponds to a 0.00414 increase in the EI score. Conversely, the percentage of households with internet access (H_IA) and the contribution of the ICT sector to the GDP (ICT_GDP) were identified to negatively impact the EI. This suggests a 1% surge in households with internet connectivity would reduce the EI score by 0.00225, and a 1% increase in the ICT sector's GDP contribution would result in a decline of 1.15 in the EI score across all EU nations. Such observations appear to diverge from literature precedents, where increased internet access and utilization were often correlated with enhanced educational opportunities due to improved "access to information" (Mello et al., 2019). Factors that might explain this anomaly include the considerable disparity in internet access among EU-27 nations, as well as the modest contribution of the ICT sector to national GDPs. It is further supported by the broad variance in internet accessibility, which spans from 3 to 99.18% across different nations (as discerned from summary statistics in Table 2) and the relatively small average contribution of the ICT sector to the GDP, estimated at 4.27% across the EU. Given these findings, the first hypothesis, stating a direct and favorable influence of digital technology dimensions on the education level for EU countries, was not supported.

The GINNOV, on the other hand, displayed a favorable and statistically significant impact on the EI at p<0.001. This suggests that an elevation of one rank in the GINNOV could lead to a 0.00246 enhancement in the EI score. Such outcomes align with the findings of Serdyukov (2017) and Kahramonovna (2021), emphasizing the potential of innovations to bolster educational outcomes and efficiency. Consequently, the second hypothesis, proposing a direct and favorable impact of the innovation index on education levels within the EU countries, received empirical support.

A positive correlation, significant at $p<0.001$, was observed between poverty reduction and the EI. The coefficient, estimated at -0.00136, suggests a decline in the education score with an increase in poverty. Consequently, the third hypothesis, postulating direct and favorable impacts of poverty alleviation on the education level within EU countries, was supported.

Regarding the influence of labor market performance, as captured by the employment rate for individuals aged 20-64 years (ER) on the EI, no statistically significant results were observed. Therefore, the fourth hypothesis, suggesting a direct and beneficial relationship between labor market performance, particularly the employment rate, and the education level within EU countries, was not validated.

Analysis of model (2) presented in Table 3 unveiled contrasting effects on the innovation index attributable to digital technologies. Positive, statistically significant impacts on the innovation index were identified with an increase in the percentage of individuals who accessed the internet in the past year (I_IU). Specifically, a 1% rise in such individuals corresponded to a 0.553 increase in the GINNOV. Similarly, a 1% augmentation in the ICT sector's contribution to the GDP (ICT_GDP) led to a 1.144 point elevation in the global innovation score. In contrast, both the percentage of households with internet access (H_IA) and the extent of high-speed internet coverage (HISC) were found to negatively influence the innovation index. A 1% increase in households accessing the internet correlated with a 0.242 point decline in the innovation index, while a similar percentage rise in high-speed internet coverage was associated with a 0.0976 point reduction in the global innovation level. This discrepancy can be attributed to the limited access to high-speed internet in numerous countries, as emphasized by both Dubey & Pandey (2020) and Martinez Puma et al. (2022). Furthermore, Yu et al. (2021) elucidated a causal relationship between ICT (as an input component of GINNOV) and innovation, gauged by the GINNOV. Yet, the fifth hypothesis, positing direct and beneficial effects of digital technology dimensions on the innovation level within EU countries, was not substantiated. It must be noted that while there exists a close association between digitalization and innovation, not all digital advancements culminate in innovation, a sentiment echoed by Afonasova et al. (2019). Lastly, the standard of living, when measured via the poverty rate, did not yield statistically significant outcomes. Hence, the sixth hypothesis, which proposed a direct and positive influence of poverty reduction on the innovation level within EU countries, was not confirmed.

In the study, significant positive effects of labor market performance, represented by the employment rate for the age bracket 20-64 years (ER), on the GINNOV were identified. Consequently, the seventh hypothesis, H7, postulating direct and favorable impacts of labor market performance on the innovation level within the EU countries, was supported.

Moreover, significant positive impacts of the EI on the innovation index for the EU-27 countries were observed ($p<0.05$, estimated coefficient being 26.17). This aligns with findings by Ezell et al. (2016) which proposed that nations possessing superior education systems generally showcase enhanced innovation capabilities. Accordingly, the eighth hypothesis, *H8*, suggesting direct and favorable impacts of the EI on the innovation level for EU countries, was also validated.

Upon analysis, it was discerned that positive associations exist between the EI and several variables: the percentage of individuals who used the internet in the previous year (*H1*), the GINNOV (*H2*), and efforts toward poverty reduction (*H3*). Similarly, the GINNOV displayed favorable relationships with the aforementioned internet usage metric, the share of the ICT sector in GDP (*H5*), labor market performance characterized by the employment rate for individuals aged 20-64 years (*H7*), and the EI (*H8*). However, negative associations were observed between the EI and both household internet accessibility and the GDP contribution of the ICT sector (*H1*). Similarly, the GINNOV had adverse relationships with household internet access and high-speed internet coverage (*H5*). The implications of these findings and potential strategies addressing them will be comprehensively discussed in the Conclusions section.

5. Conclusions

In this study, the interrelationships among digitalization, innovation, and education quality/knowledge were examined, focusing on the years of schooling for adults aged over 25 and the expected years of schooling for children within the EU member states. Two robust regression models were employed, and eight research hypotheses were tested.

For the EU nations, the key findings derived from the hypotheses assessment can be summarized as follows:

- Favorable impacts on education quality were observed when influenced by the percentage of individuals using the internet in the preceding year. Conversely, negative effects were identified when education was associated with household internet access and the ICT sector's GDP contribution (*H1*).
- Positive influences on education quality were determined from global innovation levels (*H2*).
- Favorable impacts on education quality, induced by poverty mitigation efforts, were also identified (*H3*).

- The GINNOV was positively associated with the proportion of individuals using the internet within the past year and the ICT sector's GDP contribution. However, negative correlations emerged when considering household internet access and high-speed internet coverage (*H5*).
- Favorable influences on the GINNOV, related to labor market performance (expressed by the employment rate of the population aged 20-64 years), were established (*H7*).
- The study found positive effects on the GINNOV due to education quality (*H8*).

Drawing from these results, specific strategies are recommended for EU member states. These strategies include enhancing individual or household internet accessibility by identifying the most vulnerable areas, termed "digital deserts", using proxies such as mobile network coverage or socioeconomic status (Beaunoyer et al., 2020). The emphasis on household high-speed internet coverage through innovative means, access to public guest networks, and rural broadband mapping for rural populations are also advocated. Furthermore, accentuating the ICT sector's GDP contribution via innovations in the realms of education and digitalization is deemed essential. As indicated by Borisova et al. (2016) and Kahramonovna (2021), technological advancements hold vast potential to enrich vocational education. However, caution must be exercised, as these innovations don't necessarily guarantee anticipated benefits. It was also noted that the landscape of digital learning blurs the lines between traditional education and training, introducing complexities around its validation (Safapour et al., 2019). Research by Hong et al. (2022) has further emphasized the need for governments to ramp up investments in teacher training, professional development in ICT, and the creation of high-quality educational software.

A systematic approach, built on interdependent strategies, is imperative to dissect the cost-benefit analysis of innovation and digital learning technologies. Herein lies the suggestion of establishing an intermediary organization, envisioned as a knowledge management entity. Such an organization could identify cutting-edge educational methodologies tailored to digital technologies, archive them, and facilitate their dissemination to educational institutions. This could potentially foster the sharing of best practices, and streamline the integration of educators into novel technological paradigms, maximizing their impact.

Certain limitations were encountered in this study, primarily concerning data availability. The dataset didn't encompass all indicators for the entire period of analysis or for all member states. This data scarcity could inadvertently bias the outcomes, consequently attenuating the study's statistical power. Hence, the panel analysis for EU-27 must be approached with circumspection, especially given the development disparities among member states. Future research avenues might explore granular analyses of developed versus developing EU nations and broaden the spectrum of analyzed factors, such as governance indicators. Exploring how government institutions, policy efficacy, stability, corruption control, and citizen respect intersect with education and innovation remains a pertinent subject.

In summary, the investigation underscored the pivotal roles of digital transformation, innovation, internet access, and living standards in shaping education quality. Concurrently, digital transformation, education quality, and labor market performance emerged as significant propellants for global innovation.

Author Contributions

All authors equally contributed to the article, and they have read and agreed to the published version of the manuscript.

Data Availability

The data used to support the research findings and the software code/commands are available from the corresponding authors upon request.

Conflicts of Interest

The authors declare no conflict of interest.

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