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Understanding the relationship between technological innovation and environmental sustainability under the silver lining of education

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Information and communication technology has gradually become one of the most important pillars of the economy. In addition to economic growth, environmental pollution is a product of information and communication technologies (ICTs) as well. However, whether and how ICTs may affect these systems is unclear. Based on a more comprehensive measurement of ICTs, the current study has investigated the impact of ICTs, education, and economic performance on environmental sustainability from 2000 to 2019 across 93 countries categorized as low-income, middle-income, and high-income. Contrary to preceding studies, this research has used advanced econometric techniques to counter heterogeneities and dependencies in the data and, thus, has produced more trustworthy and efficient results. The finding obtained from the Bias-corrected method of the moment's estimator and Driscoll and Kraal's standard error techniques are consistent. According to the results, ICTs have a heterogenous effect on environmental sustainability across low-, middle- and high-income countries. Further results have revealed that education plays a significant role in maintaining environmental sustainability across middle—and high-income groups but does not seem to do so for lower—income groups. Environmental education for all should be part of the policy measures to tackle climate change across all income groups.

KEYWORDS

information and communication technologies, education, environmental, middle income countries, high income countries, low income countries

1 Introduction

The largest yearly climate change conference in the world is the Conference of the Parties (COP). International organizations like the COP are promoting the Sustainable Development Goals (SDGs) to help with climate change adaptation. About 200 nations signed the Climate Pact at COP26 to lower carbon emissions worldwide. Money was the main issue of discourse during COP 26. According to developing nations, the shift to using more renewable energy and less nonrenewable energy should be facilitated by acquiring funding and transferable technologies. (Xu et al., 2020). At least $100 billion will be committed over the following year as a direct result of COP 26 to help developing countries achieve a net-zero environmental footprint. The Paris Agreement aims to keep global warming to 1.5°C between 2020 and 2025 by cutting emissions. The United Nations (hereafter UN) COP26 2021 conference on climate change provides an urgent and meaningful commitment and provides a better opportunity for world leaders to take action to limit global temperature to 1.5°C above preindustrial levels by 2050. This reversal of climate change requires a concerted effort by everyone, including researchers in information technology and related fields, to develop a robust and comprehensive research agenda (Dwivedi et al., 2022). ICTs and their development have provided a vast means for information transmission in the form of internet, telephony and media (Zhou and Li, 2022).

Nowadays, countries are facing environmental challenges, including climate change, energy efficiency improvement, proper waste management, the quality of water, and scarcity. Climate change is a universally recognized fact that affects humans, businesses, industry, and the environment in various forms (Dwivedi et al., 2022). This resulted in changing patterns of global weather, with frequent hurricane incidence, drought and mounting temperatures triggering habitats to vanish and altering ecosystems. Recently, fast-growing global society, development, and economy have brought serious environmental issues, including air pollution, the greenhouse effect, and ecosystem degradation. The significance of ICT will rebuild society and affect society for tomorrow. ICTs are essential for industrialization and eventually affect economic performance and the environment. ICTs also contribute directly and indirectly to the economic, social, and environmental dimensions of the Sustainable Development Goals (hereafter SDGs). ICTs provide the basis for monitoring climate change, mitigating and adapting its impacts, and supporting the transition to a green and circular economy. Nevertheless, in the productive role of ICTs in improving economic performance, future environmental impacts of ICTs, including the role of satellites, mobile phones, or the Internet are ignored. All of these have an important role to play in tackling the major challenges of climate change and sustainable development. Simultaneously, since the 1980s, the growing use of ICT has encouraged economic output and influence the ecological environment to a certain degree, which has this attract the scientific community to take a keen interest in evaluating the environmental impact of ICT, which has grown considerably (Wang and Xu, 2021).

Technology plays a dominant role in the promotion of intelligent development of environmental governance and innovative applications in the field of environmental protection (Wu et al., 2021a; 2021b). For the achievement of Sustainable Development Goals (SDGs), governments have dedicated themselves to promoting policies towards a sustainable environment (N'dri et al., 2021). However, sustainability through ICTs is a complex matter (Chien et al., 2021), and its environmental impact is still not clear, despite the critical role of ICT in combating climate change challenges the digital era (Zhou et al., 2019). The complex nature of ICT is similar in both developed and developing countries. In view of the exact futuristic role of ICT is not known, and how today's decision will set the direction of sustainable development is unknown. For better life standards, the inclusion of ICT should be tailored towards encouraging human rights, privacy, and security (Zhou and Li, 2022). So based on the aforementioned discussion, this study examines the role of ICTs in environmental sustainability, considering the role of education and digital trade across the globe.

The additional feature of this empirical work is as follow: first, this empirical inquiry examines the information technology-environmental sustainability relationship for 93 countries from 2005 to 2019. In this study, countries are categorized as low-income, middle-and high-income to capture the difference in environmental impact of ICT across income region. We employ a more detailed measure of ICTs by developing an index. Although available literature mainly focused on either internet use or mobile phone descriptions. We focus on three ICT services: mobile phone, fixed broadband subscription, and internet use provides better insight into policy making for improving environmental quality.

Second, this study introduces a newly developed technique of bias-corrected moment estimator that have been ignored in earlier studies and that are robust for heteroskedastic errors, higher-order autoregressive models and cross-sectional dependence. Henceforth, this paper has proposed more efficient and unbiased findings than previous studies in the ongoing literature. The robust findings of this paper provide a guideline for policymaker to make more accurate recommendations.

Third, we examine the importance of ICTs in the environment across various income groups in different countries. From a policy perspective, it is very important to examine what happens across different income groups. To overlook distributional heterogeneity during empirical analysis may generate counterfeit regression findings and, subsequently inappropriate policy suggestions. From what we know from the literature, none of the papers examined the relationship between ICTs and carbon emissions across different income groups in countries, considering education and digital trade. To summarize, such a holistic methodological assessment is lacking so far in the literature. So, the estimation results of this paper provide direction to world economies in designing better policies to tackle climate change issues.

Our study is divided into four primary portions for the remainder of it. The research gives an overview of related studies on the topic in Section 2. In Section 3, the information on the data and techniques used in this study is detailed. The detailed analysis and explanation of the projected results are covered in Section 4. Section 5 of the report concludes with conclusions and suggestions for future policy.

2 Literature review

2.1 Theoretical underpinning

The closely related literature that lends support for this area comes from production theory. An eminent economist, Robert Solow, once pointed out the productivity paradox of the US economy to explain why productivity stagnated regardless of having powerful computing abilities. Since the early debate on the productivity paradox, the role of ICTs in promoting economic growth and increasing productivity has been well acknowledged. In addition to improving productivity (Ollo-López and Aramendía-Muneta, 2012), ICTs substantially decrease emissions by supporting to building smart cities, electric grids, transportation systems, and efficient business processes. It also plays an important role in optimizing production processes and increasing carbon productivity as an input to production systems (Dedrick et al., 2010). Watson et al. (2010) believe that transformation is an important component of ICTs that can help build an environmentally sustainable society. In theory, the production perspective of ICT, such as the production of ICT equipment and instruments, energy use, and recycling of electronic waste, is responsible for enhancing CO_2 emissions. On the contrary, ICT reduces CO_2 emissions at the global level by promoting smart city projects, efficient transportation systems, smart grids, and energy-saving gains (Añón Higón et al., 2017). The impact of ICT is obvious on society and technology has brought us to the edge of a new social and cultural era of transition. The importance of ICT and advancement in technology is undeniable, but the debate on the environmental impact of ICT is still growing gradually. The notion that ICT is an important determinant of economic growth and productivity has been well acknowledged. Thus, complementing the popular environment's Kuznets curves, where an inverse relation is often expected between economic growth and environmental sustainability in the long run. To conclude, production theory and the environmental Kuznets curve hypothesis provide the foundation for this study.

2.2 ICT's and environmental Kuznets curve (EKC) studies

Empirical work regarding the ICT-pollution nexus has been widespread and continues to grow. Anyway, studies belong to individual countries, groups of countries, and cross-regional studies, and the data span covered has varied. Similarly, different measures have been used for both ICTs and the environment. Apart from this, these studies have employed various estimation tools. The studies on the evidence are summarized below in this section. Several studies have investigated the ICT-emissions nexus controlling the model for various indicators. Among those, Sahoo et al. (2021) considered financial development; Haldar and Sethi, (2022) renewable energy, innovation and trade; Evans and Mesgan (2022) governance and regulation; Danish, (2019) trade and foreign direct investment (hereafter FDI); Liu et al. (2021) corruption; Caglar et al. (2021) and Charfeddine and Kahia. (2021) renewable energy consumption; Chatti and Tariq, (2022) smart urbanization; Chatti. (2021) freight transport; Magazzino et al. (2021a) electricity consumption; Altinoz et al. (2021) total factor productivity and Ulucak and DanishKhan. (2020) globalization in ICTs and carbon emissions nexus. However, in the first strand, studies related to the impact of ICTs on carbon dioxide (hereafter CO_2) emissions within the environmental Kuznets Curve (hereafter EKC) are discussed. For instance, Chien et al. (2021) used the Methods of Moments-Quantile Regression (hereafter MMQR) method for testing the EKC hypothesis for BRICS countries. The empirical findings have recommended the beneficial role of ICT in improving environmental quality, along with the confirmation of the presence of the EKC hypothesis. A similar conclusion has been drawn by Sahoo et al. (2021) during an insight for India; Danish. (2019) for Belt and Road Initiative (hereafter BRI) countries; Danish et al. (2019) for high income, middle-income and lower income countries; Danish et al. (2018) for emerging countries; Park et al. (2018) for European Union (hereafter EU) countries; and Haldar and Sethi. (2022) for 16 emerging countries. Evans and Mesgan (2022) approved the EKC hypothesis in 31 African countries during ICT-trade and environment nexus in terms of the significance of the moderating role of governance and regulation. Añón Higón et al. (2017) estimated non-linear relationship between ICT and CO_2 emissions with the validation of the EKC hypothesis for developing and developed countries. Liu et al. (2021) investigate the effect of ICTs and corruption on CO_2 emissions within the EKC hypothesis. The empirical estimation suggests that both ICTs and corruption increase CO_2 emissions. The EKC is relevant to the significance of ICT and corruption in Asian countries.

Hypothesis 1: Whether or not EKC exists in the significance of ICT's.

2.3 ICT's and environmental degradation

In the second aspect, studies related to the linear and non-linear relationship between ICT and CO_2 emissions with various additional variables have been reviewed. These studies are divided into two groups. One group of studies has recommended the beneficial role of ICT in reducing carbon emissions. In this regard, Usman et al. (2021) conducted a symmetric and asymmetric analysis of ICT on CO_2 emissions for selected Asian countries. The number of countries where ICT disturbs the emission of CO_2 has not changed much in linear and non-linear models. However, the asymmetric impacts of ICT on CO_2 emissions intensified and were perceived in more than half of the sample countries. Following a non-linear model, Ben Lahouel et al. (2021) showed that ICT could boost economic growth and mitigate climate change. N'dri et al. (2021) identified the long run relationship between ICT and CO_2 emissions for 58 developing countries through a pooled mean group autoregressive distributive lag (hereafter PMG-ARDL) estimator. The empirical analysis clarifies that ICT usage reduces carbon emissions in low-income developing countries, whereas an insignificant relationship was found for high-income developing countries. In line with this, Khan et al. (2020) documented the beneficial role of ICT in carbon emissions reduction for a panel of 91 countries.

Another group of studies has concluded that ICT has an adverse impact on environmental quality. Asongu et al. (2018) studied whether ICT penetration decrease CO_2 emissions in sub-Saharan African countries. From the generalized method of moments (hereafter GMM), the conclusion is drawn that there is no linear relationship between ICTs and CO_2 emissions. Besides, the non-linear relationship between internet penetration and CO_2 emissions is positive and significant, whereas increasing mobile phone penetration alone decreased CO_2 emissions. Besides, Avom et al. (2020) studied the impact of various channels of ICT on CO_2 emissions in 21 sub-Saharan African countries. Both internet and mobile penetration have a linear and non-linear impact on CO_2 emissions, and these indicators of ICTs worsen environmental quality. Alataş (2021) employed various mean group estimators to investigate the impact of ICT on carbon emission in the context of globalization for 93 countries. The findings have provided evidence

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TABLE 1 Summary of descriptive statistic.

Descriptive statistic															
	Low-income countries					Middle income countries					High income countries				
Variables	Obs.	Mean	Std.Dev.	Min		Obs	Mean	Std.Dev.	Min	Max	Obs	Mean	Std.Dev.	Min	Max
Ln CO_2	300	−0.1849	0.9277	−1.9828	1.9037	435	1.0795	0.7635	−1.8428	2.7112	645	2.1443	0.5887	0.4895	3.7962
Ln gdp	300	3.2633	0.2412	2.8404	3.9607	435	3.7692	0.2289	2.9629	4.1782	645	3.3408	0.2538	3.9329	5.0508
Ln tech.	300	−0.2166	0.9881	−4.1106	1.4370	435	0.1494	0.9817	−2.8441	2.5749	645	0.1246	2.2726	15.4681	25.5109
Ln edu	300	1.0374	0.0868	0.7558	1.1789	435	2.5972	0.1060	2.3608	2.8735	645	4.4866	0.1677	2.8443	3.9249
Ln dgt.	300	0.7931	0.3613	0.1707	1.9707	435	0.9271	0.3738	0.0358	1.9107	645	20.1946	0.9550	−2.0877	2.5134
Correlation matrix															
	Ln CO2	Ln gdp	Ln tech.	Ln edu	Ln dgt	Ln CO2	Ln gdp	Ln tech.	Ln edu	Ln dgt	Ln CO2	Ln gdp	Ln tech.	Ln edu	Ln dgt
Ln CO_2	1					1.000					1				
Ln gdp	0.7536	1				0.6284	1.000				0.3927	1			
Ln tech.	0.6371	0.3917	1			0.5385	0.3592	1.000			0.0578	0.0303	1		
Ln edu	0.5871	0.6315	0.3670	1		0.3189	0.4678	0.5123	1.000		−0.3363	0.1906	0.1680	1	
Ln dgt.	0.3146	0.2877	0.4618	0.2689	1	0.3828	0.6392	0.5263	0.2015	1.000	−0.1115	−0.0291	0.2378	0.237	1

TABLE 2 Bias-corrected method of moments estimator.

Regressors	Low-income countries			Middle income countries			High income countries		
	Coeff. [*p*-value]	Coeff. [*p*-value]	Coeff. [*p*-value]	Coeff. [*p*-value]	Coeff. [*p*-value]	Coeff. [*p*-value]	Coeff. [*p*-value]	Coeff. [*p*-value]	Coeff. [*p*-value]
Ln gdp	−5.096 a [0.003]	−4.963 a [0.004]	−5.189 a [0.006	5.358 a [0.001]	5.512 a [0.000]	4.974 a [0.002]	1.243 a [0.000]	1.237 a [0.000]	1.229 a [0.000]
Ln gdp²	0.635 b [0.012]	0.594 b [0.015]	0.617 b [0.023]	−0.678 a [0.001]	−0.699 a [0.000]	−0.623 a [0.000]	−.0248 b [0.039]	−0.024 b [0.038]	−0.024 a [0.000]
Ln tech.	−0.025 [0.993]	−0.003 [0.899]	−0.011 [0.585]	−0.012 [0.460]	−0.016 [0.309]	−0.010 [0.547]	−.0514 b [0.016]	−0.052 b [0.030]	−0.053 b [0.029]
Ln dgt.	--	0.0253 b [0.025]	0.093 b [0.011]	--	−0.036 [0.269	−0.042 [0.223]	--	.0052 [0.772]	0.006 [0.727]
Ln Edu.	--		0.485c [0.097]	--	--	−0.393 c [0.054]	--	--	−0.056 b [0.023]
Constant	9.941 [0.001]		9.864 [0.002]	−10.340 [0.004]	−10.597 [0.001]	−9.219 [0.001]	0.7536 [0.005]	0.750 [0.005	0.743 [0.005]
Number of groups	20	20	20	29	29	29	43	43	43
No. of observation	240	240	240	406	406	406	559	559	559

Note: a for 1%, b for 5% and c for 10% significance level. The square bracelets cover probability values.

that ICT is one of the driving factors that contribute to CO_2 emissions. However, globalization positively contributes to carbon mitigation. The similar result for ICT and CO_2 emissions is corroborated by Charfeddine and Kahia (2021) in the significance of renewable energy consumption for the Middle East and North Africa (hereafter MENA) region. The findings were further verified by Chatti (2021) and Chatti and Tariq (2022) for 42 countries and developing and developed countries, including freight transport and smart urbanization in the ICT-CO_2 emissions nexus, respectively. However, Awad (2022) determined as insignificant relationship between ICT services and CO_2 emissions for 47 sub-Saharan African countries.

Thirdly, some papers have considered ecological footprints for measuring environmental sustainability while investigating the ICT-environment relationship. Among those, Kahouli et al. (2022) documented the impact of ICT, green energy, and total factor productivity on the ecological footprint in the Kingdom of Saudi Arabia. The empirical investigation indicates that ICT is helpful in reducing ecological footprints. In another study, Caglar et al. (2021) concluded the positive role of ICT in abating environmental deterioration in world's top 10 polluted footprint countries. Kazemzadeh et al. (2022) highlighted the ICT impacts on ecological footprint for in the emerging countries. The result of the study is interesting since ICT does not influence ecological footprints. Özpolat (2021) probed the link between internet use and ecological footprints for a group of seven (hereafter G-7) countries employing Augmented Mean Group (AMG) panel data estimation method. According to the study's results internet use negatively impact environmental degradation. However, Huang et al. (2022) estimated the dynamic relationship between ICT, renewable energy, economic complexity and ecological footprint by comparing of the E–7 (developing) and G-7 (developed) countries. According to the empirical findings, ICT increases pollution in E–7 countries and decrease ecological footprint in G-7 countries.

Hypothesis 2: ICTs has significant either positive or negative impact on the environmental sustainability.

2.4 Information technology, education and CO_2 emissions studies

Only a few studies in the literature have included education as a determinant of carbon emissions in the ICT and CO_2 emissions model. Likewise, Shobande and Asongu. (2022) discussed the critical role of ICT and education in the environment, and the empirical findings infer that both information technology and education play prominent role in promoting environmental sustainability. For South Asian economies Zafar et al. (2022a) captured the effect of ICT and education on environmental quality. Panel data estimation tools recommended the positive role of both ICT and education in CO_2 emissions. The similar negative role of education in environmental quality is found by 22 top remittance-receiving countries. Zhang et al. (2022) unveiled the role of education in the environmental impact of ICT in developing countries. According to the study's findings, ICT increases environmental quality, but interestingly, education has a detrimental effect on the environment. Apart from this, Zaman et al. (2021) and Liu

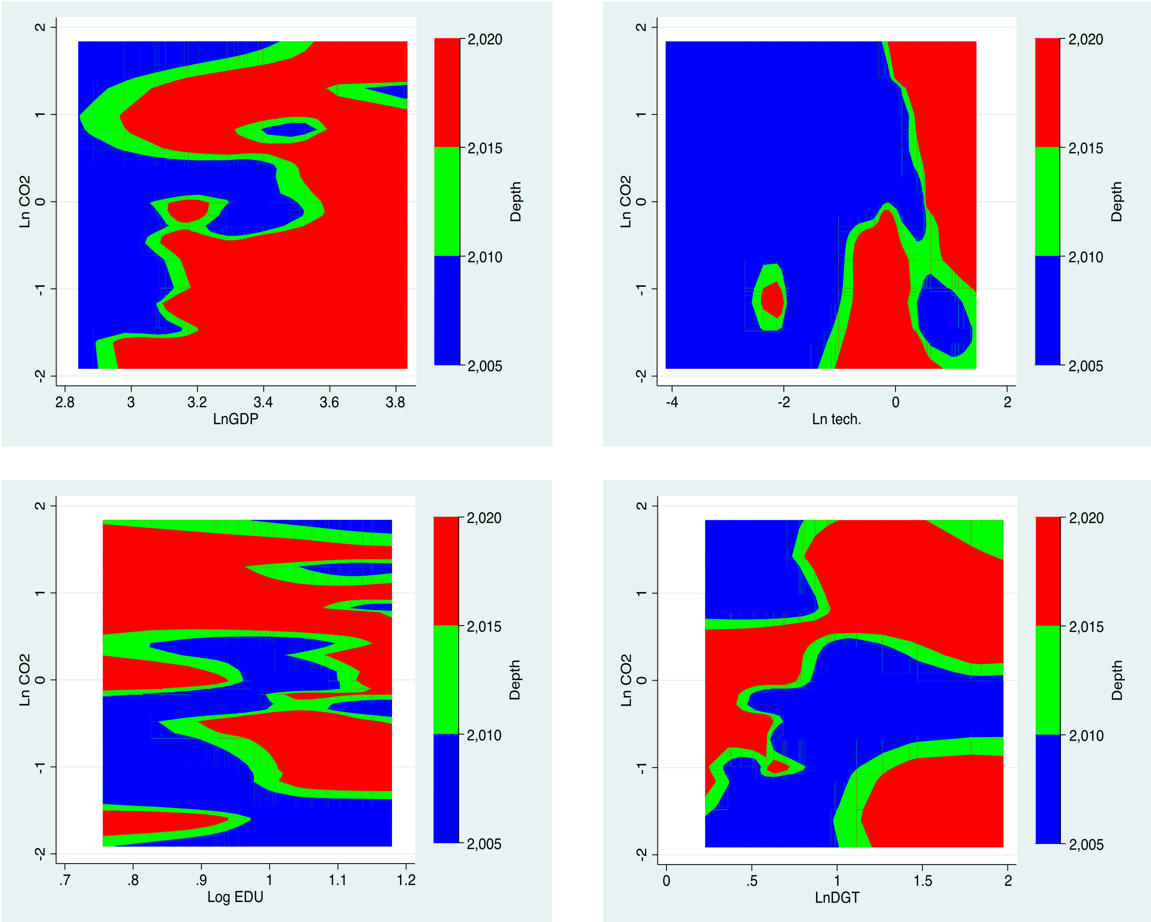

FIGURE 1
Shows the impact of explanatory variables on CO_2 emissions for low-income countries.

et al. (2022) concluded that education helps reduce carbon emissions in China. Sarwar et al. (2021) analyze that environmental quality can be improved through better education standards across 179 countries, and a similar argument was developed by Mehmood (2021) for G-11 countries.

Hypothesis 3: Education helps in improving environmental sustainability.

2.5 Literature gap

From the evaluation of earlier studies, the role of ICT in environmental degradation is unknown, and the future role of ICT in environmental degradation is unknown. Despite the larger number of studies that have investigated the impact of ICT on environmental quality, we found some deficiencies in the earlier studies. First the results are misleading because of result differences, so the conclusion and recommendations are deceptive. Second, measurement of ICT services is based on two proxies: mobile phone penetration and/or internet penetration. So, the misleading results might be due to ICTs measurement and/or the empirical methodologies employed in earlier studies. To gain a better understanding of the role of technology in the environment, this inquiry focuses on the role of technology, education, and digital trade in the environment across various income groups of countries. This paper considers a more comprehensive measure of information technology and recently developed econometric tools for empirical analysis such as Bias-corrected method of moments estimator by Breitung et al. (2021).

3 Materials and methods

3.1 Model formulation

The widespread use of mobile phones, the internet, and other ICT applications has encouraged substantial investments in ICT assets. The concept of smart cities, smart grid transportation systems, and the achievement of energy-savings globally are expected due to huge ICT investment, and these can help in energy efficiency improvement. For example, shifting from paper books to electronic books and electronic paper, tele-conferencing instead of traveling,

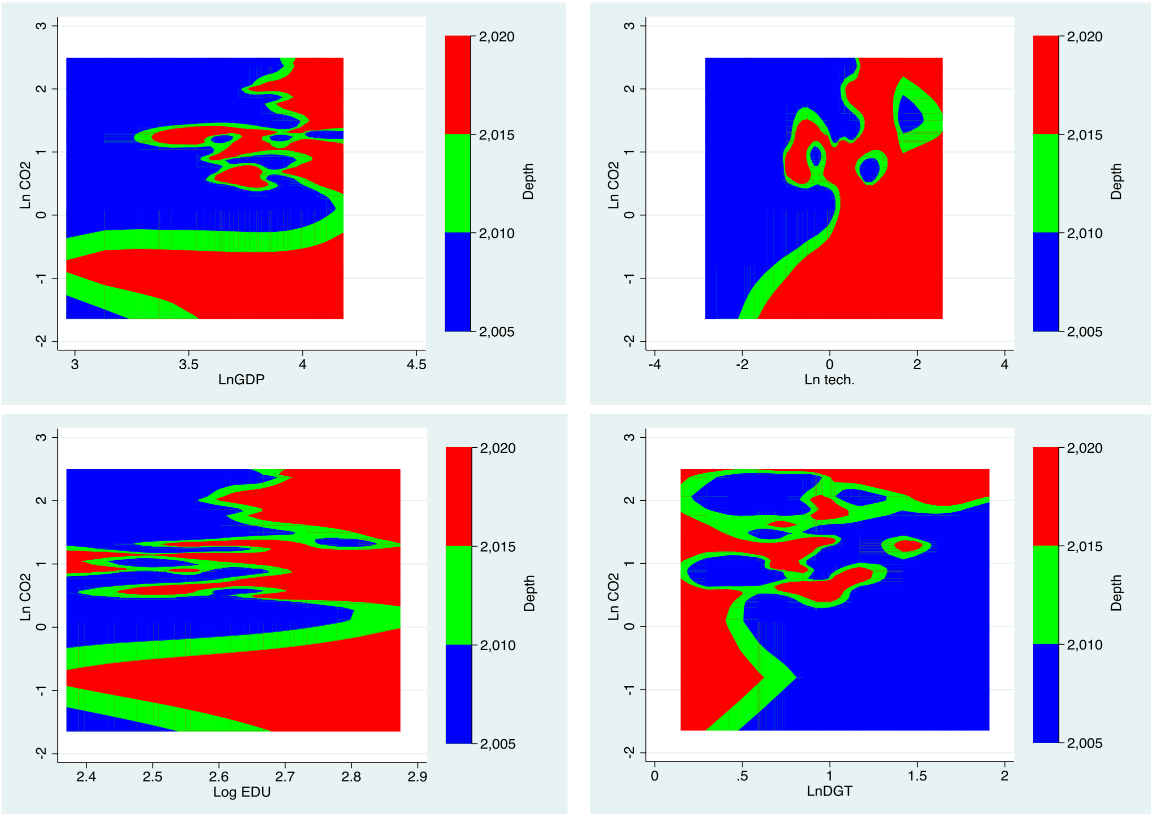

FIGURE 2
Shows the impact of explanatory variables on CO_2 emissions for Middle-income countries.

working from home rather than at the workplace, online food services, and online shopping all become possible only due to ICT advancement. All these activities have limited outdoor activities, so ultimately energy consumption will decline. Another aspect of ICT advancement is that energy saving has become easier in some areas of life, which exceeds ICT-induced surplus energy use in other areas. Likewise, smaller ICT devices, including laptops, smartphones, and others, are energy efficient. It can be assumed that the world is benefiting from the technology spillover effect because of meaningful technological development over the past 3 decades. To interpret this ICT use, the quality of the environment and the environmental implication of ICT become significant. To this end, the ICT-pollution nexus for the study is investigated with the EKC framework, which is expressed as:

$$Ln\,(CO)_{2it} = \alpha_0 + Ln\,\beta_1\,(Tech)_{it} + Ln\,\beta_2\,(GDP)_{it} + Ln\,\beta_3\,(GDP)^2_{it} + Ln\,\beta_4\,(dgt)_{it} + +Ln\,\beta_5\,(Edu)_{it} + \varepsilon_{it} \tag{1}$$

Where CO_2 emissions mean carbon dioxide emissions as a proxy for environmental sustainability, technology refers to information and communications technologies, *DT* is digital trade, *GDP* means gross domestic product as a measure of economic performance, and *EDU* indicates education for "i" cross-section and time period of "t". If the co-efficient values of β_1 greater than zero and β_2 less than zero are directed toward the existence of the *EKC hypothesis*. Motivation of control variables in the model is determined by the perception of their impact on CO_2 emissions, as mentioned in the literature. Recently, education has been observed to be the key driving force behind environmental quality. Climate change is influenced directly by inhabitants' lifestyles and the lives of individuals, so education is important to raise awareness among citizens and should be a significant part of the policy drive. With this in mind, "education for the future" aims to provide youth and children with climate awareness so that policy analysts can use their creativity, benefit from their willingness to learn and energy to develop sustainable solutions, particularly through ICT technology (World Economic Forum, 2021). Education is expected to have a positive effect on environmental quality by lowering CO_2 emissions.

3.2 Econometric methods

For panel data, empirically implausible dynamic models are widely used. Since the work of Anderson and Hsiao (1981) for short panel data with large samples and short periods GMM estimators have been broadly used for linear dynamic panel data model estimation. But the GMM method by Eakin et al. (1988) and Arellano and Bond (1991) suffers from the weak-

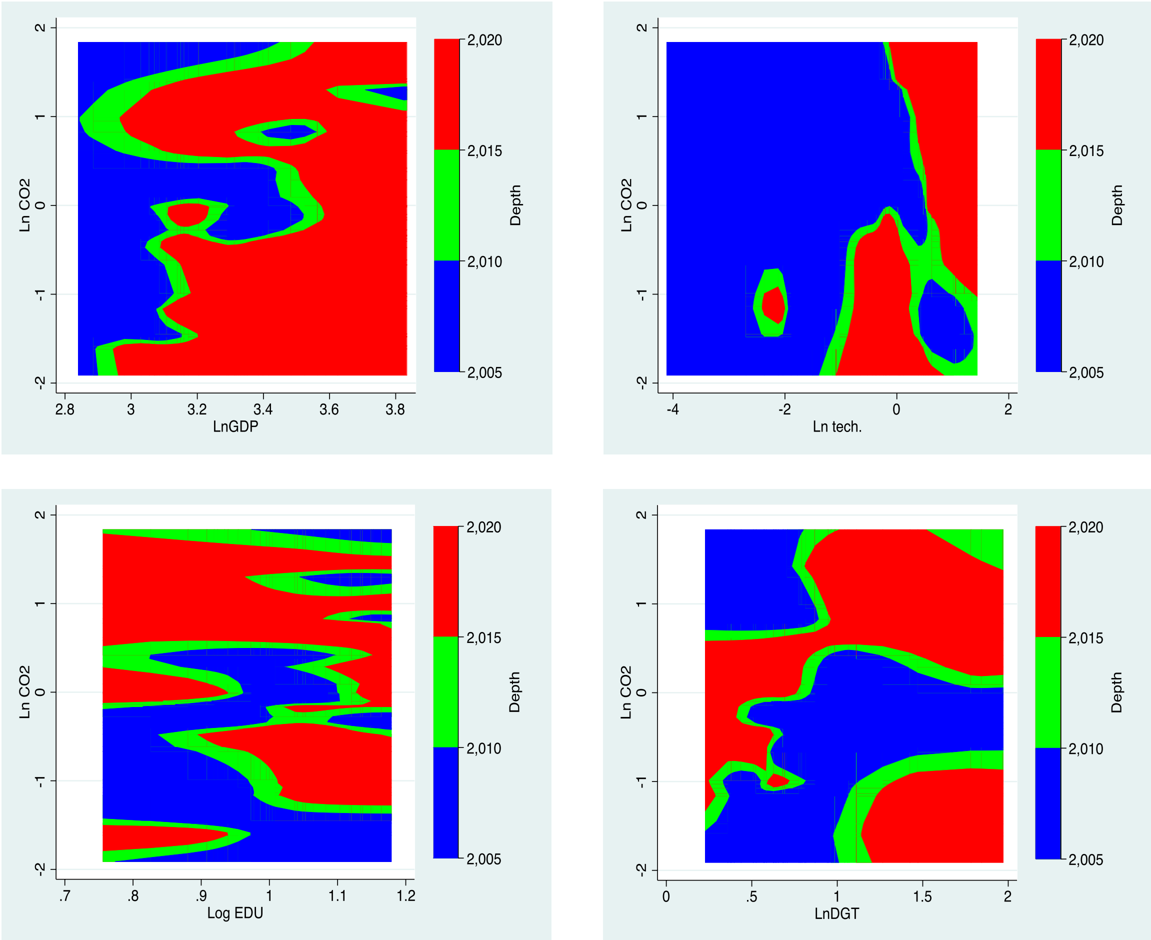

FIGURE 3
Shows the impact of explanatory variables on CO_2 emissions for Middle-income countries.

instruments issue in the case of the strong persistency of the data, as verified by (Blundell and Bond, 1998). As an alternative, they developed the so-called system GMM method, which mitigates the problem for models in levels with first-differenced instruments. Nowadays, the system GMM method is widely used but Bun and Windmeijer, (2010) disclosed that dynamic GMM suffers from the issue of weak instruments when the variance of the individual-specific effects is larger than that of the idiosyncratic errors. On this note, Breitung et al. (2021) proposed a newly developed technique. Recently the bias-corrected method of moment (BCMM) method overtakes prevalent GMM approach with regard to efficiency and accurately sized tests. This technique can adjust both fixed-effects and random-effects heteroskedastic errors in higher- order autoregressive models as well. If cross sectional dependance is present in the data and there is moderate persistence, the Breitung et al. (2021) estimator appears robust. The BCMM test is free from the assumption of preliminary standards of the dynamic process, and a preliminary estimator is not necessary. With regard to model specification, employing the Breitung et al. (2021) estimator tolerates additional control variables in large numbers and handles an equitably dynamic adjustment process in the independent variables, too.

3.3 Data

This study's sample covered 93 countries from 2005 to 2019. The selection of countries and the time were based on the availability of data. Panel data allow academics to model dissimilarities in behavior within groups more efficiently and flexibly. The ICT index is based on three the ICT services: mobile cellular subscriptions (per 100 people), fixed broadband subscriptions (per 100 people), and individuals using the internet (per 100 people). For construction of the ICT index, we have used the principal component analysis (PCA) technique for three ICT services[1]. Digital trade is calculated as the amount of sum of the exports and imports of ICT goods and services. Education is measured through the education index, defined as the average mean years of schooling (of adults) and anticipated years of schooling (of children). Economic performance is calculated through *per capita* GDP (constant 2015 US dollar), and its square was also integrated to validate the EKC hypothesis.

1 The PCA analysis results are not shown in the paper due to space constraints, but they can be provided upon request.

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TABLE 3 Results of DK-Regression method with fixed effect for low-, middle- and high-income countries.

Regressors	Low-income countries			Middle income countries			High income countries		
	Coeff. [*p*-value]	Coeff. [*p*-value]	Coeff. [*p*-value]	Coeff. [*p*-value]	Coeff. [*p*-value]	Coeff. [*p*-value]	Coeff. [*p*-value]	Coeff. [*p*-value]	Coeff. [*p*-value]
Ln gdp	−0.661 [c] [0.076]	−0.857 [b] [0.036]	−0.966 [a] [0.034]	21.506 [a] [0.000]	21.375 [a] [0.000]	20.984 [a] [0.000]	13.042 [a] [0.000]	10.455 [a] [0.000]	10.109 [a] [0.000]
Ln gdp^2	0.091[c] [0.098]	0.119 [b] [0.048]	0.134 [c] [0.045]	−2.712 [a] [0.000]	−2.688 [a] [0.000]	−2.603 [a] [0.000]	−1.498 [a] [0.000]	−1.186 [a] [0.000]	−1.135 [a] [0.000]
Ln tech.	0.007 [0.180]	0.004 [0.594]	0.003 [0.608]	0.220 [a] [0.000]	0.235 [a] [0.000]	0.267 [a] [0.000]	−0.094 [a] [0.004]	−.0827 [b] [0.013]	−0.028 [b] [0.026]
Ln dgt.	--	0.026 [0.122]	0.026 [0.114]	--	−0.099 [0.177]	−0.160 [b] [0.040]	--	0.202 [c] [0.051]	0.185 [c] [0.065]
Ln edu	--	--	0.052 [0.109]	--	--	−0.878 [a] [0.001]	--	--	−1.420 [0.002]
Constant	1.2029 [c] [0.055]	1.5185 [b] [0.026]	1.6648 [b] [0.025]	−41.344 [a] [0.000]	−41.100 [a] [0.000]	−38.500 [a] [0.000]	−26.083 [a] [0.000]	−20.996 [a] [0.000]	−18.746 [a] [0.000]
R-squared	0.021	0.032	0.034	0.54	0.53	0.53		0.195	0.233
F-value	6.72	7.04	5.69	1,542.82	1,535.25	3,540.38		103.16	161.58
Prob > F	0.0056	0.0030	0.0054	0.000	[0.000]	0.000		0.000	0.0000
Number of groups	20	20	20	29	29	29	43	43	43
No. of observation	280	280	280	435	435	435	860	860	860

Note: a for 1%, b for 5% and c for 10% significance level. The square bracelets cover probability values.

Various sources were accessed to collect the data for the variables of the study. Data on the GDP *per capita* and three measures for the ICT index and digital trade were gathered from the database of the World Bank (http://data.worldbank.org). Data about the education index is borrowed from the Human Development Data Center (http://hdr.undp.org/en/data). It is beneficial to conduct a preliminary analysis of variables before exploring the relationship between them. The outcome of descriptive statistics and the correlation matrix are shown in Table 1.

4 Results and discussion

This paper estimated the empirical model (Eq. 1) through the bias-corrected method of moment estimators. The reported results in Table 2 suggest the impact of economic performance (Ln GDP) and its square (LnGDP^2) on carbon emissions is negative and positive for low-income countries. The negative-positive impact of GDP denied the existence of the EKC curve in low-income countries. Against this, for the impact of economic performance, positive and negative coefficients of GDP are observed for middle- and high-income countries. The positive-negative effect of GDP infers that middle- and high-income countries confirm the EKC hypothesis. So, results found a U-shape in low-income countries and an inverted U-shape relationship for middle- and high-income countries, corresponding to economic performance and CO_2 emissions. Likewise, ICT has positive and significant impact on environmental degradation in low-income countries. For middle income countries, ICT has an insignificant relationship with carbon emissions, and finally information technology averts environmental pollution in high-income countries. Another variable that reveals a negative relationship with carbon emissions across low-income, middle- and high-income groups is education. Further results show that digital trade increases carbon emissions in low-income countries but decreases them in middle- and high-income countries. The graphical representation of the impact of explanatory variables on CO_2 emissions for low-income, middle-income, and high-income countries is shown in Figure 1, Figure 2 and Figure 3 respectively.

5 Discussion

According to the results (Table 3), economic performance led to environmental pollution in low-income countries. The negative-positive relationship between economic performance and its square recommends a U-shaped relationship for the EKC curve. From an economic point of view, as economy of low-income countries are in their developing stages, as the economies grow, consumption of goods and services increase, which causes a rise in energy demand and CO_2 emissions. The negative role of economic performance in environmental pollution in the ICT-growth-emissions model can be associated with earlier work that estimated the same results. For instance, Lin and Zhou (2021) estimated a U-shaped relationship between economic performance and environmental conditions in Chinese provinces. Contrary to this, economic performance is a driver for environmental sustainability, as well as reflected in the results that better economic performance lowers carbon emissions once the economy reaches it optimum level. The positive and negative coefficients of economic performance validated the inverted U-shaped relationship and directed toward the EKC curve in middle- and high-income countries. For an economic perspective, this finding is corroborated by the fact that environmentally cognizant customers are willing to control energy use through the purchasing of energy-efficient appliances, electric vehicles, or trains instead of a short-distance flight (Herweg and Schmidt, 2022). So, this indicates a trade-off between higher economic performance and environmental quality. This result is supported by Sahoo et al. (2021), Chien et al. (2022), and others, as discussed in this paper earlier in the literature review.

ICT is the sole factor in carbon emissions under investigation in the study. The heterogeneous effect of ICTs on carbon emissions is observed across different income regions. In low- and middle-income countries, ICT has an insignificant relationship with carbon emissions as compared to high-income countries, where ICT is beneficial for the environment. These results could be due to the delay in the development of technology in low- and middle-income groups. The same conclusion is drawn by Amri et al. (2019). On the other hand, information technology is beneficial for the environment by helping in carbon emission reduction in high-income countries. Technology advancement is fruitful for pollution mitigation in high-income countries since these economics have shifted to e-paper, tele-conference, e-commerce, and online shopping. These activities improve energy efficiency through the avoidance of dirty fuel (oil, gas, and coal) consumption. High-income countries also mitigate pollution through proper waste management, particularly electronic waste. The results similar to us drawn by Ben Lahouel et al. (2021) for Tunisia and concluded that information technology help in pollution reduction through boosting economic growth. N'dri et al. (2021) identified long ICT usage reduces carbon emissions in low-income developing countries, whereas no relationship exists high-income developing countries. In line with this, Khan et al. (2020) documented the beneficial role of ICT in carbon emissions reduction for panel of 91 countries. Similar results is found by (Nwani et al., 2022) for Africa; (Faisal et al., 2020); for fast-emerging economies; (Ulucak and DanishKhan, 2020); for BRICS countries; (Zhao et al., 2022); for emerging Asian economies. Likewise, (Danish et al., 2019), found that ICT help to form inverted U-shape hypothesis of EKC curve for Belt and Road countries. Contrary to this, (Magazzino et al., 2021b; 2021a), found increasing effect of ICT on pollution European Union and OECD countries. Similar argument developed by (Danish et al., 2018) for emerging economies. Charfeddine and Kahia (2021) argued that ICT affect environmental quality by increasing CO_2 emissions in Middle East and North Africa region. The heterogenous effect of ICT on CO_2 emissions is found by Dehghan Shabani and Shahnazi. (2019) and Danish et al. (2019) for various sectors and different regions respectively. But a cross-regional comparison of countries on an income basis divulges that ICT promotes environmental sustainability in high-income countries and middle-income while low-income economies show the *vice versa*.

Another core variable of the study is education, and the results show that education does contribute to pollution in low-income countries, but it reduces pollution in middle- and high-income countries. Conclusively highly educated citizens use more ICT software and services. Date advocates that ICT dominance is subordinate in countries with low ratios of education. Our findings proposed that education could help raise awareness among citizens regarding climate change mitigation and global warming impacts on pollution by providing a foundation for science, technology and innovation. Likewise, mobile phones and the internet are better sources for connectivity among people, which contributes to pollution mitigation and endorses sustainability. Access to newer and broader ICT coverage helps in carbon monitoring and the sharing of knowledge (Shobande and Asongu, 2022). Education enables citizens to change the behavior and attitudes by understanding the climate change on this planet. Education motivates people to adopt a sustainable lifestyle and grow their skills in managing climate change. IT and IoT require a profound educational transformation to enhance teaching and learning about environmental sustainability. In the context of climate change, teaching required an interdisciplinary and cross-disciplinary approach to integrate different perspectives. Information regarding the impact of climate change impact be part of the syllabus. Information technology use would be a useful approach for interactive activities that benefit students by allowing them to know and learn about climate change awareness. Along with information technology, students should be learning how to measure carbon emissions along with the practical application of the same. At the graduate and undergraduate level, students should provide opportunities to learn about attaining environment sustainability; for example, environmental-related projects would be a much better option for handling climate change problems using IT and IoT technologies (Dwivedi et al., 2022). The negative role of education is causing pollution is associated with Zhang et al. (2022) and Zafar et al. (2022b) who found education contributes to carbon emissions in developing countries, but they failed to provide any logical reason. However, Shobande and Asongu (2022) and Liu et al. (2022) claim *vice versa* for the role of education in carbon emissions. The same evidence is found by Zaman et al. (2021) for China.

6 Conclusion and policy measures

6.1 Findings

In the 1980s, ICT advancement and the progressively noticeable environmental crisis, a rising global interest in evaluating the environmental impact of ICTs through econometric tools was observed. Based on production theory and EKC hypotheses, this paper contributes to the literature by assessing the empirical association between CO_2 emissions, economic performance, ICT, education, and digital trade across low-, middle-, and high-income countries. In terms of empirical evidence, this paper relies on the BCMM and DK-regression estimators for panel data from 93 countries from 2005 to 2019. Several important findings are observed: 1) an inverted U-shaped relationship between economic performance and environmental quality is observed across middle- and high-income countries, but reserved findings are obtained for low-income countries. 2) The heterogenous effect of ICTs on CO_2 emissions is concluded. 3) Education is found to be a key driver for carbon emission mitigation.

6.2 Policy recommendation

The findings of the study have important policy implications. In low-income countries where ICT is detrimental to the environment, it does not make sense to stop adopting ICT, but to promote a clean, green, low-carbon, and sustainable ICT industry and encourage ICT equipment favorable to environmental quality. Governments in these low-income countries should devise policies associated with the development of green ICTs to achieve the status of a low-carbon economy. Production of carbon intensive ICT products should be restricted through consolidating of environmental measures. Along with this, policymakers should develop an effective system for monitoring ICT equipment processes that are energy and carbon intensive, and it is urged the government in lower and higher-income countries take to measures to limit the inefficient use of ICT equipment. Also, data centers with high energy consumption need to be regulated by taking appropriate measures and setting targets for their power consumption by engaging more stakeholders. Further, governments should support research on green ICT and innovative ICT technologies such as green mobile communication fifth generation (5G) technology and allocate funds for its promotion through direct investment or public-private partnerships that would benefit in controlling emissions. Likewise, the government can establish research centers to study ICT energy efficiency with the help of private companies or universities. Financial institutions need to ease the process of credit availability for environmentally friendly ICT projects and companies that manufacture equipment for green ICT and innovative technologies. It was concluded from the results that education is playing a great role in reducing pollution, so governments in low- and middle-income countries should teach about environment education and include environment as a special subject in the syllabus. Apart from this, the curriculum should encourage the young generation to be made aware of how mobile and the internet can be used for philanthropic purposes, business purposes and to improve the quality of the environment.

6.3 Limitations of the study

The study has some important limitations. Various ICT measures have been used in the study; however, the ICT measure can be extended by including social media, and future studies study should focus on the potential role of social media in pollution mitigation across the globe. Further, future studies in this direction can focus on the role of ICTs in waste management, which contribute to reducing pollution and leading a country toward a circular economy. This study only goes up to 2019, so future researchers can investigate newer drivers of CO2 emissions with extended data from recent years. Furthermore, ICT-related CO2 emissions should be investigated further in other sectors of the economy, including the agriculture sector, the industrial sector, and the services sector.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

KI and YW conceived and designed the manuscript, Danish analyzed the data, and SK wrote the literature review. NM and WS proofread the manuscript. NL contributed to the final version of the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2023.1235376/full#supplementary-material

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