Cover Letters

This study is an extension of our previous research, “Gender Inequality, Institutional Quality, and Economic Outcomes in the European Union” by Nam, Ryu, and Szilagyi (2024), which is currently in press at *European Financial Management*.

While Nam, Ryu, and Szilagyi (2024) have focused on the relationship between social characteristics, particularly gender inequality, and innovation, the current study explores the critical topic of technological progress and its environmental impact. Specifically, we examine the impact of digital trade, high-tech trade, and R&D investment, driven by the rapidly growing sectors of Internet platform services and advanced manufacturing technologies.

Our research offers several significant contributions:

1. **Comprehensive Environmental Insights**: By analyzing environmental data across all 27 EU countries, our study enhances the understanding of how technological progress affects CO_2 emissions in these developed economies.

2. **Contrary Findings to the EKC Theory**: While the Environmental Kuznets Curve (EKC) theory posits an inverted U-shaped relationship between GDP and environmental quality—suggesting that environmental issues might diminish as GDP surpasses a certain peak—our findings indicate a U-shaped effect. Post-peak, technological progress appears to increase CO_2 emissions, challenging the assumption that advanced economies with technological advancements can anticipate a reduction in environmental problems.

3. **The urgency of Addressing Technological Impact**: The severity of the issue highlighted by our findings underscores the urgent need for resolution, particularly in developed countries with advanced technologies. This insight is crucial for policymakers and stakeholders aiming to balance technological advancement with environmental sustainability.

4. **Role of Institutional Quality**: We find that the quality of institutions is strongly associated with the environmental impact of technological progress. Initially, institutional quality may not decrease CO2 emissions driven by technological advancements, but over time, it fosters a decrease in carbon emissions. This suggests that improving institutional quality can be an effective solution to mitigating the environmental impacts of technological progress.

We believe that our study offers valuable insights into the intersection of technological progress and environmental impact, making it a timely and relevant addition to the literature on European Financial Management.

Technological progress and carbon emission: Evidence from EU

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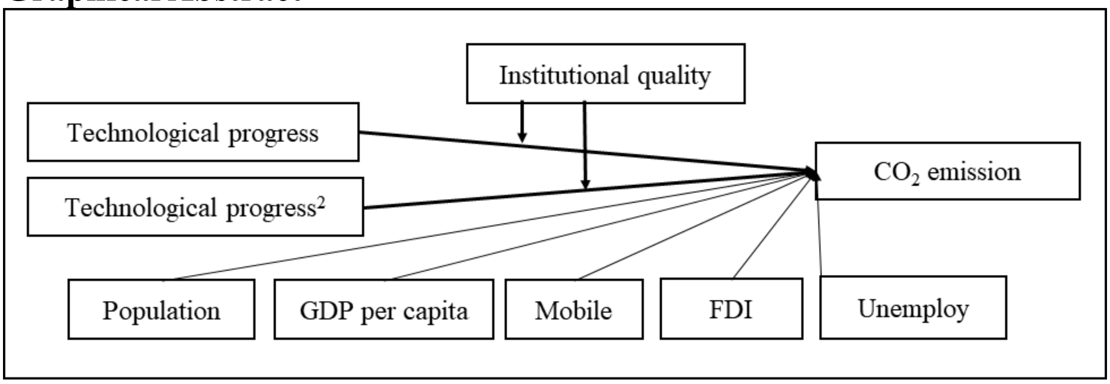
Highlight

•We examine the effects of technological progress on CO_2 emissions in the European Union.
•Low-level (High-level) digital and high-tech trade decreases (increases) the carbon emissions.
•Low-level (High-level) R&D expenditure and the number of researchers in R&D decrease (increase) carbon emissions.
•Institutional quality plays a moderating role in the U relationship between technological progress and CO_2 emissions.

Graphical Abstract



This graphical abstract shows the U-shaped effects of technological progress on CO_2 emissions. Digital trade, high-technology trade, and R&D investment are proxies for *Technological progress*. Carbon emissions per purchasing power parity dollar of GDP, CO_2 emissions in kilotons, CO_2 emissions in metric tons per capita, and total greenhouse gas emissions are proxies for *CO_2 emission*. *Institutional quality* is the moderator variable, measured by the rule of law. Control variables include population, GDP per capita, mobile subscriptions, FDI inflow, and unemployment.

Abstract

We examine the effect of technological progress on CO_2 emissions in 27 European Union (EU). We confirm the U-shaped effect of digital and high-tech trade and R&D investment on CO_2 emissions in the EU, including transition economies. A low level of digital and high-tech trade and R&D investment decreases CO_2 emissions. Beyond a certain threshold, they lead to increased CO_2 emissions. To reduce the negative impact that technological progress has on CO_2 emissions, we suggest the moderating role of institutional quality. Institutional quality acts as a mitigator in the relationship between technological progress and CO_2 emissions, reducing the negative impacts of technological progress on emissions in mature stages.

Keywords: CO_2 emissions; European Union; Institutional quality; Technological progress
JEL Classification: B27 (International trade and finance), F14 (Empirical studies of trade), F18 (Trade and environment), F41 (Open economy macroeconomics), G15 (International financial markets), G18 (Government policy and regulation), P18 (Energy • environment), R58 (Regional development planning and policy)

1. Introduction

Climate change is already manifesting, most notably through rising temperatures. The carbon risk premium hypothesis suggests that corporations manage their carbon footprint to enhance returns as investors are becoming increasingly aware of environmental concerns (Duan, Li, and Wen, 2023; Sautner, Van Lent, Vilkov, and Zhang, 2023). Individuals are becoming more sensitive to climate change due to its direct impacts on their daily lives, such as extreme weather events, health risks, and economic consequences. In response, national governments and institutions have launched initiatives aimed at mitigating environmental changes in Europe. According to a recent report by the European Environmental Agency, European Union (EU) countries are on track to achieve a collective net reduction in emissions of 43% by 2030 compared to 1990 levels. Despite these policies and regulations on CO_2 emissions and increased energy efficiency due to technological progress, considerable carbon dioxide continues to be emitted, albeit at a decreasing rate (Hsu, Li, and Tsou, 2023). This study addresses several critical questions regarding the impact of technological progress on carbon emissions, focusing on the EU as an exemplar of an advanced society from 1990 to 2020. First, does technological progress affect CO_2 emissions? Specifically, does it benefit or exacerbate the environmental impact? Second, does institutional quality mitigate the negative effects of technological progress on the environment? In particular, does institutional quality play a positive moderating role in the relationship between technological progress and CO_2 emissions? We use key variables to measure technological progress: *i*) digital trade, *ii*) high-tech trade, *iii*) research and development (R&D) investment. We utilize CO_2 emissions per purchasing power parity dollar of GDP as a key environmental variable. Additionally, we incorporate metrics such as greenhouse gas emissions in CO_2 kilotons and CO_2 emissions in metric tons per capita. Identifying significant factors to reduce CO_2 emissions provides critical insights for formulating environmental regulations in industrialized countries and offers essential guidance for emerging economies in addressing the challenges of carbon emissions.

The Environmental Kuznets Curve (EKC) suggests that pollutant levels may initially rise with GDP, boosted by trade; however, as incomes increase, pollution levels may decline. This theory has been both supported and critiqued in various studies (Bashir, Ma, Bashir, Bilal, and Shahzad, 2021; Dasgupta, Laplante, Wang, and Wheeler, 2002; Frodyma, Papież, and Śmiech 2022; Naveed, Ahmad, Aghdam, and Menegaki, 2022; Stern, 2004; Wang, Yang, and Li, 2023). Critics such as Dinda (2004) and Luzzati and Orsini (2009) argue that the intensification of industrial activities continues to exacerbate environmental problems, challenging the assumption that technological advances can prevent environmental degradation. In light of these critiques, which challenge the effectiveness of technological advancements in preventing environmental degradation, it remains uncertain whether the shift towards industries associated with recent technological advancements significantly reduces CO_2 emissions. Although technological advancement may initially increase energy efficiency and reduce CO_2 emissions, an increase in export-related activities in technological advancement—namely mass production and transportation—could lead to higher CO_2 emissions. As technological progress reshapes key industries for economic growth, it becomes imperative to assess the effects of these advancements on CO_2 emissions and to guide policy responses and regulatory frameworks aimed at CO_2 reduction (Mayer, 2021). We propose that technological progress could result in a U-shaped curve that behaves differently from the traditional U-shaped pattern suggested by the EKC.

Recent research has increasingly focused on the impact of digital trade and high-tech trade, driven by the rapidly growing sectors of Internet platform services and advanced manufacturing technologies (Herman and Oliver, 2023; Nam, Bilgin, and Ryu, 2024; Wang, Hu, and Li, 2024). Digital trade, which transcends physical boundaries, not only reduces transaction costs and increases transaction speeds but also opens new avenues for market access, representing a more efficient and accessible form of modern trade compared to traditional methods (Dong, and Doukas, 2022). High-tech exports, which include products with high R&D intensity are pivotal in driving trade and economic development (Perla, Tonetti, and Waugh, 2021). Technological progress, a key topic for sustainable development (Dasaratha, 2023; Giorcelli, 2019; Globerman and Shapiro, 2003; Nam, Ryu, and Szilagyi, 2024), impacts broader economic progress and societal advancement. The increase in digital and high-tech trade not only simplifies the innovation processes within societies but also promotes economic development, particularly in the EU (Cumming, Farag, and Johan, 2024; Franks and Sussman, 2005; Guraău, 2002; Ryu and Nam, 2024; Sampson, 2023). However, despite the extensive developments, there is scant evidence regarding the impact of such technological progress on carbon emissions in the EU, highlighting a gap that needs to be filled given the significant role developed countries play in driving both technological innovation and environmental sustainability.

This study examines the impact of technological progress on CO_2 emissions and assesses how institutional quality influences the environmental impacts of digital and high-tech trade across 27 EU countries from 1990 to 2020. Our findings indicate that technological progress has a U-shaped effect on CO_2 emissions: proxies such as digital trade, high-tech trade, R&D expenditure, and the number of researchers initially contribute to a decrease in carbon emissions but fail to mitigate them at more mature stages. In the initial stages, energy efficiency in digital and high-tech industries is directly linked to technological advancements. Innovations enhance energy efficiency through new manufacturing processes, materials, and management systems, ultimately leading to reduced carbon emissions. However, in the mature stages of digital and high-tech trade, as the scale of operations expands, the increased energy demands often outpace the initial gains in energy efficiency. The mature stages of trade involve complex, often global, supply chains that can increase CO_2 emissions due to the logistics and transportation demands across greater distances. We also find that the quality of institutions is strongly associated with the environmental impact of technological progress. Initially, institutional quality may not decrease CO_2 emissions driven by technological advancements, but over time, it fosters a decrease in carbon emissions.

Our study contributes to the body of research on the role of institutions in addressing CO_2 emissions. Rooted in the institutional theory originally proposed by North (1990), this area has gained prominence, as evidenced by recent studies including those by Aller, Ductor, and Grechyna (2021), Franks (2020), Jensen (2010), Nam and Ryu (2023), Nam, Bang, and Ryu (2023a), and Nwani and Adams (2021) and further expanded upon by Khan and Rana (2021), Karim, Appiah, Naeem, Lucey, and Li (2022), and Yang, Ali, Hashmi, and Jahanger (2022). These studies underscore the critical role that institutions play in developing regulations and policies aimed at mitigating CO_2 emissions. The issue of carbon dioxide emissions is particularly acute within the EU, which is among the global leaders in reducing greenhouse gas emissions through well-established institutional initiatives. Research by Khan, Weili, and Khan (2021) not only reinforces that institutional quality significantly contributes to the reduction of CO_2 emissions in developed countries but also highlights how these initiatives increase energy efficiency. Our study further emphasizes the decrease in CO_2 emissions within the EU, driven by these effective institutional frameworks.

Our research provides insights into environmental studies across all 27 EU countries, enhancing our understanding of the impacts of technological progress on CO_2 emissions in these developed economies. While the prevailing theory of the EKC suggests an inverted U-shaped relationship between GDP and environmental quality—offering hope that environmental issues may decrease as GDP increases beyond a peak point—our findings indicate a contrary U-shaped effect. Beyond this peak, technological progress starts to lead to increased CO_2 emissions. This suggests that developed countries with technological advancements cannot expect a reduction in environmental problems. The severity of this issue urgently requires resolution, particularly in developed countries with advanced technologies. In 2020, the top five CO_2 emitters within the EU—Germany, Italy, Poland, France, and Spain—illustrated that high technological advancement does not necessarily correlate with lower emissions. Poland's significant CO_2 output is primarily driven by its extensive heavy industry and manufacturing sectors, which consume large amounts of energy. Despite their high levels of technological advancement, countries like Germany, Italy, France, and Spain continue to report high CO_2 emissions, highlighting that technological progress is a pressing concern due to its adverse effects on the environment in developed countries. Our research has also yielded significant findings from an analysis of 11 transition economies within the 27 EU member states. These 11 transition economies have demonstrated a U-shaped relationship between technological progress and CO_2 emissions, supporting our primary results. Transition economies in the EU are characterized by relatively lower GDP per capita and distinct cultural and political backgrounds compared to other EU countries (Nam and Ryu, 2024a). Despite these differences, our research confirms that in these 11 transition economies, technological progress exhibits a U-shaped effect on CO_2 emissions. Thus, our results are not only consistent with our claims across the EU but also extend to the unique cultural and political contexts of the transition economies in the EU.

The remainder of this paper is organized as follows. Section 2 presents the sample data, outlines the variables investigated, and describes the methodological approach adopted. Section 3 presents the results of the empirical analysis. Section 4 concludes the study.

2. Data and Methodology

2.1 Data

This study examines the correlation between technological progress and CO_2 emissions using data from the 27 European Union countries for the period 1990–2020 including Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovenia, Slovakia, Spain, and Sweden.[1]

We incorporate diverse dependent variables as a proxy for CO_2 emissions: *i*) *CO₂gdp* is defined as kilograms of carbon emissions per purchasing power parity dollar of GDP. *ii*) *GreenH* includes total CO_2 emissions, other sources of biomass burning, and all anthropogenic sources, expressed in hundreds of thousands. *iii*) *CO₂kt* measures CO_2 emissions in kilotons, expressed in hundreds of thousands. *iv*) *CO₂gdppc* denotes CO_2 emissions in metric tons per capita.

We incorporate key variables as a proxy for technological progress: *i*) Digital trade (*Digital*) represents the Information and Communication Technology (ICT) services volume. This includes computer and communications services (telecommunications, postal, and courier services) and information services (computer data and news-related service transactions), expressed in hundreds of billions of USD. *ii*) High-tech trade (*Hitech*) captures high-technology exports, which are products with high R&D intensity such as aerospace, computers, pharmaceuticals, scientific instruments, and electrical machinery, expressed in hundreds of billions of USD. *iii*) *R&D* represents the ratio of research and development expenditure to GDP, expressed as a percentage. *iv*) *Researcher* represents the number of researchers in R&D per ten billion people. Additionally, we demonstrate the relationship between all trade volumes and CO_2 emissions. *Trade* encompasses the sum of all export and import volumes, expressed in trillions of USD (Nam and Ryu, 2024b).

[1] CO_2 emissions data, downloaded on July 25, 2024, from the World Bank, reflect the most recent data available to 2020.

We have a moderator variable: Institutional quality is measured as a rule of law (*Rule*), a sub-indicator of the Worldwide Governance Indicators. It specifically measures the effectiveness of contract enforcement, property rights, law enforcement, and the judicial system.

Control variables in this study include: Population (*Popul*), based on the de facto definition of population, counting all residents regardless of legal status or citizenship, expressed in hundred million. GDP per capita (*GDPpc*) represents the gross domestic product divided by the population, expressed in hundreds of millions. Mobile cellular telephone subscriptions (*Mobile*) refer to subscriptions to a public mobile telephone service, expressed in billions. Foreign Direct Investment (*FDI*) represents the inflow of foreign direct investment, expressed in trillions of USD. Unemployment (*Unempl*) is the ratio of unemployment to the total labor force, adjusted to one-tenth of its original value.

Table 1 presents the descriptive statistics of the variables used to examine the impact of technological progress in trade CO_2 emissions. All observations are annual data provided by the World Bank, which are suitable for the longitudinal analysis of trends over the 30 years from 1990 to 2020. The observation of *Hithech* is 378, since *Hithech* is provided from 2007 at World Bank. The mean *CO_2gdp*, which represents kilograms of carbon emissions per purchasing power parity dollar of GDP in the EU, is 7.85. The mean of *GreenH* and *CO_2kt,* which represent the amount of total greenhouse gas emissions and CO_2 emissions, are 1.49 and 1.20, respectively.

Table 1. Descriptive statistics

		Obs	Mean	Std	Min	Max
CO_2 emissions	*CO_2gdp*	837	7.85	3.81	2.93	30.37
	GreenH	837	1.49	2.06	0.02	11.30
	CO_2kt	837	1.20	1.74	0.01	9.55
	CO_2gdppc	837	7.85	3.81	2.93	30.37
Technological progress	*Digital*	684	0.05	0.12	0.00	1.58
	Hitech	378	0.23	0.42	0.00	2.16
	R&D	648	1.43	0.88	0.20	3.87
	Researcher	629	0.30	0.17	0.03	0.79
Trade		753	0.35	0.54	0.00	3.52
Rule		594	1.07	0.62	-0.63	2.12
Popul		837	0.16	0.21	0.00	0.83
GDPpc		824	0.03	0.02	0.00	0.12
Mobile		837	0.01	0.02	0.00	0.11
FDI		809	0.02	0.05	-0.33	0.73
Unempl		812	0.01	0.00	0.00	0.03

Notes. This table illustrates the descriptive statistics. *Obs* denotes the number of country-year observations. *Mean*, *Std*, *Min*, and *Max* represent the average, standard deviation, minimum, and maximum values, respectively. *CO_2gdp* represents kilograms of carbon emissions per purchasing power parity dollar of GDP. *GreenH* represents total greenhouse gas emissions in kilotons of CO_2 totals, other biomass burning, and all anthropogenic sources, expressed in hundreds of thousands.

CO_2kt measures CO_2 emissions in kilotons, expressed in hundreds of thousands. *CO_2gdppc* denotes CO_2 emissions in metric tons per capita. *Digital* represents the ICT services volume, serving as a proxy for digital trade, expressed in hundreds of billions of USD. *Hitech* captures high-technology exports, which are products with high R&D intensity, expressed in hundreds of billions of USD. *R&D* represents the ratio of research and development expenditure to GDP, expressed as a percentage. *Researcher* represents the number of researchers in R&D per ten billion people. *Trade* encompasses the sum of all export and import volumes, expressed in trillions of USD. *Rule* represents the rule of law. *Popul* is population, expressed in hundreds of millions. *GDPpc* is GDP per capita, expressed in hundred million. *Mobile* is mobile cellular telephone subscriptions, expressed in billions. *FDI* represents foreign direct investment inflow, expressed in trillions of USD. *Unempl* is the ratio of unemployment to the total labor force, adjusted to one-tenth of its original value.

2.2 Model

We assess the nonlinear effect of technological progress on CO_2 emissions and the moderating role of institutional quality in this relationship in Equation (1) using the fixed effect (FE) regression model and Equation (2) using the quantile regression (QR) model.

FE regression model:

$$CO_{i,t} = \alpha_0 + \alpha_1 TP_{i,t} + \alpha_2 TP^2{}_{i,t} + \alpha_3 Rule_{\,i,t} + \alpha_4 TP \cdot Rule_{i,t} + \alpha_5 TP^2 \cdot Rule_{i,t} + \alpha_c Control_{\,i,t} + \mu_i + \varepsilon_{i,t}, \tag{1}$$

QR model:

$$CO_2gdp_{i,t} = \beta_0(\tau) + \beta_1(\tau)TV_{i,t} + \beta_2(\tau)TV^2{}_{i,t} + \beta_3(\tau)Rule_{i,t} + \beta_4(\tau)TV \cdot Rule_{i,t} + \beta_5(\tau)TV^2 \cdot Rule_{i,t} + \beta_c(\tau)Control_{i,t} + \varepsilon_{i,t}, \tag{2}$$

where *i* denotes the country and *t* denotes the year. α_j is the coefficient in the FE regression model. $\beta_j(\tau)$ is the adjusted coefficient of the τ-th quantile in the QR model. $CO_{i,t}$={ $CO_2gdp_{i,t}$, $GreenH_{i,t}$, $CO_2kt_{i,t}$, $CO_2gdppc_{i,t}$}. *CO_2gdp* is defined as kilograms of carbon emissions per purchasing power parity dollar of GDP. *GreenH* represents total greenhouse gas emissions in kilotons of CO_2 totals, other biomass burning, and all anthropogenic sources. *CO_2kt* is measured as CO_2 emissions in kilotons. *CO_2gdppc* denotes CO_2 emissions in metric tons per capita. $TP_{i,t}$={$Digital_{i,t}$, $Hitech_{i,t}$, $R\&D_{i,t}$, $Researcher_{i,t}$}. Digital trade (*Digital*) represents the ICT services volume. High-technology (*Hitech*) captures high-technology exports, which are products with high R&D intensity. *R&D* represents the ratio of research and development expenditure to GDP (Chan, Lakonishok, and Sougiannis, 2001). *Researcher* represents the number of researchers in R&D. $TV_{i,t}$= {$Digital_{i,t}$, $Hitech_{i,t}$}. *Rule* represents the rule of law, serving as the moderate variable. *TP·Rule*, *TP^2·Rule*, *TV·Rule*, and *TV^2·Rule* are interaction terms. In all the models, $Control_{i,t}$={$Popul_{i,t}$, $GDPpc_{i,t}$, $Mobile_{i,t}$, $FDI_{i,t}$, $Unempl_{i,t}$}. *Popul* is population. *GDPpc* is GDP per capita. *Mobile* is mobile cellular telephone subscriptions. *FDI* represents foreign direct investment inflow. *Unempl* is the ratio of unemployment to the total labor force. μ denotes country effects, and ε denotes idiosyncratic errors.

3. Empirical Results

Table 2 presents the results of the nonlinear effects of technological progress and CO_2 emissions and the moderating role of institutional quality in these relationships using the FE model. The results for columns (1) to (3), (4) to (6), and (7) to (9) indicate the effect of digital trade, high-tech trade, and all trade volumes on CO_2 emissions. The linear terms, *Digital*, *Hitech*, and *Trade*, negatively affect CO_2gdp, and the nonlinear terms, $Digital^2$, $Hitech^2$, and $Trade^2$, positively affect CO_2gdp. Our finding implies that both digital trade, high-tech trade, and all trade volumes have U-shaped relationships with CO_2 emissions (Nam, Bang, and Ryu, 2024). In the early phases, tech companies often develop new technologies that minimize the energy consumption of their products. For example, in fields such as semiconductors, information technology, and telecommunications equipment, there is a continual development of energy-efficient chips and devices. These technologies not only reduce power consumption but also maintain or improve performance. Companies with advanced technological capabilities optimize production processes to reduce energy usage. This often includes the introduction of automation, precision engineering, and smart technologies. For instance, real-time data monitoring allows for the maximization of productivity while minimizing energy consumption. However, in the mature stage of digital and high-tech trade, the scale of operations and complex supply chains may increase CO_2 emissions. As digital and high-tech trade grows, the sheer scale of operations can lead to increased energy demands, often outpacing the initial energy efficiency gains. Mature stages of trade involve complex, often global, supply chains that can increase CO_2 emissions due to logistics and transportation needs across greater distances.

Table 2. Effects of digital, high-tech, and all trade volumes on CO_2 emissions in EU: FE

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Digital	-2.18***	-1.98***	-5.71***						
	(-10.29)	(-10.84)	(-9.05)						
$Digital^2$	1.16***	1.00***	6.64***						
	(8.08)	(8.69)	(6.53)						
Hitech				-0.28***	-0.28***	-1.86***			
				(-2.80)	(-2.86)	(-7.70)			
$Hitech^2$				0.06	0.06	0.85***			
				(1.41)	(1.45)	(5.95)			
Trade							-0.89***	-0.83***	-1.47***
							(-14.47)	(-14.66)	(-9.22)
$Trade^2$							0.19***	0.17***	0.55***
							(10.82)	(11.01)	(7.30)
Rule		-0.26***	-0.23***		0.07***	-0.01		-0.26***	-0.28***

		(-7.31)	(-7.08)		(2.83)	(-0.55)		(-8.14)	(-9.05)
Digital·Rule			3.44^{***}						
			(9.02)						
Digital²·Rule			-4.23^{***}						
			(-6.08)						
Hitech·Rule						1.15^{***}			
						(7.63)			
Hitech²·Rule						-0.53^{***}			
						(-6.15)			
Trade·Rule									0.86^{***}
									(8.94)
Trade²·Rule									-0.32^{***}
									(-6.57)
Popul			3.77^{***}			-0.09			3.12^{***}
			(5.31)			(-0.10)			(4.34)
GDPpc			-10.18^{***}			-1.27			-9.01^{***}
			(-12.75)			(-1.39)			(-10.57)
Mobile			-2.16^{***}			-1.49			-2.30^{***}
			(-3.41)			(-1.05)			(-2.76)
FDI			0.12			0.05			0.03
			(1.36)			(0.98)			(0.34)
Unempl			-0.95			1.11			-2.05
			(-0.58)			(0.99)			(-1.44)
Intercept	0.43^{***}	0.65^{***}	0.26^{**}	0.26^{***}	0.18^{***}	0.34^{**}	0.58^{***}	0.80^{***}	0.46^{***}
	(38.08)	(16.48)	(2.08)	(15.56)	(5.67)	(2.17)	(35.58)	(21.25)	(3.71)
F-test	54.12^{***}	56.81^{***}	59.90^{***}	5.20^{***}	6.20^{***}	10.96^{***}	120.61^{***}	99.46^{***}	72.75^{***}
R^2	0.12	0.16	0.02	0.03	0.00	0.02	0.15	0.16	0.02
Obs	684	535	534	378	378	378	753	576	575

Notes. This table presents the effect of trade including digital and high tech on CO_2 emissions and the moderating role of institutional quality in this relationship using fixed-effect regressions. *CO_2gdp*, serving as a dependent variable, represents kilograms of carbon emissions per purchasing power parity dollar of GDP. Digital trade (*Digital*) represents the ICT services volume. High-tech trade (*Hitech*) captures high-technology exports. All trade volumes (*Trade*) encompass the sum of all export and import volumes. *$Digital^2$*, *$Hitech^2$*, and *$Trade^2$* are the square terms of *Digital*, *Hitech*, and *Trade. Rule* represents the rule of law. *Digital·Rule*, *Hitech·Rule*, *Trade·Rule*, *$Digital^2$·Rule*, *$Hitech^2$·Rule*, and *$Trade^2$·Rule* are interaction terms. *Popul* is population. *GDPpc* is GDP per capita. *Mobile* is mobile cellular telephone subscriptions. *FDI* represents foreign direct investment inflow. *Unempl* is the ratio of unemployment to the total labor force. *F*-test represents the *F*-test statistic, indicating a test of the null hypothesis that all the coefficients are zero. R^2 is the overall R-squared value. *Obs* denotes the country-year observations. The number of countries is 27 in all the models. Figures in parentheses are *t*-statistics. *** and ** denote statistical significance at the 1% and 5% levels, respectively.

The linear interaction term, *Digital·Rule*, *Trade·Rule*, and *Hitech·Rule* exhibits a positive effect on CO_2 emissions per GDP (*CO_2gdp*), whereas the nonlinear interaction term, *$Digital^2$·Rule*, *$Trade^2$·Rule*, and *$Trade^2$·Rule*, demonstrates a negative effect on *CO_2gdp*. These findings underscore the significant moderating role that institutional quality plays in the relationship between technological progress and CO_2 emissions. High institutional quality, characterized by robust regulations and effective policies, does not contribute to the reduction of CO_2 in the initial stage. Our analysis indicates that while institutional quality may not immediately reduce emissions attributable to technological advancements, it facilitates substantial reductions over time.

Table 3 presents the results of the nonlinear effects of R&D investment on CO_2 emissions and the moderating role of institutional quality in these relationships, using the FE model. The results show the effects of R&D expenditures in columns (1) to (4) and the number of researchers in R&D in columns (5) to (8) on CO_2 emissions. *R&D* and *Researcher* have significantly negative effects on *CO_2gdp*, while *$R\&D^2$* and *$Researcher^2$* have significantly positive effects on *CO_2gdp*, indicating U-shaped relationships between *R&D* and CO_2 emissions. Our findings suggest a U-shaped relationship between R&D investment and CO_2 emissions per GDP, initially decreasing and then eventually increasing emissions. R&D in technology, especially green technology, focuses on efficiency improvements. These improvements can reduce emissions per unit of output by making processes cleaner and more energy-efficient. As technological progress enhances productivity and trade volumes increases, the overall energy demand may increase. The energy supply remains significantly dependent on fossil fuels and total emissions could rise despite efficiency gains. The interaction term between the number of researchers and institutional quality (*Researcher·Rule*) shows a positive impact on *CO_2gdp*, whereas the interaction term (*$Researcher^2$·Rule*) indicates a negative impact on *CO_2gdp*. Institutional quality plays a critical role in both the establishment and implementation of regulations and policies (Nam, Bang, and Ryu, 2023b; Nam, Frijns, and Ryu, 2024). Our analysis suggests that although the rule of law may not lead to immediate reductions in emissions due to technological advancements, it significantly contributes to reducing emissions over the long term.

Table 3. Effects of R&D investment on CO_2 emissions in EU: FE

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
R&D	-0.63***	-0.60***	-0.49***	-0.60***				
	(-14.06)	(-13.96)	(-14.26)	(-7.84)				
$R\&D^2$	0.09***	0.09***	0.09***	0.09***				
	(8.14)	(8.24)	(10.46)	(3.04)				
Researcher					-2.65***	-2.62***	-1.96***	-3.53***
					(-15.39)	(-16.17)	(-12.33)	(-8.50)
$Researcher^2$					1.99***	1.97***	1.51***	3.20***
					(9.19)	(9.72)	(8.24)	(4.28)
Rule		-0.22***	-0.14***	-0.29***		-0.27***	-0.19***	-0.45***

		(-7.55)	(-5.54)	(-6.05)		(-10.02)	(-7.53)	(-9.75)
R&D·Rule				0.18^{***}				
				(3.00)				
R&D²·Rule				-0.02				
				(-1.09)				
Researcher·Rule								1.57^{***}
								(5.85)
Researcher²·Rule								-1.57^{***}
								(-3.69)
Popul			3.07^{***}	2.89^{***}			3.90^{***}	3.40^{***}
			(5.76)	(5.42)			(7.13)	(6.41)
GDPpc			-7.62^{***}	-7.86^{***}			-4.58^{***}	-5.46^{***}
			(-13.35)	(-13.81)			(-6.63)	(-7.99)
Mobile			-3.53^{***}	-3.41^{***}			-3.68^{***}	-3.69^{***}
			(-7.86)	(-7.66)			(-8.12)	(-8.43)
FDI			0.05	0.06			0.08	0.08
			(0.62)	(0.76)			(1.05)	(1.06)
Unempl			1.98	0.76			0.75	-0.67
			(1.64)	(0.62)			(0.60)	(-0.55)
Intercept	0.95^{***}	1.14^{***}	0.63^{***}	0.76^{***}	0.86^{***}	1.13^{***}	0.43^{***}	0.76^{***}
	(25.43)	(23.55)	(6.51)	(6.98)	(29.56)	(27.58)	(4.36)	(6.93)
F-test	177.21^{***}	132.06^{***}	126.52^{***}	106.04^{***}	245.06^{***}	202.78^{***}	118.83^{***}	107.54^{***}
R^2	0.13	0.12	0.03	0.03	0.21	0.18	0.01	0.02
Obs	648	576	575	575	629	563	562	562

Notes. This table presents the effect of R&D investment on CO_2 emissions and the moderating role of institutional quality in this relationship using fixed-effect regressions. *CO_2gdp*, serving as a dependent variable, represents CO_2 emissions, defined as kilograms of carbon emissions per purchasing power parity dollar of GDP. *R&D* represents the ratio of research and development expenditure to GDP. *Researcher* represents the number of researchers in R&D. *R&D²* and *Researcher²* are the square terms of *R&D* and *Researcher*, respectively. *Rule* represents the rule of law. *R&D·Rule*, *R&D²·Rule*, *Researcher·Rule*, and *Researcher²·Rule* are interaction terms. *Popul* is population. *GDPpc* is GDP per capita. *Mobile* is mobile cellular telephone subscriptions. *FDI* represents foreign direct investment inflow. *Unempl* is the ratio of unemployment to the total labor force. *F*-test represents the *F*-test statistic, indicating a test of the null hypothesis that all the coefficients are zero. R^2 is the overall R-squared value. *Obs* denotes the country-year observations. The number of countries is 27 in all the models. Figures in parentheses are *t*-statistics. *** denotes statistical significance at the 1% level.

We utilize several dependent variables for proxy of CO_2 emission: greenhouse gas emissions in columns (1) to (2), CO_2 kt in columns (3) to (4), and CO_2 per GDP per capita in columns (5) to (6) in Table 4. Across all dependent variables, such as *GreenH*, *CO_2kt*, and *CO_2gdppc*, the linear terms, *Digital* and *Hitech*, have significantly negative effects, while the nonlinear terms, *Digital²* and $Hitech^2$, have significantly positive effects. This finding implies that both digital and high-tech trade exhibit U-shaped relationships with various forms of CO_2 emissions. The effect of *Digital·Rule* on CO_2kt, the effect of *Hitech·Rule* on *GreenH*, CO_2kt, and CO_2gdppc are positive, whereas $Digital^2 \cdot Rule$ on CO_2kt, the effect of $Hitech^2 \cdot Rule$ on *GreenH*, CO_2kt, and CO_2gdppc are negative. Our analysis suggests that although institutional quality may not lead to immediate reductions in emissions due to technological advancements, it significantly contributes to reducing emissions over the long term.

Table 4. Effects of trade for digital and high-tech on CO_2 emissions in EU: FE

	(1)	(2)	(3)	(4)	(5)	(6)
Digital	-3.95^{***}		-4.35^{***}		-17.05^{***}	
	(-3.53)		(-4.32)		(-2.64)	
$Digital^2$	4.36^{**}		4.85^{***}		27.93^{***}	
	(2.42)		(2.99)		(2.69)	
Hitech		-4.56^{***}		-4.19^{***}		-12.94^{***}
		(-7.30)		(-7.24)		(-2.62)
$Hitech^2$		1.24^{***}		1.29^{***}		6.85^{**}
		(3.37)		(3.79)		(2.35)
Rule	0.01	-0.12^{*}	0.01	-0.11^{*}	1.36^{***}	0.90^{*}
	(0.18)	(-1.78)	(0.24)	(-1.72)	(4.17)	(1.68)
Digital·Rule	0.55		1.22^{**}		2.62	
	(0.81)		(2.01)		(0.67)	
$Digital^2 \cdot Rule$	-1.92		-2.45^{**}		-14.55^{**}	
	(-1.56)		(-2.21)		(-2.04)	
Hitech·Rule		2.88^{***}		2.59^{***}		10.32^{***}
		(7.35)		(7.14)		(3.32)
$Hitech^2 \cdot Rule$		-0.92^{***}		-0.89^{***}		-5.00^{***}
		(-4.11)		(-4.27)		(-2.81)
Popul	-1.03	-24.87^{***}	-1.37	-23.16^{***}	-5.19	-60.72^{***}
	(-0.82)	(-10.08)	(-1.21)	(-10.14)	(-0.71)	(-3.11)
GDPpc	3.02^{**}	6.02^{**}	2.39^{*}	5.17^{**}	-70.49^{***}	-21.99
	(2.13)	(2.54)	(1.88)	(2.35)	(-8.63)	(-1.17)
Mobile	-8.95^{***}	8.24^{**}	-6.84^{***}	9.39^{***}	19.79^{***}	15.02
	(-7.97)	(2.25)	(-6.77)	(2.77)	(3.05)	(0.52)
FDI	0.10	-0.07	0.14	-0.09	1.59*	1.01
	(0.66)	(-0.56)	(0.95)	(-0.74)	(1.74)	(0.96)
Unempl	-8.20^{***}	-7.50^{***}	-8.22^{***}	-7.72^{***}	-66.97^{***}	-58.85^{**}
	(-2.83)	(-2.60)	(-3.15)	(-2.89)	(-4.00)	(-2.57)
Intercept	1.92^{***}	5.43^{***}	1.66^{***}	4.87^{***}	9.78^{***}	16.78^{***}
	(8.60)	(13.29)	(8.23)	(12.86)	(7.56)	(5.18)

F-test	42.66***	34.16***	35.29***	31.45***	27.04***	5.90***
R^2	0.75	0.93	0.77	0.89	0.05	0.01
Obs	534	378	534	378	534	378

Notes. This table presents the effect of digital and high-tech on CO_2 emissions and the moderating role of institutional quality in this relationship using fixed-effect regressions. Dependent variables are *GreenH* in columns (1) to (2), *CO_2kt* in columns (3) to (4), and *CO_2gdppc* in columns (5) to (6). *GreenH* represents total greenhouse gas emissions in kilotons of CO_2 totals, other biomass burning, and all anthropogenic sources. *CO_2kt* measures CO_2 emissions in kilotons. *CO_2gdppc* denotes CO_2 emissions in metric tons per capita. Digital trade (*Digital*) represents the ICT services volume. High-tech trade (*Hitech*) captures high-technology exports. *$Digital^2$* and *$Hitech^2$* are the square terms of *Digital* and *Hitech. Rule* represents the rule of law. *Digital·Rule*, *Hitech·Rule* *$Digital^2$·Rule*, and *$Hitech^2$·Rule* are interaction terms. *Popul* is population. *GDPpc* is GDP per capita. *Mobile* is mobile cellular telephone subscriptions. *FDI* represents foreign direct investment inflow. *Unempl* is the ratio of unemployment to the total labor force. F-test represents the F-test statistic, indicating a test of the null hypothesis that all the coefficients are zero. R^2 is the overall R-squared value. *Obs* denotes the country-year observations. The number of countries is 27 in all the models. Figures in parentheses are t-statistics. ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.

Table 5 illustrates the effects of digital trade in Panel A, high-tech in Panel B, and trade volume in Panel C on CO_2 emissions using quantile regression. Across all quantiles of all panels, the *Digital*, *Hitech*, and *Trade*, negatively affect *CO_2gdp,* and *$Digital^2$*, *$Hitech^2$*, and *$Trade^2$*, positively affect *CO_2gdp*. Our finding also technological progress has U-shaped relationships with CO_2 emissions. We confirm that institutional quality moderates the relationship between technological progress and CO_2 emission. Institutional quality may decrease CO_2 emissions in the context of low technological progress and increase it under high technological progress across all quantiles. Across all models from Panel A to Panel C, institutional quality plays a moderating role. In the mature stages, institutional quality contributes to a decrease in CO_2 emissions through technological progress.

Table 5. Effects of digital, high-tech, and all trade volumes on CO_2 emissions in EU: QR
Panel A. Effect of digital trade on CO_2 emissions

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Digital	-3.80***	-4.15***	-5.17***	-5.30***	-5.56***	-5.36***	-4.84***	-4.73***	-5.92***
	(-11.80)	(-15.74)	(-7.04)	(-7.16)	(-8.67)	(-8.28)	(-8.24)	(-5.83)	(-3.94)
$Digital^2$	3.93***	4.23***	5.12***	5.20***	5.77***	8.36***	7.42***	7.52***	9.55***
	(7.59)	(9.95)	(4.33)	(4.37)	(5.59)	(8.02)	(7.85)	(5.76)	(3.95)
Rule	-0.08***	-0.11***	-0.15***	-0.14***	-0.13***	-0.12***	-0.14***	-0.14***	-0.19**
	(-4.85)	(-8.33)	(-4.04)	(-3.68)	(-4.10)	(-3.78)	(-4.70)	(-3.36)	(-2.47)
Digital·Rule	1.81***	2.03***	2.71***	2.90***	3.15***	3.40***	3.04***	2.87***	3.75***
	(9.32)	(12.74)	(6.09)	(6.48)	(8.11)	(8.69)	(8.56)	(5.86)	(4.12)
$Digital^2$·Rule	-2.26***	-2.45***	-3.03***	-3.13***	-3.55***	-5.53***	-4.90***	-4.94***	-6.35***

	(-6.36)	(-8.41)	(-3.74)	(-3.83)	(-5.02)	(-7.75)	(-7.56)	(-5.52)	(-3.83)
Popul	1.21***	1.38***	1.78**	2.23***	2.45***	2.76***	3.31***	3.84***	7.00***
	(3.34)	(4.66)	(2.15)	(2.68)	(3.40)	(3.79)	(5.01)	(4.21)	(4.14)
GDPpc	-4.26***	-4.58***	-5.94***	-7.71***	-8.80***	-10.56***	-9.52***	-9.35***	-10.14***
	(-10.47)	(-13.73)	(-6.39)	(-8.24)	(-10.83)	(-12.88)	(-12.81)	(-9.11)	(-5.33)
Mobile	0.15	-0.11	-0.31	-0.99	-0.94	-2.50***	-3.75***	-4.68***	-8.40***
	(0.46)	(-0.41)	(-0.42)	(-1.34)	(-1.46)	(-3.85)	(-6.36)	(-5.74)	(-5.56)
FDI	-0.05	0.04	0.03	0.09	0.10	0.16*	0.15*	0.13	0.25
	(-0.99)	(0.97)	(0.28)	(0.87)	(1.09)	(1.75)	(1.84)	(1.15)	(1.18)
Unempl	2.50***	1.67**	-0.40	-2.11	-3.57**	-2.36	-2.52*	-2.52	-4.00
	(3.00)	(2.44)	(-0.21)	(-1.10)	(-2.15)	(-1.41)	(-1.66)	(-1.20)	(-1.03)
Country effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Obs	534	534	534	534	534	534	534	534	534

Panel B. Effect of high-tech trade on CO_2 emissions

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Hitech	-1.01***	-1.15***	-1.32***	-1.39***	-2.21***	-2.38***	-2.19***	-2.10***	-2.11***
	(-3.27)	(-5.04)	(-9.22)	(-5.04)	(-6.69)	(-5.87)	(-7.05)	(-9.00)	(-6.18)
Hitech^2	0.46**	0.51***	0.60***	0.63***	1.00***	1.02***	0.93***	0.91***	0.91***
	(2.53)	(3.81)	(7.08)	(3.91)	(5.16)	(4.25)	(5.05)	(6.59)	(4.51)
Rule	-0.00	-0.01	-0.03*	-0.03	-0.10***	-0.12***	-0.09***	-0.08***	-0.12***
	(-0.11)	(-0.54)	(-1.73)	(-0.92)	(-2.90)	(-2.79)	(-2.78)	(-3.15)	(-3.22)
Hitech·Rule	0.57***	0.67***	0.86***	0.89***	1.38***	1.47***	1.34***	1.32***	1.31***
	(2.95)	(4.67)	(9.57)	(5.17)	(6.66)	(5.80)	(6.86)	(9.03)	(6.13)
Hitech^2*·Rule*	-0.27**	-0.31***	-0.39***	-0.41***	-0.63***	-0.65***	-0.59***	-0.58***	-0.58***
	(-2.42)	(-3.76)	(-7.58)	(-4.14)	(-5.27)	(-4.43)	(-5.24)	(-6.96)	(-4.74)
Popul	-2.40**	-2.14**	-1.27**	-1.18	-0.54	-0.13	-0.65	-0.46	-0.98
	(-1.98)	(-2.38)	(-2.25)	(-1.09)	(-0.41)	(-0.08)	(-0.53)	(-0.50)	(-0.73)
GDPpc	-2.29*	-0.35	0.07	0.14	0.77	0.48	-1.15	-1.25	-1.41
	(-1.96)	(-0.40)	(0.14)	(0.13)	(0.61)	(0.31)	(-0.97)	(-1.41)	(-1.09)
Mobile	0.86	0.42	-0.42	-0.50	-1.24	-1.51	-1.46	-1.70	-0.10
	(0.47)	(0.31)	(-0.50)	(-0.31)	(-0.64)	(-0.63)	(-0.80)	(-1.24)	(-0.05)
FDI	0.05	-0.03	-0.01	-0.00	0.01	0.06	0.05	0.08	0.08
	(0.73)	(-0.69)	(-0.34)	(-0.08)	(0.20)	(0.64)	(0.74)	(1.52)	(1.12)
Unempl	6.28***	5.83***	5.17***	4.73***	2.12	-0.86	-2.18	-2.94***	-3.87**
	(4.42)	(5.53)	(7.79)	(3.72)	(1.39)	(-0.46)	(-1.52)	(-2.73)	(-2.45)
Country effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Obs	378	378	378	378	378	378	378	378	378

Panel C. All trade volumes

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)

Trade	-0.89***	-1.02***	-1.19***	-1.46***	-1.63***	-1.71***	-1.61***	-1.71***	-1.88***
	(-7.84)	(-8.25)	(-5.39)	(-7.30)	(-10.49)	(-11.47)	(-10.65)	(-8.97)	(-6.12)
Trade^2	0.46***	0.44***	0.48***	0.53***	0.60***	0.58***	0.54***	0.72***	0.84***
	(8.55)	(7.63)	(4.61)	(5.57)	(8.16)	(8.21)	(7.62)	(8.03)	(5.81)
Rule	-0.11***	-0.13***	-0.11***	-0.16***	-0.19***	-0.22***	-0.25***	-0.30***	-0.40***
	(-5.27)	(-5.67)	(-2.68)	(-4.13)	(-6.42)	(-7.55)	(-8.70)	(-8.12)	(-6.83)
Trade·Rule	0.50***	0.57***	0.63***	0.75***	0.85***	0.94***	0.92***	1.03***	1.11***
	(7.31)	(7.64)	(4.71)	(6.20)	(9.08)	(10.46)	(10.05)	(9.00)	(6.00)
Trade^2*·Rule*	-0.28***	-0.26***	-0.27***	-0.28***	-0.33***	-0.32***	-0.31***	-0.41***	-0.46***
	(-7.99)	(-6.94)	(-4.02)	(-4.65)	(-6.92)	(-7.10)	(-6.62)	(-6.97)	(-4.91)
Popul	0.31	1.32**	2.05**	2.89***	2.67***	2.72***	2.59***	1.55*	2.85**
	(0.61)	(2.37)	(2.05)	(3.19)	(3.81)	(4.03)	(3.80)	(1.80)	(2.05)
GDPpc	-6.27***	-6.06***	-7.27***	-6.88***	-6.27***	-6.81***	-7.75***	-7.54***	-7.31***
	(-10.37)	(-9.18)	(-6.12)	(-6.41)	(-7.54)	(-8.54)	(-9.57)	(-7.38)	(-4.45)
Mobile	-0.82	-1.80***	-1.95*	-1.97*	-1.97**	-2.22***	-3.40***	-6.43***	-7.57***
	(-1.39)	(-2.79)	(-1.68)	(-1.87)	(-2.42)	(-2.84)	(-4.30)	(-6.44)	(-4.72)
FDI	-0.00	0.01	0.02	0.07	0.10	0.06	0.06	0.01	0.12
	(-0.02)	(0.20)	(0.16)	(0.66)	(1.13)	(0.78)	(0.77)	(0.07)	(0.69)
Unempl	4.03***	3.18***	0.83	-3.20*	-3.71***	-4.37***	-4.09***	-2.47	-4.27
	(3.98)	(2.88)	(0.42)	(-1.78)	(-2.67)	(-3.27)	(-3.01)	(-1.45)	(-1.55)
Country effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Obs	575	575	575	575	575	575	575	575	575

Notes. This table presents the effect of trade including digital and high tech on CO_2 emissions and the moderating role of institutional quality in this relationship using quantile regressions. (1)–(9) represent the 10–90% quantiles. *CO_2gdp*, serving as a dependent variable, represents CO_2 emissions, defined as kilograms of carbon emissions per purchasing power parity dollar of GDP. Digital trade (*Digital*) represents the ICT services volume. High-tech trade (*Hitech*) captures high-technology exports. *Trade* encompasses the sum of all export and import volumes. *Digital*^{2}, *Hitech*^{2}, and *Trade*^{2} are the square terms of *Digital*, *Hitech*, and *Trade. Rule* represents the rule of law. *Digital·Rule*, *Hitech·Rule*, *Trade·Rule*, *Digital*^{2}*·Rule*, *Hitech*^{2}*·Rule*, and *Trade*^{2}*·Rule* are interaction terms. *Popul* is population. *GDPpc* is GDP per capita. *Mobile* is mobile cellular telephone subscriptions. *FDI* represents foreign direct investment inflow. *Unempl* is the ratio of unemployment to the total labor force. *Country effect* indicates that the model includes country fixed effect. *Obs* denotes the country-year observations. The number of countries is 27 in all the models. Figures in parentheses are *t*-statistics. ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.

Table 6 presents the effect of technological progress and CO_2 emission using 11 transition economies within the EU: Bulgaria, Croatia, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, Slovakia, and Slovenia. Our research shows a U-shaped correlation between digital and high-tech trade and CO_2 emissions in 11 EU transition economies in Table 6. These 11 economies are distinct from other EU nations due to their relatively lower GDP per capita and unique cultural and political histories (Doukas and Zhang, 2021). Nevertheless, our study proves that technological advancement in these nations tends to follow a U-shaped impact on CO_2 emissions.

Table 6. Effects of digital, high-tech, and all trade volumes on CO_2 emissions in transition economies: FE

	(1)	(2)	(3)	(4)	(5)	(6)
Digital	-21.19***	-12.72***				
	(-11.47)	(-3.16)				
Digial^2	183.83***	153.05***				
	(7.65)	(3.01)				
Hitech			-2.50***	-5.82***		
			(-5.43)	(-4.31)		
Hitech^2			3.08***	18.28***		
			(3.05)	(3.37)		
Trade					-3.31***	-1.67**
					(-11.21)	(-2.35)
Trade^2					3.21***	2.52**
					(6.18)	(2.40)
Rule	-0.32***	-0.14**	-0.09*	-0.22**	-0.33***	-0.18**
	(-6.16)	(-2.40)	(-1.92)	(-2.32)	(-7.10)	(-2.55)
ICT·Rule		13.77***				
		(2.70)				
ICT^2*·Rule*		-213.65**				
		(-2.29)				
Hitech·Rule				5.08***		
				(3.59)		
Hitech^2*·Rule*				-18.14***		
				(-3.41)		
Trade·Rule						2.47***
						(2.87)
Trade^2*·Rule*						-4.44**
						(-2.35)
Popul		2.37		1.50		4.48
		(0.71)		(0.34)		(1.48)
GDPpc		-26.87***		-14.43***		-26.65***
		(-10.91)		(-4.38)		(-8.07)
Mobile		-4.60***		-1.49		-4.61**
		(-3.23)		(-0.41)		(-2.12)
FDI		0.25		0.14		0.25
		(0.55)		(0.58)		(0.56)

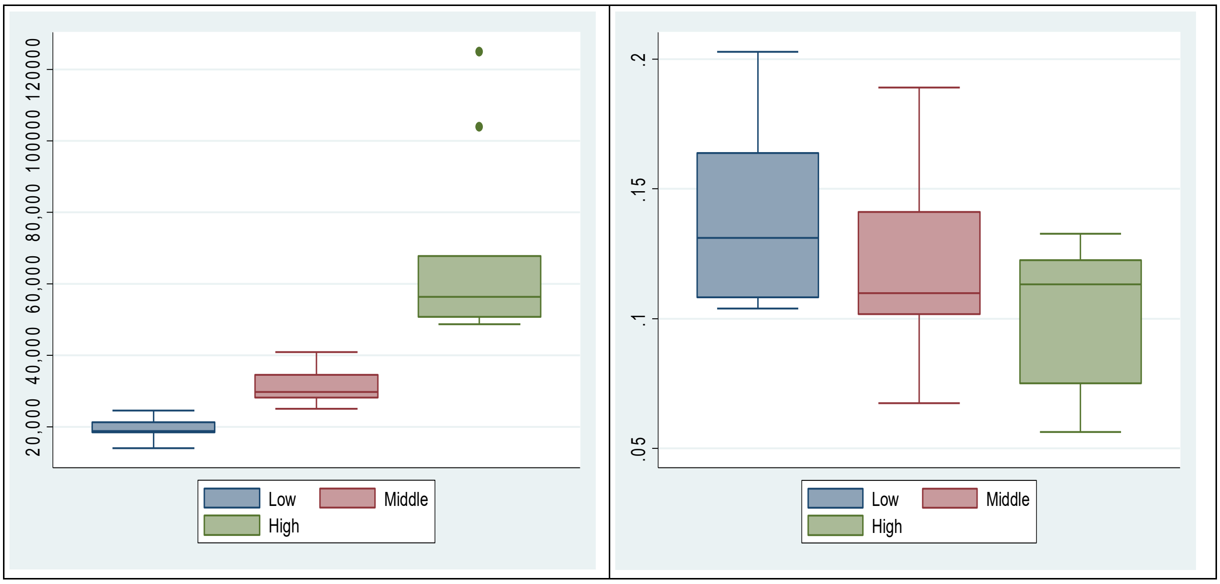
Unempl		-3.24		0.07		-1.07
		(-1.30)		(0.04)		(-0.44)
Intercept	0.71***	0.65*	0.45***	0.59	0.84***	0.45
	(25.48)	(1.77)	(13.86)	(1.25)	(31.39)	(1.39)
F-test	116.61***	75.28***	22.94***	16.50***	146.62***	75.53***
R^2	0.15	0.28	0.00	0.02	0.09	0.13
Obs	225	225	154	154	242	242

Notes. This table presents the effect of trade including digital and high tech on CO_2 emissions and the moderating role of institutional quality in this relationship using fixed-effect regressions. *CO_2gdp*, serving as a dependent variable, represents CO_2 emissions, defined as kilograms of carbon emissions per purchasing power parity dollar of GDP. Digital trade (*Digital*) represents the ICT services volume. High-tech trade (*Hitech*) captures high-technology exports. *Trade* encompasses the sum of all export and import volumes. $Digital^2$, $Hitech^2$, and $Trade^2$ are the square terms of *Digital*, *Hitec*, and *Trade. Rule* represents the rule of law. *Digital·Rule*, *Hitech·Rule*, *Trade·Rule*, $Digital^2 \cdot Rule$, $Hitech^2 \cdot Rule$, and $Trade^2 \cdot Rule$ are interaction terms. *Popul* is population, expressed in hundreds of millions. *GDPpc* is GDP per capita, expressed in hundred million. *Mobile* is mobile cellular telephone subscriptions. *FDI* represents foreign direct investment inflow. *Unempl* is the ratio of unemployment to the total labor force. *F*-test represents the *F*-test statistic, indicating a test of the null hypothesis that all the coefficients are zero. R^2 is the overall R-squared value. *Obs* denotes the country-year observations. The number of countries is 11 in all the models. Figures in parentheses are *t*-statistics. ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.

We examine the effects of technological progress on CO_2 emissions by GDP per capita across the 27 EU member states. The EU features diverse economies, with GDP per capita ranging from USD 13,974 to USD 125,006. We have divided the data into three groups based on GDP per capita levels: low level (below USD 25,000), middle level (USD 25,000 to 45,000), and high level (USD 45,000 to the maximum). The countries with a low GDP per capita are Bulgaria, Romania, Hungary, Croatia, Poland, Greece, Slovakia, Latvia, and Portugal. The middle GDP per capita group includes Lithuania, the Czech Republic, Estonia, Slovenia, Spain, Cyprus, Malta, Italy, and France. The high GDP per capita group comprises Germany, Belgium, Finland, Austria, Sweden, the Netherlands, Denmark, Ireland, and Luxembourg. Figure 1 presents GDP per capita in Panel A and CO_2 emissions by GDP per capita in Panel B for the 27 EU countries. The group with a low level of GDP per capita exhibits high levels of CO_2 emissions, while the group with a high level of GDP per capita exhibits low levels of CO_2 emissions.

Figure 1. GDP per capita and CO_2 emission in 27 EU

Panel A. GDP per capita	Panel B. CO_2 emissions



Notes. This figure shows the GDP per capita and CO_2 emissions in the 27 EU countries for 2020. The countries are divided into three groups based on GDP per capita. Panel A shows a box plot of GDP per capita for countries categorized as having low, middle, and high levels. Panel B presents a box plot of CO_2 emissions, grouped by countries with low, middle, and high GDP per capita. The *y*-axis denotes GDP per capita in Panel A and CO_2 emissions in Panel B. CO_2 emission is measured as kilograms of carbon emissions per purchasing power parity dollar of GDP. Source: https://databank.worldbank.org

Table 7 presents the effects of digital, high-tech, and all trade volumes on CO_2 emissions by GDP per capita in the EU. The groups with low, middle, and high levels of GDP per capita are shown in Panels A, B, and C, respectively. The low GDP group in Panel A demonstrates that digital and high-tech sectors, along with trade, negatively affect CO_2 emissions per GDP unit (CO_2gdp), while their squared terms ($Digital^2$, $Hitech^2$, and $Trade^2$) positively affect CO_2gdp, supporting a U-shaped effect of technological progress on CO_2 emissions. As we move from the low to the high GDP per capita groups, the inverse U effect on CO_2 emissions disappears. This suggests that countries with low GDP per capita primarily drive the U-shaped technological effect on CO_2 emissions. Countries with high GDP per capita typically have more stringent and advanced environmental policies. These countries often possess mature environmental policies that might already effectively limit emissions, regardless of technological advancements, and manage CO_2 emissions more strictly compared to low GDP countries and transition economies. High GDP countries may have reached a level of technological saturation where the incremental benefits of new technologies on CO_2 reduction are less pronounced. Initially, technological development often brings significant efficiency gains, but over time, the impact of new technologies may plateau.

Table 7. Effects of digital, high-tech, and all trade volumes on CO_2 emissions in the EU
Panel A. Low level of GDP per capita

	(1)	(2)	(3)	(4)	(5)	(6)

Digital	-21.97***	-17.89***				
	(-15.88)	(-6.71)				
Digial²	189.15***	239.08***				
	(10.67)	(6.20)				
Hitech			-4.81***	-3.60***		
			(-9.56)	(-3.99)		
Hitech²			13.49***	9.90**		
			(7.03)	(2.41)		
Trade					-3.61***	-3.27***
					(-17.11)	(-6.51)
Trade²					3.59***	4.23***
					(9.83)	(6.06)
Rule	-0.08**	-0.06	0.06**	0.01	-0.10***	-0.16***
	(-2.00)	(-1.50)	(2.14)	(0.16)	(-2.95)	(-3.43)
Digital·Rule		21.46***				
		(6.44)				
Digital²·Rule		-366.27***				
		(-4.83)				
Hitech·Rule				2.19*		
				(1.67)		
Hitech²·Rule				-7.62		
				(-1.23)		
Trade·Rule						3.17***
						(6.05)
Trade²·Rule						-5.48***
						(-4.66)
Popul		8.04***		16.41***		9.31***
		(3.67)		(7.92)		(4.66)
GDPpc		-16.75***		-0.16		-9.43***
		(-9.01)		(-0.07)		(-3.62)
Mobile		-5.17***		-2.69		-2.51
		(-5.40)		(-1.10)		(-1.63)
FDI		0.20		0.05		0.27
		(0.72)		(0.32)		(0.93)
Unempl		-2.12		0.49		0.40
		(-1.53)		(0.45)		(0.30)
Intercept	0.56***	-0.31	0.37***	-1.62***	0.73***	-0.43
	(27.86)	(-1.04)	(19.83)	(-6.46)	(33.56)	(-1.62)
F-test	127.66***	116.09***	41.16***	31.21***	178.25***	119.10***
R^2	0.30	0.21	0.00	0.14	0.13	0.17

Obs	184	184	126	126	197	197

Panel B. Middle level of GDP per capita

	(1)	(2)	(3)	(4)	(5)	(6)
Digital	-7.94***	-11.14***				
	(-7.37)	(-2.91)				
Digial^2	27.82***	35.20				
	(5.14)	(1.07)				
Hitech			-1.61***	-0.78		
			(-5.18)	(-0.75)		
Hitech^2			0.74***	0.15		
			(4.24)	(0.13)		
Trade					-1.52***	-1.28**
					(-8.14)	(-2.52)
Trade^2					0.57***	0.76**
					(6.46)	(2.56)
Rule	-0.44***	-0.34***	0.13***	0.11**	-0.38***	-0.34***
	(-7.29)	(-5.74)	(2.82)	(2.25)	(-6.91)	(-5.93)
Digital·Rule		6.25**				
		(2.00)				
Digital^2·Rule		-19.94				
		(-0.80)				
Hitech·Rule				-0.43		
				(-0.51)		
Hitech^2·Rule				0.40		
				(0.45)		
Trade·Rule						1.12***
						(3.15)
Trade^2·Rule						-0.56**
						(-2.45)
Popul		-1.38		-5.35**		-1.96
		(-0.67)		(-2.45)		(-1.34)
GDPpc		-17.51***		-10.32***		-19.83***
		(-9.55)		(-4.08)		(-9.75)
Mobile		5.81***		3.63		1.86
		(3.42)		(1.23)		(1.11)
FDI		1.07*		0.22		0.92
		(1.72)		(0.59)		(1.65)
Unempl		0.72		0.55		-1.52
		(0.21)		(0.26)		(-0.56)
Intercept	0.91***	1.29***	0.31***	1.58***	1.04***	1.44***

	(13.22)	(3.31)	(5.23)	(3.64)	(14.36)	(5.26)
F-test	33.47***	29.16***	11.53***	6.67***	38.39***	29.79***
R^2	0.18	0.24	0.11	0.17	0.18	0.23
Obs	178	178	126	126	198	198

Panel C. High level of GDP per capita

	(1)	(2)	(3)	(4)	(5)	(6)
Digital	-1.27***	1.21**				
	(-14.67)	(2.21)				
Digial²	0.62***	-0.92				
	(11.45)	(-1.48)				
Hitech			0.29***	-0.82*		
			(3.31)	(-1.70)		
Hitech²			-0.12***	0.36*		
			(-3.60)	(1.69)		
Trade					-0.50***	0.07
					(-11.28)	(0.21)
Trade²					0.09***	-0.04
					(8.06)	(-0.41)
Rule	-0.10*	0.10	0.20***	-0.04	-0.05	-0.07
	(-1.72)	(1.54)	(4.55)	(-0.49)	(-0.86)	(-0.61)
Digital·Rule		-1.18***				
		(-3.42)				
Digital²·Rule		0.81*				
		(1.94)				
Hitech·Rule				0.63**		
				(2.34)		
Hitech²·Rule				-0.30**		
				(-2.38)		
Trade·Rule						-0.10
						(-0.49)
Trade²·Rule						0.04
						(0.56)
Popul		-3.32***		-7.59***		-5.36***
		(-3.65)		(-6.43)		(-4.13)
GDPpc		-3.16***		-1.74**		-4.25***
		(-7.53)		(-2.19)		(-7.29)
Mobile		-0.30		3.94**		-1.07
		(-0.75)		(2.21)		(-1.39)
FDI		0.01		0.02		0.03
		(0.17)		(0.47)		(0.59)

Unempl		5.47^{***}		-4.11		4.50^{*}
		(2.87)		(-1.30)		(1.81)
Intercept	0.52^{***}	0.84^{***}	-0.25^{***}	1.46^{***}	0.57^{***}	1.51^{***}
	(5.14)	(4.26)	(-2.96)	(6.05)	(5.22)	(5.08)
F-test	79.74^{***}	52.11^{***}	10.37^{***}	11.10^{***}	61.30^{***}	36.32^{***}
R^2	0.18	0.01	0.01	0.03	0.02	0.01
Obs	173	172	126	126	181	180

Notes. This table presents the effect of trade including digital and high tech on CO_2 emissions and the moderating role of institutional quality in this relationship using fixed-effect regressions. Panels A, B, and C show results using each dataset: low, middle, and high GDP per capita countries, respectively. Low GDP per capita countries are Bulgaria, Romania, Hungary, Croatia, Poland, Greece, Slovakia, Latvia, and Portugal. Middle GDP per capita countries are Lithuania, Czech Republic, Estonia, Slovenia, Spain, Cyprus, Malta, Italy, and France. High GDP per capita countries include Germany, Belgium, Finland, Austria, Sweden, Netherlands, Denmark, Ireland, and Luxembourg. *CO_2gdp*, serving as a dependent variable, represents CO_2 emissions, defined as kilograms of carbon emissions per purchasing power parity dollar of GDP. Digital trade (*Digital*) represents the ICT services volume. High-tech trade (*Hitech*) captures high-technology exports. *Trade* encompasses the sum of all export and import volumes. *$Digital^2$*, *$Hitech^2$*, and *$Trade^2$* are the square terms of *Digital*, *Hitech*, and *Trade. Rule* represents the rule of law. *Digital·Rule*, *Hitech·Rule*, *Trade·Rule*, *$Digital^2$·Rule*, *$Hitech^2$·Rule*, and *$Trade^2$·Rule* are interaction terms. *Popul* is population. *GDPpc* is GDP per capita. *Mobile* is mobile cellular telephone subscriptions. *FDI* represents foreign direct investment inflow. *Unempl* is the ratio of unemployment to the total labor force. *F*-test represents the *F*-test statistic, indicating a test of the null hypothesis that all the coefficients are zero. *R^2* is the overall R-squared value. *Obs* denotes the country-year observations. The number of countries is 9 in all models. Figures in parentheses are *t*-statistics. ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.

The results concerning the relationship between technological change and CO_2 emissions across the EU are similar to those observed in countries with a low level of GDP per capita and transition economies, where less economically developed countries drive overall outcomes. As less developed countries emit considerably more CO_2 compared to countries with a high level of GDP per capita, it leads to environmental degradation. Countries with a higher level of GDP per capita can have a high level of energy efficiency and strong regulations for the environment, and technological progress potentially has an insignificant effect on environmental degradation.

4. Conclusion and Policy Implications

This study delves into the intricate relationship between technological progress and CO_2 emissions within the EU from 1990 to 2020. Contrary to the optimistic perspective often associated with the EKC, our findings suggest a U-shaped effect of technological advancement on CO_2 emissions. Initially, technological progress and energy efficiency improvements lead to reduced emissions. However, as digital and high-tech industries mature and expand, the associated increase in production and global supply chain logistics tends to negate early environmental gains, ultimately leading to higher CO_2 emissions. These findings underscore that technological advancements alone are insufficient to guarantee sustained reductions in environmental degradation.

Furthermore, the study emphasizes the significant role of institutional quality in moderating the environmental impact of technological progress. High institutional quality, characterized by effective regulations and policies, is crucial in ensuring that the benefits of technological advancements, are not offset at initial stages. Our analysis reveals that although institutional quality may not immediately reduce emissions driven by technological advancements, it eventually fosters significant reductions over time. This insight is particularly relevant for policymakers aiming to craft long-term strategies that harmonize technological progress with environmental sustainability.

Finally, the consistency of our findings across both EU economies and transition economies highlights the pervasive nature of the challenges posed by technological progress to environmental sustainability. Even in transition economies with lower GDP per capita and distinct cultural and political backgrounds, the U-shaped relationship between technological progress and CO_2 emissions persists. This demonstrates that both developed and developing nations within the EU must prioritize strengthening institutional frameworks to mitigate the adverse environmental impacts of technological advancements. In conclusion, while technological progress is essential for economic development, it must be complemented by robust institutional policies to achieve a sustainable reduction in CO_2 emissions and address the pressing issue of climate change.

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