Digital trade and environmental performance: The moderating role of environmental policy stringency

Nguyen Thi Thu Huong

Faculty of Economics, Vietnam Maritime University, Viet Nam

Chronicle

Article history

Received	20 Oct 2025
Revised	19 Apr 2026
Accepted	20 May 2026

Keywords

Digital trade, Environmental performance, Environmental policy stringency

Citation:

Nguyen, T. T. H. (2026). Digital trade and environmental performance: The moderating role of environmental policy stringency. *Journal of Economic and Banking Studies, 6*(1), 86-100. http://doi.org/10.59276/JEBS.2026.06.2731

Abstract

This research investigates the nexus between digital trade and environmental performance across 40 countries over the period 2005- 2020, with a particular emphasis on the moderating role of environmental policy stringency. Using fixed-effects estimators with Driscoll-Kraay standard errors, the results show that higher levels of digital trade are associated with lower ecological footprint and greenhouse gas emissions, suggesting a potential link between digitalization and improved environmental performance. Moreover, the findings reveal that environmental policy stringency is associated with a more positive relationship between digital trade and environmental performance. Additional results indicate that energy consumption and globalization are associated with poorer environmental performance, whereas environmental policy stringency, R&D expenditure, and urbanization are linked to better environmental performance. From a policy perspective, the findings imply that digital trade is associated with improved environmental performance, particularly when supported by robust environmental regulations. Policies promoting digital trade may be more effective when coordinated with stricter environmental standards, investments in clean energy, and support for green innovation, thereby contributing to sustainable development goals.

1. Introduction

Environmental degradation, driven by deforestation, pollution, population growth, and climate change, has wide-ranging effects, including increased vulnerability to natural disasters, harm to ecosystems, and direct impacts on human health (Ahmad et al., 2023). Biodiversity loss, exacerbated by urbanization and industrialization, undermines ecosystem health and the delivery of essential services, further threatening sustainable development (Lu et al., 2020; Pörtner et al., 2023). In 2023, total CO_2 emissions reached approximately 40.6 gigatonnes, and early 2024 data show a further increase of about 0.8% in fossil fuel emissions compared to the previous year (Friedlingstein et al., 2024). The global atmospheric CO_2 concentration rose to 422.45 ppm in 2024, marking a 52% increase compared with pre-industrial concentrations (Friedlingstein et al., 2024). In the meantime, deforestation of primary forests surged in 2024 to 6.7 million hectares, an 80% increase from the previous year, releasing roughly 3.1 gigatonnes of CO_2 into the atmosphere (Goldman et al., 2025). Therefore, the essential focus of development worldwide should be on fostering economic growth that aligns with environmental performance to secure long-term prosperity.

E-mail address: huongntt.ktb@vimaru.edu.vn

The increasing prominence of digital service trade, with a larger share of cross-border transaction value in recent years, has redefined global economic structures and dynamics (The Organisation for Economic Co-operation and Development [OECD], 2024; the International Monetary Fund [IMF] et al., 2023a). By lowering information gaps and reducing transaction costs, the increasing use of ICT tools, online trading platforms, and digital knowledge-exchange systems has helped firms, including many small and medium-sized enterprises, reach international markets with greater ease (Bargoni et al., 2024; Wang et al., 2024). In addition, cloud services, digital platforms, and data-driven solutions have boosted innovation and productivity while broadening the scope of trade beyond conventional goods. As a result, digital service trade has emerged as a key driver of inclusive growth, enabling developing economies to engage more effectively in global value chains (Yeerken & Feng, 2024).

Previous research has explored how digital trade relates to environmental performance, yet their findings remain controversial. Some scholars argue that digital trade can advance environmental performance by enhancing resource efficiency, facilitating the exchange of green technologies, and supporting the transition toward low-carbon production systems (Ashraf et al., 2024; Liang & Qiao, 2024; Sun et al., 2024). However, other studies highlight the environmental costs associated with the rapid growth of digital trade, including rising energy consumption from data transmission and storage, the carbon footprint of global ICT infrastructure, and the proliferation of electronic waste linked to digital devices (Notley, 2019; Yang et al., 2025). These mixed findings suggest that the environmental effects of digital trade are multifaceted and highly dependent on national contexts, technological capacity, and policy frameworks.

Although digital trade has expanded rapidly, there is still limited empirical research on how environmental policy frameworks shape its environmental consequences. In particular, the moderating role of environmental policy stringency in shaping the digital trade-environment relationship remains underexplored. This study addresses this gap by analyzing data from 40 countries between 2005 and 2020, using the OECD Environmental Policy Stringency (EPS) index to capture the intensity of environmental regulation. This study focuses on two specific objectives. First, it examines whether digital trade is associated with environmental performance. Second, it investigates whether stricter environmental policies strengthen the environmental benefits of digital trade by moderating this relationship. By combining information on digital trade flows, environmental performance indicators, and policy stringency, the analysis examines whether stronger environmental governance is linked to greater environmental benefits of digital trade. The results provide practical guidance for policymakers seeking to advance digital trade in ways that are compatible with long-term environmental objectives.

The remainder of this paper is organized as follows. Section 2 reviews the relevant literature and develops the research hypotheses. Section 3 explains key variables, their data sources, and the empirical model. Section 4 analyzes and discusses the main findings. Finally, Section 5 summarizes the key results and their policy implications.

2. Literature review and hypothesis development

The relationship between digital trade and environmental performance remains controversial, reflecting the existence of multiple mechanisms through which digital trade may influence environmental outcomes. On the one hand, a number of studies emphasize the environmental benefits of digital trade. From this perspective, digital trade is argued to promote environmental performance through substitution and dematerialization effects, whereby physical goods, paper-based transactions, and transport-intensive activities are replaced by digitally delivered services. Such transformations can reduce material intensity, lower transportation emissions, and improve overall resource efficiency. In addition, digital trade facilitates cross-border knowledge diffusion, accelerates the transfer of green technologies, and supports industrial upgrading, thereby enhancing environmental performance. Empirical evidence supporting these mechanisms is provided by Ashraf et al. (2024), who find that digital trade is associated with long-term carbon reduction in major emitting economies. Similarly, Liang and Qiao (2024) use provincial data from China and show that digital trade development stimulates green innovation through industrial upgrading and technology diffusion. Sun et al. (2024) further demonstrate that, in developing countries, digital trade growth improves mineral resource utilization efficiency and supports green recovery by fostering technological advancement.

On the other hand, several studies highlight the environmental costs associated with the expansion of digital trade. Notley (2019) argues that the global digital economy is deeply material- and energy-intensive, relying heavily on data centers, cloud computing, communication networks, and digital devices that consume substantial amounts of electricity, water, and raw materials. These processes generate significant carbon emissions and electronic waste, often obscured within global production chains. Complementing this argument, Yang et al. (2025) provide empirical evidence of a U-shaped relationship between digital trade development and carbon emissions in China, indicating that digital trade may initially exacerbate environmental degradation due to scale expansion and rebound effects before efficiency gains emerge at more advanced stages of digitalization. These findings imply that reductions in unit costs and efficiency improvements associated with digital trade do not automatically translate into lower aggregate environmental pressure, particularly when increased accessibility stimulates higher overall consumption.

The aforementioned studies indicate that the impact of digital trade on environmental performance is not consistently positive or negative. Instead, its net environmental influence depends on the relative strength of competing mechanisms. While the literature highlights potential environmental costs related to scale and rebound effects, these concerns are mainly linked to large increases in energy-intensive digital infrastructure rather than to incremental changes in digitally deliverable services trade. Given the relatively low material intensity and limited transportation needs of digitally deliverable services, the increasing growth in digital trade is expected to work mainly through substitution, dematerialization, and efficiency improvements rather than through resource-intensive production. Theoretically, this expectation aligns with the substitution and efficiency-effect frameworks, which suggest that digitalization may lower environmental pressure by replacing resource-intensive activities and improving energy and resource efficiency (Grossman & Krueger, 1995; Hilty & Aebischer, 2015). As a result, despite the presence of competing mechanisms identified in the literature, this study expects a positive net relationship between digital trade and environmental performance. The first hypothesis is proposed as follows:

H_1: Digital trade is expected to be associated with improved environmental performance.

A growing body of literature suggests that the environmental consequences of digital trade are strongly influenced by the broader regulatory and policy environment. Particularly, several studies identify the role of regulatory quality, green technological innovation, and renewable energy use in shaping the digital trade-environment performance nexus. Using data from 31 African countries during 2000- 2020, Evans and Mesagan (2022) find that ICT-trade expansion is associated with increased pollution in the absence of strong governance, suggesting that digital trade growth alone may exacerbate environmental degradation. However, their results also demonstrate that when supported by effective regulatory frameworks and sound governance institutions, ICT-trade contributes to reducing environmental pollution and promoting cleaner growth. In an empirical work on BRICS economies, Qiu and Wan (2023) indicate that digital trade significantly reduces the ecological footprint, thereby improving environmental quality. Moreover, the incorporation of green technological innovation plays a vital complement to digital trade, substantially enhancing its capacity to create positive environmental outcomes.

Besides, other research highlights environmental policy stringency as a key mechanism for reducing the ecological costs of economic expansion by incentivizing firms to adopt cleaner technologies, shift toward renewable energy, and upgrade production. Using firm-level export data, Du et al. (2023) show that stricter environmental regulations not only enhance the environmental performance of exporting firms but also drive technological upgrading, thereby reducing firms' reliance on pollution-intensive products. Bibi et al. (2024) reach similar conclusions in the context of China's textile and fashion industry. Their findings demonstrate that policy measures, when combined with cleaner production technologies and renewable energy use, can simultaneously support industrial development and improve environmental outcomes. These results reveal the significance of well-designed policies to separate industrial expansion from environmental degradation by stimulating technological progress. Other studies at the regional level reinforce this pattern. Benatti et al. (2024) examine 15 Euro Area countries and find that tighter environmental regulations significantly boost clean-technology patenting without displacing other forms of innovation. Likewise, in a study of 32 OECD economies, Hassan et al. (2024) show that higher policy stringency consistently increases renewable energy consumption, with all policy types contributing positively. The findings suggest that stricter and well-designed environmental regulations, especially those combining market mechanisms with technology supports, are effective in accelerating the transition toward renewable energy in OECD economies.

Despite this growing body of evidence, limited research directly examines how the stringency of environmental policies conditions the environmental effects of digital trade. Existing studies often treat environmental regulations as an independent determinant of environmental outcomes or discuss various channels, such as innovation and energy transition, without explicitly analyzing how regulatory stringency alters the relationship between digital trade and environmental performance. Building on this gap, this study treats environmental policy stringency as a contextual factor that influences how digital trade affects environmental outcomes, rather than as an intermediate channel. When environmental regulations are stringent, the efficiency gains, innovation effects, and cleaner energy adoption associated with digital trade are more likely to translate into improved environmental outcomes. In contrast, weaker regulatory frameworks may allow scale and rebound effects to offset potential benefits. Accordingly, this study proposes the following hypothesis:

H_2: Stricter environmental policies are likely to strengthen the relationship between digital trade and environmental performance.

3. Data and model specification

3.1. Digital trade

This study follows the definition of digital service trade proposed by IMF et al. (2023b). Accordingly, digital trade includes those service sectors within the Extended Balance of Payments Services Classification (EBOPS 2010) that can be delivered digitally. Digitally deliverable services capture the extent to which cross-border service exchanges are enabled by digital technologies, rather than implying that all transactions are fully conducted through digital channels. This concept reflects the digital intensity embedded in international services trade and is therefore well-suited for cross-country analysis, where transaction-level information on actual modes of delivery is generally unavailable. These categories comprise "insurance and pension services", "financial services", "charges for the use of intellectual property", "telecommunications", "computer and information services", "other business services", "audiovisual and related services", as well as "personal, cultural, and recreational services". Data on service trade are obtained from the most recent version of the OECD-WTO Balanced Trade in Services (BaTIS) database, which offers detailed coverage for over 200 countries and reports total services and 26 EBOPS 2010 categories spanning the period 2005- 2023. In line with the IMF's definition, this study calculates the aggregate values of digital service exports and imports for each country.

3.2. Environmental performance

Following Can et al. (2022) and Ahmed et al. (2022), this analysis adopts per capita ecological footprint, denoted by "*EFPC*", as the indicator representing environmental degradation. This indicator reflects the amount of biologically productive land and water needed to provide the resources that a person uses and to absorb the waste that they produce. In international trade, environmental impacts do not arise from a single mechanism but emerge through multiple interconnected channels, including changes in production structures, consumption patterns, transportation demand, and energy use. Accordingly, digital trade can influence these channels in both mitigating and amplifying ways, as it may reduce material intensity through substitution and dematerialization while simultaneously expanding economic activities and consumption demand. Therefore, the ecological footprint, which is a composite indicator encompassing multiple dimensions of environmental pressure, is suitable for capturing the overall environmental impacts associated with these interacting mechanisms. By measuring the extent to which economic activity places demands on biologically productive land and water resources, "*EFPC*" provides an integrated assessment of whether trade-related activities operate within the regenerative capacity of ecosystems. Standardizing the ecological footprint at the per capita level allows comparisons across countries and regions. The Global Footprint Network provided the dataset for the ecological footprint per person, which is expressed in global hectares (gha).

Besides, to verify the stability of results obtained by "*EFPC*", this study further employs greenhouse gas emissions per capita, denoted by "*GHGC*", as an alternative indicator of environmental performance. This variable is constructed by dividing total greenhouse gas emissions (measured in megatonnes of CO_2 equivalent) by population. The resulting variable is expressed in metric tons of CO_2 equivalent per capita. Data for this variable's construction is taken from the World Bank's World Development Indicators (WDI).

3.3. Empirical model specification

First, to investigate the effect of digital trade on environmental performance, this study applies a panel fixed effects regression. Despite the use of country and time fixed effects, potential endogeneity concerns may still arise in the relationship between digital trade and environmental performance. In particular, reverse causality may arise since countries with better environmental outcomes are also more likely to develop digital trade. In addition, omitted variables may simultaneously affect both digital trade and environmental outcomes. While fixed effects estimation helps control for time-invariant unobserved heterogeneity, it does not fully address these sources of endogeneity.

To mitigate these concerns, this study adopts a lagged-variable approach by using one-period lagged values of all explanatory variables in the empirical specifications. By relating current environmental outcomes to past levels of digital trade and other control variables, this approach helps reduce simultaneity bias and alleviates concerns regarding reverse causality.

The baseline model is developed as follows:

$$\ln(EFPC)_{i,t} = \alpha_0 + \alpha_1\ln(dig\_trade)_{i,t-1} + \alpha_2\ln(env\_pol)_{i,t-1} + \alpha_3\ln(ene\_use)_{i,t-1} + \alpha_4\ln(KOFGI)_{i,t-1} + \alpha_5\ln(R\&D)_{i,t-1} + \alpha_6\ln(urb\_pop)_{i,t-1} + \gamma_i + \Omega_t + \varepsilon_{i,t} \quad (1)$$

where *i* denotes the country index, *t* represents the year, γ_i captures country-specific fixed effects, Ω_t refers to year-specific dummy variables, and $\varepsilon_{i,t}$ denotes the well-behaved error term. Table 1 provides the definitions, data sources, and expected signs of the variables included in Model (1).

To examine the hypothesis H_2, Model (1) is extended as follows:

$$\ln(EFPC)_{i,t} = \alpha_0 + \alpha_1 \ln(dig\_trade)_{i,t-1} + \alpha_2 \ln(env\_pol)_{i,t-1} + \alpha_3 \ln(dig\_trade)_{i,t-1} * \ln(env\_pol)_{i,t-1} + \alpha_4 \ln(ene\_use)_{i,t-1} + \alpha_5 \ln(KOFGI)_{i,t-1} + \alpha_6 \ln(R\&D)_{i,t-1} + \alpha_7 \ln(urb\_pop)_{i,t-1} + \gamma_i + \Omega_t + \varepsilon_{i,t} \quad (2)$$

The study's final sample comprises 40 countries over the period 2005- 2020. The specific list of countries can be found in Appendix 1, while Table 2 outlines the descriptive statistics for the variables used in this study.

3.4. Tests for the model suitability

To determine the most suitable estimation method for the model, this study first applies the Breusch–Pagan Lagrangian Multiplier test to compare the Pooled Ordinary Least Squares (POLS) model with the random effects model (REM). The test yielded a p-value of less than 0.01, suggesting the rejection of the null hypothesis that POLS is more appropriate. This indicates that the random effects model is more suitable for analyzing the dataset than the Pooled OLS model. Subsequently, this study proceeds to employ the Hausman test to evaluate whether the random effects model (REM)

Table 1. Descriptions of independent variables used in Model (1)

Variable	Variable's name	Descriptions	Expected effects	References	Data sources
Dependent variable					
ln(EFPC)	Environmental performance (ecological footprint per capita)	This variable captures the logged value of per capita ecological footprint (global hectares).		Can et al. (2022) and Ahmed et al. (2022)	The Global Footprint Network
Independent variable					
ln(dig_trade)	Digital trade	This variable represents the natural logarithm of total digital service exports and imports as a share of GDP. It measures the relative scale of a country's digital trade in relation to its economic size.	-	IMF et al. (2023b), Wen et al. (2023), Suh and Roh (2023)	The OECD-WTO's BaTIS database and The WB's WDI
ln(env_pol)	Environmental policy stringency	It is the natural logarithm of the OECD Environmental Policy Stringency index, measuring the degree of strictness in environmental rules, including market, non-market, and technology-oriented policies.	-	Wang et al. (2020) and Hassan et al. (2024)	The OECD database
ln(KOFGI)	Globalization	It is the natural logarithm of globalization index. It reflects the extent of a country's integration into global networks.	+	Hussain and Zhou (2022)	The KOF Swiss Economic Institute's database.

ln(ene_use)	Energy consumption	It is the natural logarithm of per capita energy usage (measured in kilograms of oil equivalent). It represents the amount of primary energy used by a country's residents, industries, and services.	+	Zhang and Cheng (2009), Sikder et al. (2022)	The WB's WDI.
ln(R&D)	Research and development (R&D) expenditure	This variable reflects the degree of a nation's financial spending on technological progress and novelty. It is calculated by taking the natural logarithm of R&D spending measured as a share of the country's GDP.	-	Ahmad et al. (2020), Ahmad et al. (2023)	
ln(urb_pop)	Urbanization	It is the natural logarithm of the annual urban population growth rate. The original variable is expressed in percentage terms. Prior to the logarithmic transformation, percentage values are converted into proportion form by dividing by 100. As urban population growth may take negative values, observations with non-positive values are excluded from the estimation sample. This treatment is appropriate as the log specification focuses on proportional changes under conditions of urban expansion rather than contraction. The excluded observations are limited (approximately 10%) and do not materially affect the representativeness of the sample.	+	Hussain and Zhou (2022), Sikder et al. (2022)	

Source: Author's elaboration

or fixed effects model (FEM) is more suitable in this case. The test rejects the null hypothesis of no systematic difference in coefficients (p-value=0.0082), suggesting that FEM is more suitable than REM. Given that the fixed effects model is selected as the baseline, this study conducts several diagnostic tests to assess potential violations of standard panel regression assumptions. The analysis examines heteroskedasticity, serial correlation, and multicollinearity. The modified Wald test for groupwise heteroskedasticity strongly rejects the null hypothesis of homoskedasticity (p=0.0000), indicating the presence of heteroskedasticity across panels. In addition, the Wooldridge test for autocorrelation rejects the null hypothesis of no first-order serial correlation (p=0.0053), suggesting that the error terms are serially correlated. By contrast, the variance inflation factor (VIF) results in Table 3 show values below the conventional threshold of 10, implying that multicollinearity is not a serious concern.

In light of the detected heteroskedasticity and serial correlation in the panel data, this study adopts the fixed-effects estimator with Driscoll-Kraay standard errors for the final estimations. This approach provides consistent inference in the presence of heteroskedasticity and autocorrelation.

Regarding cross-sectional dependence, formal tests, such as the Pesaran CD test, were considered. However, due to the highly unbalanced structure of the panel, such tests could not be reliably implemented. Given this data constraint, Driscoll-Kraay standard errors are adopted as a conservative inference strategy, as they provide reliable estimates under different types of cross-sectional

Table 2. Descriptive statistics of all variables used in the empirical analysis

Variable	Obs	Mean	Std. Dev.	Min	Max
ln(EFPC)	624	1.53	0.56	-0.29	2.65
ln(GHGC)	640	2.29	0.50	0.61	3.36
ln(dig_trade)	640	-4.84	0.98	-7.07	-1.29
ln(env_pol)	637	0.77	0.64	-1.79	1.59
ln(ene_use)	640	8.10	0.62	6.05	9.81
ln(KOFGI)	640	4.35	0.11	4.01	4.50
ln(R&D)	600	0.42	0.65	-2.49	1.74
ln(urb_pop)	574	-4.70	0.94	-10.70	-3.25

Source: Author's calculation based on data from the Global Footprint Network, the OECD-WTO's BaTIS, The World Bank's WDI, the OECD, and the KOF Swiss Economic Institute's databases.

and time-related dependence. As a result, this estimation approach enhances the robustness and credibility of the reported results.

3.5. Data analysis

Figure 1 illustrates the trends in the digital trade share of GDP and two environmental performance indicators, namely ecological footprint per capita and greenhouse gas emissions per capita, across 40 countries between 2005 and 2020. In general, the digital trade share of GDP, represented by the bars, shows a substantial upward trend throughout the period. The value increased from about 9.12% in 2005 to over 20% in 2020. The increasing movement becomes more consistent after 2015, with only modest variations in the earlier years. In contrast, both environmental indicators, represented by the lines, display gradual downward movements over the same period, although with some minor fluctuations across years. More specifically, the ecological footprint per capita decreases from approximately 5.8 global hectares per person in 2005 to about 4.7 global hectares per person by 2020. Similarly, greenhouse gas emissions per capita show a downward trajectory from around 12 to about 10 tCO_2e per capita over the same timeframe, which indicates reduced emissions intensity.

Table 3. Multicollinearity test

Variable	VIF
l.ln(KOFGI)	4.29
l.ln(ene_use)	2.30
l.ln(dig_trade)	1.99
l.ln(env_pol)	1.84
l.ln(R&D)	1.67
l.ln(urb_pop)	1.23
Mean VIF	2.22

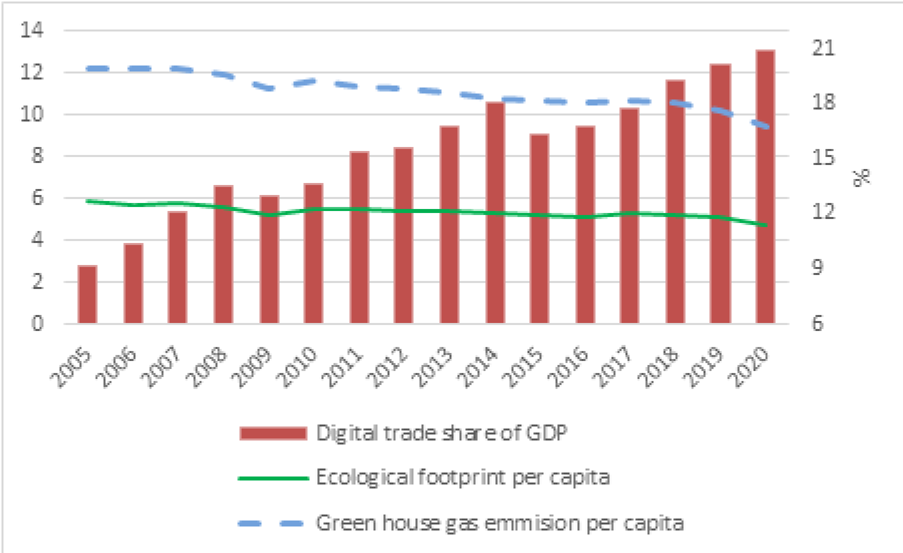
Source: Author's calculation using Stata 14 software

4. Empirical results

4.1. Impact of digital trade on environmental performance

Table 4 outlines the empirical findings for Model (1) using fixed-effects estimators with Driscoll-Kraay standard errors. In Column (1) of Table 4, the natural logarithm of per capita ecological footprint, denoted by "*ln(EFPC)*", is adopted as the dependent variable. For robustness, this study replaces "*ln(EFPC)*" in Model (1) with the natural logarithm of per capita greenhouse gas emissions, denoted by "*ln(GHGC)*", and reports the corresponding outcomes in Column (2) of Table 4.

The results in Columns (1)-(2) of Table 4 consistently revealed that the coefficients for the digital trade variable (denoted as "*dig_trade*") are negative and statistically significant at the 1% level. This finding suggests that greater digital trade is associated with lower environ-



Source: Author's calculation based on data from the Global Footprint Network, the OECD-WTO BaTIS database, and the WDI of the World Bank database

Figure 1. Trends in digital trade share of GDP and two indicators measuring environmental performance across 40 countries, 2005- 2020

mental degradation. Specifically, holding other factors constant, a 10% increase in the previous period's digital trade share of GDP is correlated with a 1.53% decrease in per capita ecological footprint and a 2.26% decrease in per capita greenhouse gas emissions. These conclusions support hypothesis H1 and are consistent with earlier research that recognized digitalization's capacity to alleviate environmental strains. For instance, Qiu and Wan (2023) observed a notable reduction in the ecological footprint due to digital trade in BRICS countries. However, unlike some earlier research that suggested adverse or mixed effects of digitalization on environmental outcomes (Notley, 2019; Yang et al., 2025), the findings of this study indicate a consistently negative and statistically significant relationship between digital trade and environmental degradation.

Turning to control variables, the results show that energy consumption (denoted by "*ene_use*") and globalization (denoted by "*KOFGI*") have positive and statistically significant effects on environmental degradation indicators, while environmental policy stringency (denoted by "*env_pol*"), research and development expenditure (denoted by "*R&D*"), and urbanization (denoted by "*urb_pop*") exert negative and significant impacts. These outcomes are broadly consistent with theoretical expectations. To be more specific, the positive coefficients of energy consumption suggest that increased energy use contributes significantly to ecological footprint and greenhouse gas emissions. Specifically, a 10% rise in energy consumption in the previous period is linked to a 7.09% increase in ecological footprint per capita and a 8.5% increase in greenhouse gas emissions per capita. This finding aligns with previous studies such as Zhang and Cheng (2009) and Sikder et al. (2022), who documented that higher energy use, particularly the significant dependency on fossil fuels to satisfy expanding energy demands associated with industrialization and economic development, exacerbates environmental pressures and accelerates climate change.

Similarly, the globalization variable has a positive and significant coefficient. This result implies that greater economic, financial, and

Table 4. Impact of digital trade on environmental performance (40 countries, 2005- 2020)

	(1)	(2)
Variables	ln(EFPC)	ln(GHGC)
l.ln(dig_trade)	-0.153***	-0.226***
	(0.0413)	(0.0310)
l.ln(env_pol)	-0.0244*	-0.0110
	(0.0124)	(0.0123)
l.ln(ene_use)	0.709***	0.850***
	(0.0616)	(0.0643)
l.ln(KOFGI)	0.352**	0.639***
	(0.154)	(0.200)
l.ln(R&D)	-0.0390**	-0.00842
	(0.0155)	(0.0185)
l.ln(urb_pop)	-0.0119***	-0.0117**
	(0.00193)	(0.00441)
Constant	-5.445***	-6.968***
	(0.482)	(0.783)
Year FEs	YES	YES
Country FEs	YES	YES
Observations	488	498
R-squared	0.7018	0.7732

*Notes: Driscoll-Kraay standard errors are reported in parentheses. *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively.*

Source: Author's calculation using Stata 14 software

social integration may intensify environmental pressures. Holding other factors unchanged, a 10% increase in the lagged globalization index corresponds to a 3.52% rise in per capita ecological footprint and a 6.39% rise in greenhouse gas emissions per capita. This result supports the "pollution haven" hypothesis, which says that globalization can shift industries that produce heavy pollution to countries with less stringent environmental rules (Kamal et al., 2021). However, it contrasts with studies such as Tahir et al. (2021) and Aydin et al. (2024), which found that globalization can enhance environmental quality through the diffusion of cleaner technologies and environmental norms. The disparity may reflect differences in the influence of globalization across regions. More specifically, globalization can foster the transfer of technology and enhance production efficiency. However, it may also drive industrial growth and accelerate the depletion of natural resources.

In contrast, environmental policy stringency, R&D expenditure, and urbanization exhibit negative and significant coefficients in Column (1) of Table 4, suggesting their crucial role in mitigating environmental degradation. Specifically, a 10% increase in the lagged Environmental Policy Stringency Index is associated with a 0.244% reduction in ecological footprint per capita. This result aligns with findings by Benatti et al. (2024), Bibi et al. (2024), and Hassan et al. (2024), who documented that stringent environmental policies encourage green innovation, energy efficiency, and cleaner production methods. This result highlights the importance of policy enforcement and regulatory frameworks in achieving sustainable environmental outcomes. Similarly, R&D expenditure is found to have a mitigating effect on environmental degradation, with a 10% increase in R&D spending per GDP in the previous period being linked to a 0.39% reduction in ecological footprint per capita. This result suggests that increased investment in research and innovation is associated with improvements in environmental performance. It supports the argument that technological innovation plays a vital role in promoting green growth and protecting the environment. This outcome is consistent with extant literature emphasizing the positive role of innovation in environmental protection. For instance, Ahmad et al. (2023) and Mamkhezri and Khezri (2024) found that R&D spending enhances green technology development, which in turn reduces carbon emissions. Interestingly, this study finds that urban population growth has a positive effect on environmental quality. This outcome contrasts with the findings of Hussain and Zhou (2022) and Sikder et al. (2022), who observed that urbanization often increases environmental stress due to higher energy demand and consumption. A possible explanation is that, in the countries examined, urban population growth is associated with greater population density, advanced infrastructure, public transportation, and environmental services, which can reduce per capita resource use and emissions. In addition, urban areas often benefit from economies of scale in environmental regulation and technology adoption, allowing environmental pressures to be managed more effectively despite population growth.

4.2. Impact of environmental policy stringency on the digital trade-environmental performance nexus

To examine how environmental policy stringency affect the digital trade-environmental performance relationship, this section performs regressions of Model (2) and reports the outcomes in Table 5. Columns (1) and (2) show the results for the natural logarithm of the per capita ecological footprint and the natural logarithm of per capita greenhouse gas emissions, respectively.

As shown in Table 5, the coefficient of lagged digital trade is negative and statistically significant, indicating that digital trade is associated with lower ecological footprints and greenhouse gas emissions. More importantly, the interaction term between lagged digital trade and lagged environmental policy stringency is consistently negative and significant at the 1% level. This finding suggests that environmental policy stringency play a moderating role, strengthening the negative relationship between digital trade and environmental indicators.

To provide a more meaningful interpretation, this study computes and visualizes the average marginal effects of lagged digital trade, conditional on different levels of lagged environmental policy stringency. The outcomes are illustrated in Figure 2. The marginal effects analysis shows that the environmental benefits

Table 5. Impact of environmental policy stringency on the digital trade-environmental performance nexus (40 countries, 2005- 2020)

	(1)	(2)
VARIABLES	**ln(EFPC)**	**ln(GHGC)**
l.ln(dig_trade)	-0.119***	-0.179***
	(0.0367)	(0.0249)
l.ln(dig_trade)* l.ln(env_pol)	-0.0348***	-0.0492***
	(0.00864)	(0.0103)
l.ln(env_pol)	0.0194	0.0512**
	(0.0196)	(0.0214)
l.ln(ene_use)	0.650***	0.767***
	(0.0651)	(0.0698)
l.ln(KOFGI)	0.272*	0.532**
	(0.147)	(0.214)
l.ln(R&D)	-0.0473***	-0.0195
	(0.0134)	(0.0155)
l.ln(urb_pop)	-0.0113***	-0.0109**
	(0.00203)	(0.00481)
Constant	-4.654***	-5.876***
	(0.562)	(0.938)
Year FEs	YES	YES
Country FEs	YES	YES
Observations	488	498
R-squared	0.7092	0.784

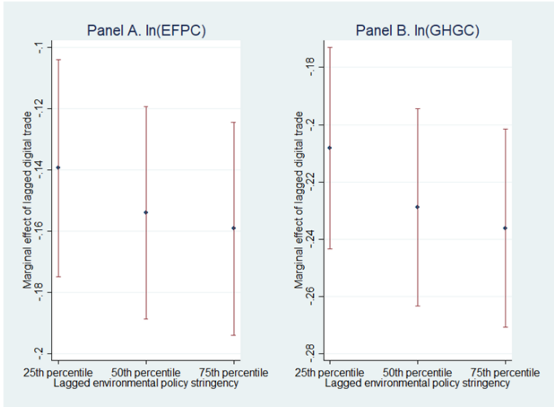
*Notes: Driscoll-Kraay standard errors are in parentheses. *, **, and *** show the 10%, 5%, and 1% statistical significance levels, respectively.*

Source: Author's calculation using Stata 14 software

of digital trade appear to be larger at higher levels of environmental policy stringency. At the 25th percentile of environmental policy stringency, the marginal effect of digital trade on environmental outcomes is negative but relatively small. When policy stringency reaches the median level (50th percentile), the marginal effect becomes larger in absolute value. At the 75th percentile, representing stricter regulatory conditions, digital trade is associated with lower levels of ecological footprints and greenhouse gas emissions. These findings support hypothesis H_2, which posits that environmental policy stringency strengthens the environmentally beneficial impact of digital trade. Regarding the main effect of environmental policy stringency, the coefficient is positive and statistically significant in Column (2) of Table 5. This finding does not imply that stricter environmental policies increase emissions. When an interaction term is included, the coefficient on environmental policy stringency reflects its marginal effect at very low or near-zero level of digital trade. The negative and statistically significant interaction term implies that environmental policy stringency moderates the impact of digital trade on environmental outcomes. Consistent with the marginal effects analysis, stricter environmental policies are associated with stronger emission-reducing relationships linked to digital trade. This suggests that environmental policy stringency may enhance the environmental benefits of digital trade.

These findings of this study are consistent with the expanding literature that highlights the pivotal role of environmental policies in alleviating the ecological impacts of economic activities. For example, research by Du et al. (2023), Benatti et al. (2024), and Hassan et al. (2024), drawn from diverse regions like China's manufacturing sector, advanced OECD countries, and Euro Area economies, indicates that environmental policies can successfully drive green technological progress and separate economic growth from environmental harm. The results of this study extend these discussions by offering robust empirical evidence that digital trade is associated with improved environmental performance, and this association appears stronger under tighter environmental policies. This outcome suggests that digital transformation and strong environmental governance are mutually reinforcing drivers of a low-carbon and sustainable global economy.

5. Conclusion and implications



Notes: Points represent estimated marginal effects of digital trade on environmental outcomes, evaluated at the 25th, 50th, and 75th percentiles of lagged environmental policy stringency. Vertical bars indicate 95% confidence intervals. All variables are defined as in the baseline regression model.

Source: Author's calculation using Stata 14 software

Figure 2. Marginal effects of digital trade on environmental performance at different levels of environmental policy stringency

This study investigates how digital trade relates to environmental performance across 40 countries between 2005 and 2020, with particular attention to how environmental policy strictness influences this relationship. The analysis applies fixed effects models with a one-period lag of all independent variables. Environmental performance is assessed through two main indicators: per capita ecological footprint (EFPC) and per capita greenhouse gas emissions (GHGC). The strength of environmental policies is measured using the OECD Environmental Policy Stringency (EPS) Index. By integrating data on digital trade, environmental performance, and environmental policy stringency, the study provides a comprehensive cross-country perspective on how regulatory environments shape the environmental impacts of digital trade.

The empirical results reveal several significant findings. First, higher levels of digital trade are associated with improved environmental performance, as indicated by lower levels of ecological footprints and greenhouse gas emissions. Second, the interaction between digital trade and environmental policy stringency is also negative and statistically significant, suggesting that this relationship may become more favourable under stricter regulatory conditions. This finding supports the view that strong environmental governance is linked to greater environmental benefits associated with digitalization. Moreover, the findings show that some control variables, such as energy use and globalization, are associated with poorer environmental performance, while environmental policy stringency, R&D expenditure, and urbanization are linked to better environmental performance.

From a policy perspective, the empirical findings indicate that digital trade is linked to improved environmental performance. At the same time, the analysis highlights that the environmental benefits of digital trade are not uniform and appear to be more substantial under stricter environmental policy regimes. Therefore, strong environmental regulations may serve a complementary function alongside digital trade expansion, being linked to more favorable environmental improvements. While digital trade is associated with improvements in environmental performance, its expansion may also involve environmental pressures related to energy use and digital infrastructure. Accordingly, policy frameworks that promote digital trade are likely to be more effective when combined with robust environmental policies, investments in clean energy, and continued support for green innovation.

Despite its valuable contributions, this study has several limitations. First, the study is restricted due to limited data availability, particularly regarding the OECD Environmental Policy Stringency (EPS) Index. Such a limitation may reduce the precision of cross-country comparisons. Second, this study focuses on aggregate national-level data, which may not reflect sectoral heterogeneity and country-specific institutional differences. Third, although fixed effects and lagged regressors are employed, potential endogeneity concerns, such as reverse causality and omitted variable bias, cannot be fully addressed. Future research could overcome these limitations by using more disaggregated data and more advanced estimation methods to better address endogeneity concerns and capture cross-country and sectoral heterogeneity. ■

References

Ahmad, M., Khattak, S. I., Khan, A., & Rahman, Z. U. (2020). Innovation, foreign direct investment (FDI), and the energy–pollution–growth nexus in OECD region: a simultaneous equation modeling approach. *Environmental and Ecological Statistics*, *27*(2), 203-232. https://doi.org/10.1007/s10651-020-00442-8

Ahmad, N., Youjin, L., Žiković, S., & Belyaeva, Z. (2023). The effects of technological innovation on sustainable development and environmental degradation: Evidence from China. *Technology in Society*, *72*. https://doi.org/10.1016/j.techsoc.2022.102184

Ahmed, Z., Ahmad, M., Rjoub, H., Kalugina, O. A., & Hussain, N. (2022). Economic growth, renewable energy consumption, and ecological footprint: Exploring the role of environmental regulations and democracy in sustainable development. *Sustainable Development*, *30*(4), 595-605. https://doi.org/10.1002/sd.2251

Ashraf, M. Z., Wei, W., Usman, M., & Mushtaq, S. (2024). How can natural resource dependence, environmental-related technologies and digital trade protect the environment: redesigning SDGs policies for sustainable environment? *Resources Policy*, *88*, 104456. https://doi.org/10.1016/j.resourpol.2023.104456

Aydin, M., Sogut, Y., & Erdem, A. (2024). The role of environmental technologies, institutional quality, and globalization on environmental sustainability in European Union countries: new evidence from advanced panel data estimations. *Environmental Science and Pollution Research*, *31*(7), 10460-10472. https://doi.org/10.1007/s11356-024-31860-x

Bargoni, A., Ferraris, A., Vilamová, Š., & Wan Hussain, W. M. H. (2024). Digitalisation and internationalisation in SMEs: a systematic review and research agenda. *Journal of Enterprise Information Management*, *37*(5), 1418-1457. https://doi.org/10.1108/JEIM-12-2022-0473

Benatti, N., Groiss, M., Kelly, P., & López-García, P. (2024). *The impact of environmental regulation on clean innovation: are there crowding out effects?* (ECB Working Paper No. 2946). European Central Bank. https://doi.org/10.2139/ssrn.4868748

Bibi, S., Khan, A., Fubing, X., Jianfeng, H., Hussain, S., & Khan, A. N. (2024). Impact of environmental policies, regulations, technologies, and renewable energy on environmental sustainability in China's textile and fashion industry. *Frontiers in Environmental Science*, *12*, 1496454. https://doi.org/10.3389/fenvs.2024.1496454

Can, M., Ben Jebli, M., & Brusselaers, J. (2022). Can green trade save the environment? Introducing the Green (Trade) Openness Index. *Environmental Science and Pollution Research*, *29*(29), 44091-44102. https://doi.org/10.1007/s11356-022-18920-w

Du, W., Fan, Y., & Li, M. (2023). A clean road to international trade: Environmental regulations and the cleanliness of export enterprises. *Heliyon*, *9*(11). https://doi.org/10.1016/j.heliyon.2023.e21180

Evans, O., & Mesagan, E. P. (2022). ICT-trade and pollution in Africa: do governance and regulation matter? *Journal of Policy Modeling*, *44*(3), 511-531. https://doi.org/10.1016/j.jpolmod.2022.06.003

Friedlingstein, P., O'sullivan, M., Jones, M. W., Andrew, R. M., Hauck, J., Landschützer, P., Quéré, L. C., Li, H., Luijkx, I. T., Olsen, A., Peters, G. P., Peters, W., Pongratz, J., Schwingshackl, C., Sitch, S., Canadell, J. G., Ciais, P., Jackson, R. B., Simone, R. A., …Zeng, J. (2024). Global carbon budget 2024. *Earth System Science Data Discussions*, *17*, 965-1039. https://doi.org/10.5194/essd-2024-519

Goldman, E., Carter, S., & Sims, M. (2025). *Fires Drove Record-Breaking Tropical Forest Loss in 2024*. World Resources Institute. https://research.wri.org/gfr/latest-analysis-deforestation-trends

Grossman, G. M., & Krueger, A. B. (1995). Economic growth and the environment. *The Quarterly Journal of Economics*, *110*(2), 353-377. https://doi.org/10.2307/2118443

Hassan, M., Kouzez, M., Lee, J.-Y., Msolli, B., & Rjiba, H. (2024). Does increasing environmental policy stringency enhance renewable energy consumption in OECD countries? *Energy economics*, *129*, 107198. https://doi.org/10.1016/j.eneco.2023.107198

Hilty, L.M., & Aebischer, B. (2015). ICT for Sustainability: An Emerging Research Field. In L. M. Hilty & B. Aebischer (Eds.), *ICT innovations for sustainability* (pp. 3–36). Springer. https://doi.org/10.1007/978-3-319-09228-7_1

Hussain, J., & Zhou, K. (2022). Globalization, industrialization, and urbanization in Belt and Road Initiative countries: implications for environmental sustainability and energy demand. *Environmental Science and Pollution Research*, *29*(53), 80549-80567. https://doi.org/10.1007/s11356-022-21520-3

International Monetary Fund, Organisation for Economic Co-operation and Development, United Nations, World Bank Group, & World Trade Organization. (2023a). *Digital trade for development*. http://documents.worldbank.org/curated/en/099633201042411300

International Monetary Fund, Organisation for Economic Co-operation and Development, United Nations Conference on Trade and Development, & World Trade Organization. (2023b). *Handbook on Measuring Digital Trade* (2nd ed.). https://doi.org/10.1787/ac99e6d3-en

Kamal, M., Usman, M., Jahanger, A., & Balsalobre-Lorente, D. (2021). Revisiting the role of fiscal policy, financial development, and foreign direct investment in reducing environmental pollution during globalization mode: evidence from linear and nonlinear panel data approaches. *Energies*, *14*(21), 6968. https://doi.org/10.3390/en14216968

Liang, J., & Qiao, C. (2024). The impact of digital trade development on regional green innovation. *Sustainability*, *16*(22), 10090. https://doi.org/10.3390/su162210090

Lu, Y., Yang, Y., Sun, B., Yuan, J., Yu, M., Stenseth, N. C., Bullock, J. M., & Obersteiner, M. (2020). Spatial variation in biodiversity loss across China under multiple environmental stressors. *Science Advances*, *6*(47), eabd0952. https://doi.org/10.1126/sciadv.abd0952

Mamkhezri, J., & Khezri, M. (2024). Assessing the spillover effects of research and development and renewable energy on CO2 emissions: international evidence. *Environment, Development and Sustainability*, *26*(3), 7657-7686. https://doi.org/10.1007/s10668-023-03026-1

Notley, T. (2019). The environmental costs of the global digital economy in Asia and the urgent need for better policy. *Media International Australia*, *173*(1), 125-141. https://doi.org/10.1177/1329878X19844022

OECD. (2024). *Revitalising Services Trade for Global Growth: Evidence from Ten Years of Monitoring Services Trade Policies through the OECD STRI*. https://doi.org/10.1787/3cc371ac-en

Pörtner, H.-O., Scholes, R., Arneth, A., Barnes, D., Burrows, M. T., Diamond, S., Duarte, C. M., Kiessling, W., Leadley, P., & Managi, S. (2023). Overcoming the coupled climate and biodiversity crises and their societal impacts. *Science*, *380*(6642). https://doi.org/10.1126/science.abl4881

Qiu, H., & Wan, Q. (2023). Inclusivity between digital trade, human development, and environmental quality: moderating role of green innovations in BRICS countries. *Economic research-Ekonomska istraživanja*, *36*(3). https://doi.org/10.1080/1331677X.2022.2150872

Sikder, M., Wang, C., Yao, X., Huai, X., Wu, L., KwameYeboah, F., Wood, J., Zhao, Y., & Dou, X. (2022). The integrated impact of GDP growth, industrialization, energy use, and urbanization on CO2 emissions in developing countries: evidence from the panel ARDL approach. *Science of the Total Environment*, *837*, 155795. https://doi.org/10.1016/j.scitotenv.2022.155795

Suh, J., & Roh, J. (2023). The effects of digital trade policies on digital trade. *The World Economy*, *46*(8), 2383-2407. https://doi.org/10.1111/twec.13407

Sun, L., Li, X., & Wang, Y. (2024). Digital trade growth and mineral resources In developing countries: Implications for green recovery. *Resources Policy*, *88*, 104338. https://doi.org/10.1016/j.resourpol.2023.104338

Tahir, T., Luni, T., Majeed, M. T., & Zafar, A. (2021). The impact of financial development and globalization on environmental quality: evidence from South Asian economies. *Environmental Science and Pollution Research*, *28*(7), 8088-8101. https://doi.org/10.1007/s11356-020-11198-w

Wang, K., Pellegrini, M. M., Xue, K., Wang, C., & Peng, M. (2024). Digital resilience in the internationalization of small and medium companies: how does it work? *Journal of Enterprise Information Management*, *37*(5), 1458-1478. https://doi.org/10.1108/JEIM-02-2023-0100

Wang, K., Yan, M., Wang, Y., & Chang, C.-P. (2020). The impact of environmental policy stringency on air quality. *Atmospheric Environment*, *231*, 117522. https://doi.org/10.1016/j.atmosenv.2020.117522

Wen, H., Chen, W., & Zhou, F. (2023). Does digital service trade boost technological innovation?: International evidence. *Socio-Economic Planning Sciences*, *88*, 101647. https://doi.org/10.1016/j.seps.2023.101647

Yang, M., Liu, Y., Wang, J., & Tang, X. (2025). How does digital trade development affect carbon emissions? Evidence from China. *Economic Analysis and Policy*, *85*, 1475-1491. https://doi.org/10.1016/j.eap.2025.02.004

Yeerken, A., & Feng, D. (2024). Does digital service trade promote inclusive domestic growth?–Empirical research of 46 countries. *The Economic and Labour Relations Review*, *35*(2), 292-318. https://doi.org/10.1017/elr.2024.26

Zhang, X.-P., & Cheng, X.-M. (2009). Energy consumption, carbon emissions, and economic growth in China. *Ecological economics*, *68*(10), 2706-2712. https://doi.org/10.1016/j.ecolecon.2009.05.011

Appendix 1. List of 40 countries in this study

Australia	Denmark	Ireland	New Zealand
Austria	Spain	Iceland	Poland
Belgium	Estonia	Israel	Portugal
Brazil	Finland	Italy	Russian Federation
Canada	France	Japan	Slovakia
Switzerland	United Kingdom	Korea	Slovenia
Chile	Greece	Luxembourg	Sweden
China	Hungary	Mexico	Turkey
Czech Republic	Indonesia	Netherlands	United States of America
Germany	India	Norway	South Africa