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RESEARCH ARTICLE

Digitalization, Green Innovation, and Carbon Emissions: Unraveling the Role of Environmental Policy and Industrial Transformation in OECD Countries

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Abstract

This study investigates the effects of digitalization, environmental innovation, environmental policy stringency, and green industrial transformation on carbon emissions in OECD economies. Using panel data from 34 OECD countries covering 1999–2024, the study employs a two-step system generalized method of moments (GMM) approach to address endogeneity and dynamic relationships among the variables. The findings reveal that digitalization and stringent environmental policies significantly reduce carbon dioxide (CO_2) emissions, highlighting their importance in promoting environmental sustainability. Conversely, environmental technological innovation and green industrial transformation are positively associated with carbon emissions, suggesting potential transitional inefficiencies, rebound effects, and continued dependence on carbon-intensive production processes. Furthermore, the interaction between environmental technology and policy stringency exhibits a positive association with emissions, indicating that technological advancements do not necessarily deliver environmental benefits without effective policy coordination. Trade openness is associated with lower emissions, while the effects of foreign direct investment vary across model specifications. Environmental taxation exhibits no statistically significant effect. These findings underscore the importance of integrating digital transformation, technological innovation, and environmental regulations into coherent decarbonization strategies. The study recommends strengthening environmental policy implementation, accelerating renewable energy integration, and promoting energy-efficient industrial restructuring to facilitate sustainable, low-carbon development across OECD economies.

Keywords: Digitalization; Environmental innovation; Carbon emissions; Environmental policy stringency; Green industrial transformation

1. Introduction

Climate change has emerged as one of the most pressing global challenges, posing substantial threats to environmental sustainability, economic stability, and human well-being. Rising greenhouse gas emissions, particularly CO_2, have intensified global warming, disrupted ecological systems, and increased the frequency and severity of climate-related hazards (IPCC, 2023; Raihan, 2023; Kumar et al., 2025). Industrialization, fossil

fuel consumption, and expanding economic activities have historically contributed to environmental degradation, highlighting the persistent tension between economic development and ecological sustainability (Infante-Amate et al., 2025). Despite international commitments to climate mitigation, achieving substantial emissions reductions remains challenging, particularly in advanced economies characterized by high energy demand, complex industrial structures, and extensive technological infrastructure. Consequently, the transition toward low-carbon development requires coordinated strategies integrating digitalization, environmental innovation, effective environmental policies, and sustainable industrial transformation.

The Organisation for Economic Co-operation and Development (OECD) economies occupy a critical position in global decarbonization efforts because of their advanced technological capabilities, substantial industrial activities, and relatively established environmental regulatory frameworks. Although these economies have made considerable progress in renewable energy deployment, environmental governance, and technological innovation, their transition toward carbon neutrality remains uneven. Persistent dependence on fossil fuels, differences in environmental policy stringency, and variations in industrial structures continue to influence emissions trajectories. Recent research emphasizes that effective environmental policies, technological advancements, and energy transitions are essential for improving environmental performance in OECD economies (Ma et al., 2023; Akram et al., 2023). Furthermore, the OECD (2024) highlights the importance of green industrial policies in accelerating the transition toward net-zero emissions. These developments underscore the need to examine how digital transformation, environmental innovation, and regulatory interventions jointly influence carbon emissions across OECD countries.

Digitalization has increasingly emerged as a potential catalyst for environmental sustainability by transforming production systems, improving resource allocation, and facilitating energy-efficient economic activities. The expansion of information and communication technologies (ICT), artificial intelligence, cloud computing, and digital infrastructure enables businesses to optimize operational processes, improve energy management, and strengthen environmental monitoring. Digital technologies may also accelerate renewable energy integration, facilitate knowledge diffusion, and support cleaner industrial production. Empirical studies suggest that digital economy development can reduce carbon emissions through improvements in energy efficiency, green technological innovation, and industrial upgrading (Bai et al., 2023; Ma & Tao, 2023; Wang & Zhong, 2023). More recent evidence highlights the potential of digitalization to improve carbon efficiency and promote green innovation, although its environmental benefits vary across regions and economic conditions (Bai et al., 2025; Liu & Fang, 2025; Xia et al., 2025). Nevertheless, digitalization may generate adverse environmental consequences through increased electricity consumption, energy-intensive data centers, electronic waste, and rebound effects. Therefore, its net contribution to environmental sustainability remains an important empirical question, particularly in technologically advanced OECD economies.

Environmental technological innovation represents another important pathway toward decarbonization by facilitating cleaner production processes, renewable energy development, and improvements in resource efficiency. Innovations in low-carbon technologies, energy storage, smart grids, and environmentally sustainable manufacturing can reduce dependence on conventional fossil fuels and enhance industrial environmental performance. Previous studies demonstrate that green technological innovation can contribute to emissions reduction, particularly when supported by renewable energy adoption and appropriate institutional frameworks (Shao et al., 2021; Xu et al., 2021; Suki et al., 2022; Obobisa, 2024). However, the environmental outcomes of technological innovation are not necessarily uniform. The development and deployment of new technologies may initially increase energy consumption, industrial activity, and resource demand, potentially offsetting anticipated environmental improvements. Chen et al. (2023) identify a nonlinear relationship between green technological innovation and carbon emissions, suggesting that environmental benefits may become more

pronounced after technological development reaches a certain threshold. These contrasting findings indicate that the effectiveness of environmental innovation depends on technological maturity, industrial conditions, and complementary policy interventions.

Environmental policy stringency and environmental taxation are equally important instruments for promoting sustainable economic development and reducing carbon emissions. Regulatory mechanisms, including emissions standards, carbon pricing, environmental taxes, and renewable energy incentives, aim to internalize environmental externalities and encourage businesses to adopt cleaner technologies. Stringent environmental policies can stimulate technological innovation, improve energy efficiency, and discourage carbon-intensive production activities. Empirical evidence suggests that environmental policy stringency contributes to emissions reduction in developed and emerging economies (Wolde-Rufael & Weldemeskel, 2020; Yirong, 2022; Ma et al., 2023; Apeaning et al., 2025). Similarly, environmental taxation may encourage cleaner production and consumption by increasing the economic costs of pollution (Wolde-Rufael & Mulat-Weldemeskel, 2023; Wang et al., 2023; Yang et al., 2024). Nevertheless, the effectiveness of these instruments depends on their design, implementation, enforcement, and interaction with technological and industrial developments. Environmental regulations may also generate unintended consequences when technological adjustments are costly or when industrial activities expand faster than improvements in environmental efficiency. Accordingly, evaluating the independent and interactive effects of environmental policies and technological innovation is essential for understanding their contribution to decarbonization.

Green industrial transformation has also gained increasing attention as an important strategy for reconciling industrial development with environmental sustainability. This transformation involves restructuring production systems, expanding renewable energy utilization, improving resource efficiency, and gradually replacing carbon-intensive technologies with cleaner alternatives. Industrial upgrading and renewable energy integration can jointly reduce emissions by improving production efficiency and decreasing dependence on fossil fuels. Previous research highlights the importance of industrial restructuring, green innovation, and sustainable energy adoption in supporting low-carbon development (Li et al., 2021; Zhai & An, 2021; Mehmood et al., 2023; Tan et al., 2024). However, the transition toward greener industrial systems may involve substantial investment requirements, technological constraints, and adjustment costs. Furthermore, the expansion of industrial production during the transition period may offset emissions reductions achieved through renewable energy adoption. These challenges suggest that green industrial transformation does not automatically guarantee improved environmental performance, emphasizing the importance of examining its empirical effects within different institutional and economic contexts.

Beyond environmental and technological factors, international trade and foreign direct investment (FDI) can influence carbon emissions through changes in production structures, technological diffusion, and investment patterns. Trade openness may facilitate the transfer of environmentally friendly technologies, encourage specialization in cleaner industries, and improve resource allocation. Conversely, expanding international trade may increase transportation activities, industrial production, and energy consumption, potentially intensifying environmental pressures. Similarly, FDI may promote environmental improvements through advanced technologies and efficient production practices, consistent with the pollution halo hypothesis, or contribute to environmental degradation by encouraging carbon-intensive investment, as suggested by the pollution haven hypothesis. Empirical evidence indicates that the environmental consequences of trade and investment depend on technological capabilities, institutional quality, and regulatory conditions (Mert & Bölük, 2016; Wang et al., 2024). Incorporating these economic factors is therefore important for obtaining a more comprehensive understanding of carbon emissions in OECD economies.

Although the existing literature provides valuable insights into the relationships among digitalization, environmental innovation, environmental policies, and carbon emissions, several important research gaps remain. First, previous studies have predominantly examined these determinants separately, offering limited evidence on their combined effects within a unified empirical framework. Second, the environmental consequences of digitalization and technological innovation remain inconclusive, particularly because improvements in production efficiency may coexist with increased energy consumption and rebound effects. Third, relatively limited attention has been devoted to the role of green industrial transformation in shaping carbon emissions across OECD economies, especially when industrial development and renewable energy consumption are considered jointly. Finally, the interaction between environmental technological innovation and environmental policy stringency requires further investigation to determine whether regulatory interventions strengthen or constrain the environmental benefits of technological progress. Addressing these gaps is essential for developing integrated and effective decarbonization strategies.

Against this background, the present study investigates the effects of digitalization, environmental technological innovation, environmental policy stringency, environmental taxation, and green industrial transformation on CO_2 emissions in OECD economies. Using a dataset covering 34 OECD countries over the period 1999–2024, the study employs the two-step system GMM estimator to account for dynamic relationships, unobserved heterogeneity, and potential endogeneity. Green industrial transformation is represented by the interaction between industrialization and renewable energy consumption, while the interaction between environmental technological innovation and environmental policy stringency is incorporated to examine their combined association with carbon emissions. Trade openness and FDI are included as additional explanatory variables to account for broader economic influences on environmental performance.

This study contributes to the existing literature in three important respects. First, it provides an integrated empirical assessment of digitalization, environmental innovation, environmental policy, and green industrial transformation within a common framework, extending previous research that primarily investigates these relationships independently. Second, it examines whether environmental technological innovation and policy stringency interact in ways that reinforce or weaken emissions reduction, thereby contributing to the understanding of potential technological rebound effects and policy coordination challenges. Third, it evaluates the environmental implications of green industrial transformation by considering the interaction between industrialization and renewable energy consumption, offering additional evidence on the challenges of industrial decarbonization in advanced economies. By integrating these dimensions, the study provides policy-relevant insights into the conditions under which digital and green transitions can support environmental sustainability. The remainder of the paper is organized as follows. Section 2 reviews the relevant literature, Section 3 presents the data and methodology, Section 4 discusses the empirical findings, and Section 5 concludes with policy implications and directions for future research.

2. Literature review

2.1. Digital economy and CO_2 emissions

The digital economy has emerged as an important driver of economic transformation, with significant implications for energy consumption, resource efficiency, and environmental sustainability. Digital technologies, including ICT, artificial intelligence, cloud computing, and digital infrastructure, can facilitate carbon emissions reduction by improving production efficiency, optimizing resource allocation, and accelerating the adoption of cleaner technologies. Nevertheless, the environmental consequences of

digitalization remain theoretically ambiguous because the expansion of digital infrastructure also increases electricity demand and resource consumption. Moyer and Hughes (2012) highlighted the potential of ICT to influence energy systems and carbon emissions, while Zhou et al. (2019) demonstrated that the ICT sector generates substantial indirect emissions through its dependence on carbon-intensive intermediate inputs and electricity consumption. Conversely, Ulucak et al. (2020) found that ICT development contributed to emissions mitigation in BRICS economies, suggesting that digitalization can support environmental sustainability under favorable economic and institutional conditions.

Recent empirical studies provide further evidence of the emissions-reducing potential of digital transformation. Bai et al. (2023), examining Chinese cities, demonstrated that digital economy development reduces carbon emissions through industrial restructuring and technological upgrading. Similarly, Chang et al. (2023) identified a negative association between digitalization and carbon emission intensity, emphasizing the importance of industrial upgrading and spatial spillover effects. Wang and Zhong (2023) reported that digital economy development improves energy efficiency, strengthens environmental governance, and facilitates cleaner urban production. At the enterprise level, Ma and Tao (2023) found that digital transformation contributes to reducing carbon emission intensity, highlighting the role of managerial and operational efficiency. These findings suggest that digital technologies can improve environmental performance through multiple interconnected mechanisms rather than through technological adoption alone.

More recent research emphasizes the heterogeneous and potentially nonlinear effects of digitalization on environmental sustainability. Bai et al. (2025) found that digital economy development can improve carbon efficiency while supporting economic growth, although its environmental benefits vary across regions. Liu and Fang (2025) identified nonlinear relationships between digital economy development and carbon emissions, with green innovation and energy consumption serving as important transmission mechanisms. Similarly, Zheng et al. (2025) highlighted the importance of environmental policy and green innovation in shaping the digitalization–emissions relationship in emerging economies. These findings indicate that digitalization may initially increase energy demand before generating substantial environmental benefits through technological maturity, improved energy efficiency, and cleaner production systems. Despite these contributions, existing research remains concentrated on China and selected emerging economies, leaving considerable scope for examining the environmental implications of digitalization across OECD countries with diverse technological capabilities and regulatory frameworks.

2.2. Environmental policy stringency and climate change

Environmental policy stringency is widely recognized as an important institutional mechanism for addressing climate change and promoting sustainable economic development. Environmental regulations influence production and consumption decisions by imposing restrictions or economic costs on environmentally harmful activities, thereby encouraging cleaner technologies, renewable energy adoption, and improvements in resource efficiency. Theoretically, stringent environmental policies can reduce carbon emissions by internalizing environmental externalities and stimulating green innovation. However, their effectiveness depends on regulatory design, enforcement capacity, technological readiness, and economic conditions. Wolde-Rufael and Weldemeskel (2020) demonstrated that environmental policy stringency contributes to reducing CO_2 emissions in emerging economies, while Demiral et al. (2021) emphasized the importance of stringent environmental regulations in influencing global emissions patterns.

Empirical evidence from developed and emerging economies generally supports the emissions-mitigating role of environmental policy stringency. Wang and Zhang (2022), using Chinese city-level data, identified a

nonlinear relationship between environmental regulation and carbon emissions, suggesting that regulatory effectiveness varies with policy intensity. Similarly, Yirong (2022) found that stronger environmental policy stringency contributes to emissions reduction in highly polluting economies. Akbulut (2022) reported threshold effects, indicating that environmental regulations may require sufficient stringency to achieve meaningful environmental improvements. In the OECD context, Ma et al. (2023) demonstrated that environmental policy and energy transition are important determinants of climate mitigation outcomes. Akram et al. (2023) further highlighted the complementary roles of environmental policy stringency, carbon taxation, and renewable energy in supporting carbon neutrality across G7 economies.

Despite these findings, the environmental effectiveness of regulatory interventions may depend on their interaction with technological innovation and industrial development. Stringent policies can stimulate the adoption of environmentally friendly technologies, but regulatory compliance costs and technological adjustment constraints may weaken their short-term effectiveness. Furthermore, environmental regulations may generate heterogeneous outcomes across countries because of differences in institutional capacity, industrial composition, and energy dependence. Consequently, examining environmental policy stringency independently may overlook important complementarities and trade-offs involving technological innovation and industrial transformation. This highlights the importance of evaluating both the direct influence of environmental regulations and their interaction with environmental technologies in shaping carbon emissions across OECD economies.

2.3. Environmental technology, energy consumption, and CO_2 emissions

Environmental technological innovation plays a central role in the transition toward low-carbon economies by improving energy efficiency, supporting renewable energy deployment, and facilitating cleaner industrial production. Innovations in renewable energy technologies, energy storage, smart grids, and pollution-control systems can reduce dependence on fossil fuels and improve environmental performance. However, the relationship between technological innovation and carbon emissions is complex because technological development may simultaneously stimulate economic activity, industrial expansion, and additional energy consumption. Shao et al. (2021) found that green technological innovation contributes to carbon emissions reduction in N-11 economies, particularly over the long term. Similarly, Xu et al. (2021) demonstrated that heterogeneous green innovations improve carbon emission performance across Chinese cities, emphasizing the importance of technological characteristics and regional conditions.

Recent research further highlights the importance of technological maturity and economic conditions in determining environmental outcomes. Suki et al. (2022) identified the emissions-reducing potential of technological innovation and renewable energy consumption in Malaysia. Khattak et al. (2022), examining G7 economies, reported that the environmental effects of green technological innovation vary across economic conditions, suggesting that technological progress does not uniformly translate into emissions reduction. Chen et al. (2023) identified an inverted U-shaped relationship between green technological innovation and carbon emission intensity in China, indicating that innovation may initially increase emissions before generating environmental improvements beyond a particular development threshold. These findings are consistent with the possibility that technological adjustment costs, production expansion, and rebound effects can temporarily offset the anticipated benefits of environmental innovation.

The interaction between environmental technology and renewable energy consumption has also received considerable attention. Akram et al. (2023) demonstrated that green energy, environmental policy, and technological innovation jointly contribute to environmental sustainability in G7 economies. Similarly, Qi et al.

(2025) emphasized the importance of green technological innovation and green finance in reducing the environmental impacts associated with energy consumption. Yan et al. (2023) reported that eco-digitalization, renewable energy, and green financing contribute to environmental sustainability in selected Middle Eastern and North African economies. Nevertheless, the environmental effectiveness of technological innovation depends on whether technological advancements replace carbon-intensive activities or merely complement existing production systems. These mixed findings justify further investigation into the direct effects of environmental technologies and their interaction with regulatory policies, particularly in OECD economies characterized by advanced innovation systems but persistent fossil fuel dependence.

2.4. Environmental taxes and CO_2 emissions

Environmental taxation is an important market-based policy instrument designed to reduce environmental degradation by increasing the economic costs of pollution and encouraging cleaner production and consumption. Environmental taxes can influence carbon emissions through changes in energy consumption, investment decisions, technological innovation, and industrial restructuring. According to the double-dividend hypothesis, appropriately designed environmental taxes may simultaneously improve environmental quality and generate economic benefits when tax revenues are used efficiently. However, their effectiveness depends on tax rates, coverage, enforcement, and the availability of cleaner technological alternatives. Wolde-Rufael and Mulat-Weldemeskel (2023) found that environmental taxes and stringent environmental policies significantly reduce CO_2 emissions in European economies, highlighting the importance of coordinated regulatory and fiscal interventions. Similarly, Wang et al. (2023) demonstrated that environmental taxation and green finance contribute to emissions mitigation in OECD countries.

Recent empirical evidence further supports the potential of environmental taxation to promote low-carbon development, although findings vary across countries and economic conditions. Sarpong et al. (2023) identified the emissions-reducing effects of environmental taxation, renewable energy, and structural transformation in E7 economies. Sharif et al. (2023) demonstrated that environmental taxes, green technologies, and renewable energy contribute to environmental sustainability in Nordic countries, while Khan et al. (2023) highlighted the importance of environmental taxation and eco-innovation in reducing emissions across European Union economies. In contrast, Degirmenci and Aydin (2023) reported that environmental taxation may increase emissions under certain economic conditions, suggesting that fiscal instruments do not necessarily generate the intended environmental outcomes. Anisiuba et al. (2023) also identified asymmetric effects of environmental taxation, indicating that changes in tax policies may produce unequal responses in carbon emissions. These contrasting findings suggest that environmental taxes alone may be insufficient to achieve substantial emissions reductions without complementary technological, regulatory, and energy-transition policies.

The effectiveness of environmental taxation may also depend on its interaction with broader environmental policy frameworks. Carbon pricing can encourage emissions reductions, but its effectiveness may be constrained by limited coverage, relatively low prices, and political or institutional barriers. The OECD (2024) emphasizes that green industrial policies should complement carbon pricing and other environmental instruments rather than operate independently. Consequently, assessing environmental taxation alongside policy stringency, digitalization, and technological innovation offers a more comprehensive understanding of the institutional mechanisms influencing carbon emissions. This integrated perspective is particularly relevant for OECD economies, where environmental policy frameworks and fiscal instruments differ considerably across countries.

2.5. Research gaps and study contribution

The reviewed literature demonstrates that digitalization, environmental innovation, environmental policy stringency, and environmental taxation are important determinants of carbon emissions. However, their environmental effects remain heterogeneous and sometimes contradictory. Although digital technologies can improve energy efficiency and facilitate cleaner production, their expansion may increase electricity demand and generate rebound effects. Similarly, environmental innovation and industrial transformation may produce different emissions outcomes depending on technological maturity, renewable energy penetration, and institutional conditions. Recent OECD-focused evidence reinforces the importance of examining these relationships jointly. For example, Alvi et al. (2025) found that digitalization, environmental patents, green finance, and energy transition contribute to reducing greenhouse gas emissions in OECD economies, whereas trade liberalization exhibits an emissions-increasing association. Such findings highlight the need to account for differences in model specification, country coverage, and complementary environmental policies.

Building on these insights, the present study extends the literature by examining the direct effects of digitalization, environmental technological innovation, environmental policy stringency, environmental taxation, and green industrial transformation on CO_2 emissions within a unified empirical framework. Particular attention is devoted to the interaction between environmental technological innovation and policy stringency, as well as the combined role of industrialization and renewable energy consumption in representing green industrial transformation. By employing a dynamic panel estimation approach, the study seeks to provide additional evidence on the complex relationships among technological progress, regulatory interventions, industrial restructuring, and environmental sustainability in OECD economies. The findings are expected to inform the development of more coordinated and effective policies for accelerating the transition toward low-carbon economic development.

3. Methodology

3.1. Data and variables

This study investigates the effects of digitalization, environmental technological innovation, environmental policy stringency, environmental taxation, and green industrial transformation on CO_2 emissions in OECD economies. The study covers 34 OECD countries over the period 1999–2024. Data are obtained from the World Development Indicators (WDI) of the World Bank and the OECD statistical database. CO_2 emissions, digital economy indicators, renewable energy consumption, industrialization, trade openness, and FDI are sourced from WDI, while environmental technological innovation, environmental policy stringency, and environmental taxation are obtained from the OECD database. The dependent variable is CO_2 emissions per capita, measured in metric tons, while the explanatory variables capture technological, regulatory, industrial, and economic determinants of environmental performance. Table 1 presents the variables, measurements, symbols, and data sources.

The digital economy (DIGE) is represented by a composite index encompassing four dimensions: digital infrastructure, social effects, digital business, and social support, following the multidimensional approach adopted in previous studies (Shahbaz et al., 2022; Yi et al., 2022). Digital infrastructure includes fixed broadband, fixed telephone, and mobile cellular subscriptions, while social effects capture internet usage and the contribution of medium- and high-technology manufacturing. Digital business is measured through ICT goods exports and imports, whereas social support is represented by per capita service-sector value added.

Environmental technological innovation (ENVTECH) is measured using environment-related patents, while environmental policy stringency (ENVTP) captures the intensity of environmental regulations. Environmental taxation (ENVTX) represents fiscal instruments aimed at discouraging environmentally harmful activities. Green industrial transformation (GIT) is constructed as the interaction between industrialization and renewable energy consumption, reflecting the integration of cleaner energy into industrial development. Trade openness (TO) and FDI are incorporated as control variables to account for international economic integration and investment-related environmental effects.

Table 1. Description and measurement of variables

Variable	Symbol	Measurement/Indicator	Source
Carbon dioxide emissions	CO_2	CO_2 emissions (metric tons per capita)	WDI
Digital economy	DIGE	Composite index comprising four dimensions	WDI
Digital infrastructure			
Fixed broadband subscriptions	FBBS	Subscriptions per 100 people	WDI
Fixed telephone subscriptions	FTS	Subscriptions per 100 people	WDI
Mobile cellular subscriptions	MCS	Subscriptions per 100 people	WDI
Social effects			
Internet usage	IUI	Individuals using the internet (% of population)	WDI
Medium- and high-tech manufacturing	MHTMVA	Medium- and high-tech manufacturing value added (% of manufacturing value added)	WDI
Digital business			
ICT goods exports	ICTGE	ICT goods exports (% of total goods exports)	WDI
ICT goods imports	ICTGI	ICT goods imports (% of total goods imports)	WDI
Social support			
Service-sector value added per capita	PCVSI	Service-sector value added per capita (US$)	WDI
Environmental technological innovation	ENVTECH	Environment-related patents	OECD
Environmental policy stringency	ENVTP	Environmental Policy Stringency Index	OECD
Environmental taxation	ENVTX	Environmental tax indicator	OECD
Renewable energy consumption	RE	Renewable energy consumption (% of total final energy consumption)	WDI
Industrialization	IND	Industry value added (annual % growth)	WDI
Green industrial transformation	GIT	Interaction between industrialization and renewable energy consumption (IND × RE)	Constructed
Trade openness	TO	Trade (% of GDP)	WDI
Foreign direct investment	FDI	Foreign direct investment, net outflows	WDI
Technology–policy interaction	INTR	Interaction between environmental technology and policy stringency (ENVTECH × ENVTP)	Constructed

3.2. Model specification

The empirical framework examines the relationship between CO_2 emissions and their technological, regulatory, industrial, and economic determinants. Digitalization and environmental technological innovation are included to capture the environmental implications of technological progress, while environmental policy stringency and taxation represent regulatory and market-based interventions. Green industrial transformation measures the combined influence of industrial development and renewable energy consumption. Trade openness and FDI are included to control for the potential environmental consequences of international economic integration. Following the existing literature, two empirical models are specified to distinguish the direct effects of the explanatory variables from the interaction between environmental technological innovation and environmental policy stringency.
The baseline model is expressed as follows:

$$CO2_{it} = \beta_0 + \beta_1 DIGE_{it} + \beta_2 ENVTECH_{it} + \beta_3 ENVTP_{it} + \beta_4 ENVTX_{it} + \beta_5 GIT_{it} + \beta_6 TO_{it} + \beta_7 FDI_{it} + \varepsilon_{it} \quad (1)$$

To investigate whether environmental policy stringency moderates the relationship between environmental technological innovation and carbon emissions, the second model incorporates an interaction term between these variables. This specification allows the study to assess whether stronger environmental regulations reinforce or weaken the emissions-related effects of technological innovation. The extended model is specified as follows:

$$CO2_{it} = \beta_0 + \rho CO2_{it} + \beta_1 DIGE_{it} + \beta_2 ENVTECH_{it} + \beta_3 ENVTP_{it} + \beta_4 ENVTX_{it} + \beta_5 GIT_{it} + \beta_6 TO_{it} + \beta_7 FDI_{it} + \beta_8 (ENVTX_{it} \times ENVTP_{it}) + \varepsilon_{it} \quad (2)$$

Here, $CO2_{it}$ captures the persistence of carbon emissions, while ρ represents the dynamic adjustment coefficient. The interaction coefficient β_8 measures how environmental policy stringency modifies the association between environmental technological innovation and carbon emissions. A negative interaction coefficient would suggest that stronger environmental policies enhance the emissions-reducing effects of technological innovation, whereas a positive coefficient would indicate that the combined association is less favorable for emissions reduction.

3.3. Econometric estimation strategy

The study employs the two-step system GMM estimator to examine the dynamic relationships among carbon emissions and their determinants. Conventional estimation approaches, including pooled ordinary least squares and fixed-effects models, may produce biased estimates in dynamic panel settings because of unobserved heterogeneity, simultaneity, reverse causality, and the correlation between lagged dependent variables and country-specific effects. Arellano and Bond (1991) introduced the difference GMM estimator to address these concerns using lagged variables as internal instruments. However, difference GMM may suffer from weak instruments when the explanatory variables are highly persistent. To overcome this limitation, Arellano and Bover (1995) and Blundell and Bond (1998) developed the system GMM estimator, which combines equations in first differences and levels to improve estimation efficiency.

The two-step system GMM estimator is particularly relevant because carbon emissions exhibit substantial persistence over time, while digitalization, environmental regulations, and technological innovation may be jointly determined with environmental outcomes. The estimator uses suitable lagged values of endogenous variables as internal instruments, thereby mitigating potential endogeneity. The two-step procedure also improves asymptotic efficiency by constructing a weighting matrix based on initial estimation residuals. Following Roodman (2009), instrument proliferation should be controlled to preserve the reliability of specification tests, particularly when the number of cross-sectional units is relatively small. Time-specific effects are incorporated to account for common shocks affecting OECD economies.

The validity of the estimated models is evaluated using the Arellano–Bond serial correlation tests and the Hansen and Sargan tests of overidentifying restrictions. The AR(1) and AR(2) tests examine first- and second-order serial correlation in the differenced residuals, respectively. While first-order serial correlation may arise naturally after differencing, the absence of statistically significant second-order serial correlation is necessary for the validity of the moment conditions. The Hansen and Sargan tests assess the joint validity of the instruments, with failure to reject their null hypotheses generally supporting instrument validity, although unusually high p-values may indicate instrument proliferation or weak diagnostic power (Roodman, 2009).

Before estimating the dynamic panel models, the study examines the time-series properties of the variables using the cross-sectionally augmented Im–Pesaran–Shin (CIPS) and cross-sectionally augmented Dickey–Fuller (CADF) unit root tests. These procedures account for potential cross-sectional dependence and help identify the stationarity characteristics of the panel variables. In addition, the Kao panel cointegration test is applied to assess whether a long-run equilibrium relationship exists among the variables. These preliminary analyses provide supplementary information on the statistical properties of the dataset, while the two-step system GMM estimator serves as the principal method for estimating the dynamic relationships.

4. Results and discussion

4.1. Descriptive statistics and correlation analysis

Table 2 presents the descriptive statistics of the study variables. The mean CO_2 emissions are 8.685 metric tons per capita, with a standard deviation of 4.056, indicating considerable variation in environmental performance across the sampled economies. Environmental technological innovation has a mean of 10.653, while environmental policy stringency and environmental taxation have mean values of 2.391 and 2.306, respectively. Green industrial transformation exhibits substantial variability, with a standard deviation of 119.737, reflecting differences in industrial development and renewable energy utilization. Trade openness also varies considerably, suggesting heterogeneous levels of international economic integration. Overall, these statistics indicate substantial differences in technological development, environmental regulation, and industrial structures across the sampled OECD economies.

The pairwise correlation coefficients reported in Table 3 provide preliminary insights into the relationships among the variables. Digitalization exhibits a weak positive correlation with CO_2 emissions (0.1350), whereas environmental technological innovation (−0.0244), environmental taxation (−0.1398), and green industrial transformation (−0.0267) are negatively correlated with emissions. Environmental policy stringency shows a weak positive correlation (0.0811), while trade openness (0.2954) and FDI (0.2923) exhibit relatively stronger positive associations.

Table 2. Descriptive statistics

Variable	Mean	Std. deviation	Minimum	Maximum
CO_2	8.685	4.056	3.0392	25.610
DIGE	−9.720	1.000	−1.458	5.475
ENVTECH	10.653	4.044	0.0001	27.120
ENVTP	2.391	1.065	0.0001	4.880
ENVTX	2.306	0.893	−1.530	5.360
GIT	27.160	119.737	−1248.396	679.517
TO	92.878	55.505	18.125	382.348
FDI	3.760	8.10e	−2.890	5.960

Table 3. Correlation matrix

Variable	CO_2	DIGE	ENVTECH	ENVTP	ENVTX	GIT	TO	FDI
CO_2	1.0000							
DIGE	0.1350	1.0000						
ENVTECH	−0.0244	−0.1165	1.0000					
ENVTP	0.0811	−0.1398	0.3717	1.0000				
ENVTX	−0.1398	−0.1521	−0.0700	0.1999	1.0000			
GIT	−0.0267	−0.0116	−0.1026	−0.1280	0.0356	1.0000		
TO	0.2954	−0.0335	0.0422	0.2477	0.1671	0.0572	1.0000	
FDI	0.2923	0.1887	−0.0396	0.1122	−0.1765	−0.0457	−0.1169	1.0000

4.2. Panel unit root and cointegration tests

Before estimating the empirical models, the stationarity properties of the variables are examined using the cross-sectionally augmented Im–Pesaran–Shin (CIPS) and cross-sectionally augmented Dickey–Fuller (CADF) tests. These tests are useful for panel datasets in which cross-sectional dependence may arise from shared economic conditions, technological developments, and environmental policy shocks. Table 4 reports the results at levels and first differences. Most variables exhibit evidence of nonstationarity at levels, although several are stationary according to at least one test. After first differencing, all variables show statistically significant test statistics at conventional significance levels. These findings indicate that the variables have mixed level-stationarity properties but generally become stationary after first differencing.

The Kao panel cointegration test is subsequently employed to investigate the existence of a long-run equilibrium relationship among the study variables. As shown in Table 5, the modified Dickey–Fuller, Dickey–Fuller, and augmented Dickey–Fuller statistics are statistically significant at the 5% level or better. The unadjusted Dickey–Fuller statistic is also significant at the 5% level, whereas the unadjusted modified Dickey–Fuller statistic is significant only at the 10% level. Collectively, these results provide evidence against the null hypothesis of no cointegration, suggesting a potential long-run equilibrium relationship among the variables.

Table 4. Panel unit root test results

Variable	CIPS I(0)	CIPS I(1)	CADF I(0)	CADF I(1)
CO_2	−1.999	−4.676***	−1.496	−3.352***
FBBS	−2.289	−3.495***	−1.926	−2.768***
FTS	−1.202	−3.474***	−1.499	−2.286**
MCS	−2.264	−3.938***	−1.941	−3.098***
IUI	−2.394	−4.569***	−1.929	−3.401***
MHTMVA	−2.193	−4.360***	−2.123	−3.202***
ICTGE	−2.368	−4.304***	−2.358***	−3.109***
ICTGI	−2.884	−4.814***	−2.070	−3.208***
PCVSI	−2.864	−4.823***	−2.070	−3.208***
ENVTECH	−3.301***	−5.038***	−2.825***	−3.827***
ENVTP	2.531**	−4.650***	−2.525***	−3.381***
ENVTX	−1.876	−4.261***	−1.744	−2.873***
RE	−2.058	−4.671***	−1.679	−3.300***
IND	−3.813**	−5.595***	−2.766***	−4.090***
TO	−1.544	−3.988***	−1.653	−2.540***
FDI	−3.001**	−5.536***	−2.051	−3.854***

Note: I(0) and I(1) denote level and first-difference test results, respectively. ** and *** indicate statistical significance at the 5% and 1% levels, respectively. The null hypothesis is the presence of a unit root.

Table 5. Kao panel cointegration test results

Test statistic	Statistic	p-value
Modified Dickey–Fuller t	2.8568	0.0021
Dickey–Fuller t	2.0791	0.0188
Augmented Dickey–Fuller t	3.6537	0.0001
Unadjusted modified Dickey–Fuller t	−1.5130	0.0651
Unadjusted Dickey–Fuller t	−2.0049	0.0225

4.3. Two-step system GMM estimation results

The two-step system GMM estimation results are presented in Table 6. Model 1 examines the direct associations between carbon emissions and the explanatory variables, whereas Model 2 additionally incorporates the interaction between environmental technological innovation and environmental policy stringency. The lagged dependent variable is positive and statistically significant in both specifications, with coefficients of 0.989 and 0.974, respectively. These findings indicate substantial persistence in carbon emissions, suggesting that current emissions are strongly associated with previous emissions levels. The high persistence also underscores the importance of sustained environmental policy interventions and long-term technological adjustments.

The digital economy exhibits a negative association with CO_2 emissions in both models, with estimated coefficients of −0.049 and −0.104, respectively. These findings suggest that digitalization contributes to improving environmental performance in OECD economies. Digital technologies can enhance energy efficiency, optimize resource allocation, facilitate environmental monitoring, and accelerate the adoption of cleaner production technologies. The results are consistent with Bai et al. (2023), Wang and Zhong (2023), and

Ma and Tao (2023), who reported that digital transformation contributes to emissions reduction through industrial upgrading, technological innovation, and improvements in operational efficiency. More recent evidence from Bai et al. (2025) also emphasizes the potential of digital economy development to improve carbon efficiency while supporting economic growth. Nevertheless, the environmental benefits of digitalization may depend on the energy sources powering digital infrastructure and the extent to which efficiency improvements offset additional electricity demand. Therefore, expanding digital infrastructure alongside renewable energy deployment is essential for maximizing its environmental benefits.

Table 6. Two-step system GMM estimation results

Variables	Model 1	Model 2
Digital economy (DIGE)	−0.049* (0.025)	−0.104* (0.060)
Environmental technology (ENVTECH)	0.017*** (0.003)	0.0274* (0.016)
Environmental policy (ENVTP)	−0.045** (0.005)	−0.235* (0.014)
ENVTECH × ENVTP	—	0.013*** (0.004)
Environmental tax (ENVTX)	0.076 (0.079)	0.144 (0.091)
Green industrial transformation (GIT)	0.001*** (0.000)	0.001*** (0.000)
Trade openness (TO)	−0.270** (0.119)	−0.0950* (0.214)
Foreign direct investment (FDI)	−0.056*** (0.016)	0.006* (0.0608)
Lagged CO_2 emissions	0.989*** (0.011)	0.974*** (0.0172)
Constant	2.224*** (0.712)	0.550 (1.991)
AR(1), z-statistic (p-value)	−2.08 (0.037)	−2.09 (0.037)
AR(2), z-statistic (p-value)	−1.25 (0.210)	−11.11 (0.265)
Sargan test (p-value)	208.65 (0.455)	202.61 (0.554)
Hansen test (p-value)	16.38 (1.000)	12.50 (1.000)
Observations	232	232

Note: Standard errors are reported in parentheses for coefficient estimates. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. Diagnostic-test p-values appear in parentheses.

Environmental technological innovation exhibits positive coefficients of 0.017 and 0.0274 in Models 1 and 2, respectively, indicating an emissions-increasing association in the estimated specifications. This finding suggests that the development of environmental technologies does not necessarily translate into immediate emissions reductions. Potential explanations include technological adjustment costs, increased energy consumption during innovation and deployment, and rebound effects arising from expanded industrial production. These results are consistent with the nonlinear relationship identified by Chen et al. (2023), who found that green technological innovation may initially increase carbon emissions before generating environmental benefits after reaching a particular development threshold. However, the findings contrast with Obobisa (2024), who reported that eco-innovation contributes to reducing CO_2 emissions in OECD economies. Such differences suggest that the environmental effectiveness of innovation depends on technological maturity, energy composition, and the practical deployment of low-carbon technologies. Accordingly, policies should prioritize not only technological invention but also the commercialization and widespread adoption of environmentally effective innovations.

Environmental policy stringency exhibits negative coefficients in both specifications (−0.045 and −0.235), suggesting that stronger environmental regulations are associated with lower CO_2 emissions. These findings are broadly consistent with Yirong (2022), Ma et al. (2023), and Akram et al. (2023), who emphasized the

importance of stringent environmental regulations in promoting emissions mitigation. Environmental policies may encourage cleaner production, strengthen energy efficiency standards, and stimulate investment in low-carbon technologies. Recent OECD evidence also indicates that environmental policy stringency and green technological innovation can support digital economic development, highlighting the interdependence of regulatory and technological transitions (Kiran et al., 2026).

In contrast, environmental taxation exhibits positive but statistically insignificant coefficients in both models, suggesting insufficient evidence of a systematic relationship with emissions in the estimated sample. This finding differs from Wolde-Rufael and Mulat-Weldemeskel (2023) and Wang et al. (2023), who reported emissions-reducing effects of environmental taxation in developed economies. The insignificant results may reflect differences in tax design, implementation, coverage, or the availability of cleaner alternatives. The results suggest that environmental taxation should be evaluated alongside regulatory enforcement and complementary incentives for cleaner technologies.

The interaction between environmental technological innovation and environmental policy stringency exhibits a positive coefficient of 0.013 in Model 2. This finding indicates that stronger environmental policy stringency is associated with a more positive marginal relationship between environmental technological innovation and CO_2 emissions, conditional on the other model variables. The result suggests that technological innovation and environmental regulation do not necessarily generate mutually reinforcing emissions reductions. Potential explanations include technological adjustment costs, policy implementation delays, and the expansion of energy-intensive activities during industrial modernization. This interpretation is consistent with Chen et al. (2023), who emphasized the nonlinear environmental consequences of technological innovation. Nevertheless, the interaction coefficient alone does not establish the presence of rebound effects or regulatory inefficiencies. Further marginal-effect analysis would be necessary to determine how the estimated relationship varies across different levels of policy stringency. The findings highlight the importance of coordinating environmental regulations with the deployment of commercially viable low-carbon technologies.

Green industrial transformation exhibits a positive coefficient of 0.001 in both models, suggesting that the interaction between industrialization and renewable energy consumption is positively associated with CO_2 emissions in the estimated sample. This unexpected result may indicate that renewable energy integration has not sufficiently offset the emissions associated with industrial expansion. The finding contrasts with the anticipated environmental benefits of industrial upgrading and cleaner energy utilization. Obobisa (2024) reported that clean energy and eco-innovation contribute to emissions reduction in OECD countries, underscoring the importance of effective energy transition strategies. The positive coefficient in the present study may reflect transitional constraints, continued fossil fuel dependence, or the scale effects of industrial activity. However, because green industrial transformation is represented by an interaction between industrial growth and renewable energy consumption, the coefficient should not be interpreted as evidence that all forms of green industrial transformation increase emissions. Instead, the result highlights the need for deeper industrial decarbonization and greater integration of renewable energy into production processes.

Trade openness exhibits negative coefficients in both models, suggesting that international trade may contribute to reducing carbon emissions through technological diffusion, improved production efficiency, and specialization in relatively cleaner industries. This finding aligns with Wang et al. (2024), who found that trade openness can support carbon neutrality by promoting economic growth without proportionate increases in emissions. However, other evidence indicates that trade openness can increase emissions under certain conditions. Wang, Zhang, and Li (2024), for example, identified heterogeneous and asymmetric environmental effects of trade openness and diversification across OECD and G20 economies. These contrasting findings

suggest that the environmental consequences of trade depend on production structures, technological capabilities, and the composition of traded goods.

FDI exhibits a negative coefficient in Model 1 (−0.056) but a small positive coefficient in Model 2 (0.006). The negative association in Model 1 is consistent with the pollution halo hypothesis, under which foreign investment may facilitate cleaner technologies and improved production efficiency. Conversely, the positive coefficient in Model 2 could reflect investment in energy-intensive sectors. Therefore, the findings do not establish a robust emissions-increasing effect of FDI. Wang et al. (2024) similarly identified complex relationships between FDI, economic development, and carbon emissions, emphasizing the importance of investment characteristics and economic conditions. These results highlight the importance of attracting environmentally responsible foreign investment while strengthening environmental standards.

The diagnostic statistics reported in Table 6 provide preliminary information on model validity. The AR(1) tests are statistically significant in both specifications, whereas the reported AR(2) p-values exceed 0.05, suggesting no evidence of second-order serial correlation. The Sargan tests also fail to reject the null hypothesis of instrument validity. Overall, the empirical findings suggest that digitalization is associated with improved environmental performance, whereas environmental technological innovation and the constructed green industrial transformation indicator exhibit positive associations with carbon emissions. Environmental taxation shows no statistically significant relationship, while the effects of trade openness and FDI vary in their statistical strength across specifications. These results underscore the importance of evaluating technological and regulatory interventions within their broader economic and institutional contexts. The findings also suggest that digitalization, environmental innovation, and industrial transformation should be coordinated with renewable energy deployment and effective environmental governance to support sustainable decarbonization across OECD economies.

5. Conclusion and policy implications

5.1. Conclusion

This study investigates the effects of digitalization, environmental technological innovation, environmental policy stringency, environmental taxation, and green industrial transformation on CO_2 emissions in OECD economies. Using panel data covering the period 1999–2024, the study employs the two-step system GMM estimator to account for dynamic relationships and potential endogeneity. The findings reveal that digitalization and environmental policy stringency are negatively associated with carbon emissions, highlighting their potential contributions to environmental sustainability. Conversely, environmental technological innovation and green industrial transformation exhibit positive associations with emissions, suggesting that technological advancement and industrial restructuring do not necessarily generate immediate environmental benefits. Furthermore, the positive interaction between environmental technology and policy stringency indicates that stronger environmental regulations do not automatically enhance the emissions-reducing potential of technological innovation. Environmental taxation exhibits no statistically significant relationship with emissions, while trade openness is generally associated with lower emissions. The relationship between FDI and carbon emissions varies across model specifications. Overall, these findings emphasize the importance of coordinated technological, regulatory, and industrial strategies in achieving sustainable decarbonization.

5.2. Policy implications

The findings offer several important policy implications for OECD economies. First, policymakers should accelerate digital transformation by promoting energy-efficient digital infrastructure, smart energy systems, and digital technologies that optimize industrial production and resource utilization. However, the expansion of digital infrastructure should be accompanied by renewable energy deployment and energy efficiency standards to minimize the environmental impacts of increasing electricity demand. Second, governments should strengthen environmental policy implementation through effective regulatory enforcement, transparent emissions monitoring, and targeted incentives for cleaner production. Given the insignificant relationship between environmental taxation and emissions, policymakers should also evaluate the design, coverage, and effectiveness of environmental taxes and integrate them with complementary regulatory and technological measures.

Third, the positive associations of environmental technological innovation and green industrial transformation with carbon emissions highlight the need to move beyond technological development toward effective implementation and commercialization of low-carbon innovations. Governments should prioritize research and development, renewable energy integration, clean industrial technologies, and the modernization of carbon-intensive production systems. Particular attention should be given to aligning environmental regulations with technological capabilities to minimize transitional inefficiencies and potential rebound effects. Furthermore, industrial policies should encourage the replacement of fossil fuels with renewable energy rather than merely expanding industrial production alongside existing carbon-intensive energy systems. Finally, trade and investment policies should facilitate the transfer of cleaner technologies, encourage environmentally responsible FDI, and strengthen international cooperation in sustainable industrial development. Collectively, these measures can support a more integrated approach to achieving long-term environmental sustainability and carbon neutrality across OECD economies.

5.3. Limitations and future research directions

Despite its contributions, this study has certain limitations that provide opportunities for future research. First, the analysis focuses on OECD economies, potentially limiting the generalizability of the findings to developing countries with different technological capabilities, industrial structures, and institutional conditions. Second, the composite digital economy index and the interaction-based measure of green industrial transformation may not fully capture the multidimensional characteristics of digitalization and industrial decarbonization. Third, the aggregate panel framework may conceal country-specific differences in environmental policies, technological development, and energy transitions. Future studies could employ alternative indicators, nonlinear estimation techniques, and country-specific analyses to examine potential threshold effects and heterogeneous environmental outcomes. Further research could also investigate the mechanisms through which environmental innovation, renewable energy adoption, and policy stringency interact, particularly the roles of technological maturity, rebound effects, and regulatory effectiveness. Such investigations would provide deeper insights into the conditions under which digitalization and green industrial transformation contribute to sustainable, low-carbon economic development.

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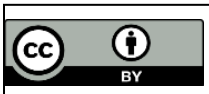
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