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Impact of Digitalization, Technological Innovation, and ICTs on Sustainability Management and Strategies

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Abstract: This study examines the impact of technological innovation, digitalization, and information and communication technologies (ICTs) on trade-related carbon emissions (TAEs) and the role of economic growth in this relationship. Using data from the 15 countries with the highest carbon emissions in the world for the period 1997–2022, analyses were conducted with Panel-Corrected Standard Errors (PCSEs), Seemingly Unrelated Regression (SUR), and Driscoll–Kraay (D-K) estimators. TAEs provide a more comprehensive environmental assessment than traditional emission calculations by taking into account the impact of international trade on carbon emissions. The findings show that technological innovation, digitalization, and ICTs use increased trade-related carbon emissions, and economic growth further strengthens this effect. These results reveal that sustainable production models and green energy policies should be emphasized more in order to minimize the environmental impacts of technological developments and economic growth. The findings of this study provide important strategic information for policymakers, environmental regulators, and international trade institutions in developing sustainable technology and trade policies to reduce carbon emissions.

Keywords: trade-adjusted carbon emissions; information and communication technologies; technological innovation; digitalization

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1. Introduction

Information and communication technologies (ICTs), digitalization, and technological innovation have direct and indirect effects on environmental quality. One of these effects is shaped by trade-adjusted carbon emissions (TAEs). The proliferation of ICT-based technologies, the expansion of data centers, and the development of digital infrastructure can contribute to carbon emissions by increasing electricity consumption [1,2]. However, ICTs also have the potential to contribute to environmental sustainability by increasing energy efficiency [3,4]. In particular, the digitalization of trade and the proliferation of smart logistics systems can optimize energy consumption in supply chain processes and reduce trade-related carbon emissions in the long term [5]. However, the positive environmental effects of these processes may vary depending on the energy resources and industrial structures of countries.

The impact of technological innovation on environmental quality varies across renewable energy technologies, industrial production processes, and trade flows. While ref. [6] emphasizes that green technology innovation has the potential to reduce carbon emissions, refs. [7,8] show that technological advances can increase energy consumption and carbon emissions in countries with intensive industrial production. This indicates that the environmental impacts of technological advances are not always positive [9]. Especially in developing countries, with the increase in industrial production, carbon-intensive sectors can export more and spread carbon emissions to other countries through global trade [10,11]. For example, ref. [12] shows that technological innovation supported by foreign direct investment (FDI) in China can increase trade-related carbon emissions.

Another impact of digitalization and ICTs on environmental quality is evaluated in the context of international trade flows and trade-based carbon emissions (TAEs). The use of digital technologies in globalizing economies can save energy by making production and consumption processes more efficient [13]. However, these processes can also shift carbon emissions to different countries, causing carbon leakage on a global scale [1]. Ref. [11] reveals that trade-adjusted carbon emissions are spread among different countries due to the impact of digitalization and global production processes. In particular, developed countries can reduce their local emissions by shifting carbon-intensive production activities to developing countries due to strict environmental regulations, while increasing their trade-based carbon emissions on a global scale [10]. In this context, ref. [2] states that the carbon emission-reducing effect of technological innovation is directly related to countries' energy policies and industrial strategies. If digitalization and technological innovation are not supported by renewable energy sources, they may negatively affect environmental quality by increasing the use of fossil fuels in industrial production [14].

Economic growth is one of the main factors determining the relationship between ICTs, digitalization, and technological innovation. Since economic growth is directly linked to industrial production and energy consumption, it tends to increase trade-related carbon emissions [15,16]. However, the environmental impact of growth may vary within the framework of the Environmental Kuznets Curve (EKC) hypothesis. Refs. [17,18] supports the N-shaped EKC hypothesis by suggesting that economic growth can increase environmental degradation up to a certain point, but then promote environmental sustainability. Ref. [12] shows that economic growth can support environmental sustainability when evaluated together with renewable energy investments. However, in scenarios where growth is not sustainable, trade-related carbon emissions may continue to spread globally, and carbon leakage effects may become more pronounced among countries. Therefore, the balanced implementation of technological innovation, digitalization, and trade policies with economic growth is a critical factor in reducing trade-related carbon emissions.

However, the environmental effects of digitalization should not be assessed solely through technological infrastructure and production processes but rather within a broader theoretical framework. In particular, the contradiction between digitalization's contribution to environmental sustainability and its potential to increase environmental burdens is referred to in the literature as the "digitalization paradox". According to this paradox, while digital technologies improve energy efficiency and optimize resource use on the one hand, they may also increase energy consumption and carbon emissions due to the growing demand for data processing, digital devices, and cloud-based services. This duality suggests that the environmental impact of digitalization should be analyzed not only from a technological standpoint but also in relation to economic structures, energy policies, and consumption patterns. In this context, the concept of trade-adjusted carbon emissions (TAEs) should be situated within the frameworks of environmental economics, ecological modernization theory, and global environmental justice. Environmental economics emphasizes the need to internalize environmental externalities and advocates for the use of indicators like TAEs in policy formulation. Ecological modernization theory argues that technological progress can contribute to environmental improvement, but only when supported by appropriate institutional structures and sustainable energy strategies. On the other hand, the global environmental justice perspective criticizes the shifting of carbon-intensive production from industrialized nations to developing countries, pointing out that this leads to an inequitable distribution of environmental burdens—a phenomenon that TAEs help to reveal. Therefore, the environmental consequences of digitalization and technological innovation must be examined not only through performance indicators but also through a multidimensional lens informed by these theoretical perspectives.

Although the existing literature has extensively examined the impact of technological innovation, digitalization, and information and communication technologies on carbon emissions, it has addressed the specific effects of these factors on trade-based carbon emissions to a limited extent. In particular, how digitalization and technological innovation can increase or decrease carbon emissions has not been sufficiently investigated in the context of trade flows between countries. In addition, the transformative role of economic growth in this process has been ignored in most studies. Based on these shortcomings, this study evaluates the impact of digitalization, technological innovation, and ICTs on trade-based carbon emissions and examines the moderating role of economic growth in this relationship. In the study, data for the period 1997–2022 belonging to the 15 countries with the highest carbon emissions in the world were used, and analyses were conducted with PCSE, SUR, and D-K estimators. These methods provide reliable estimates by taking into account statistical problems such as autocorrelation, heteroskedasticity, and cross-sectional dependence in the panel data set.

This study is expected to contribute to the literature in several significant ways. First, unlike traditional studies that predominantly rely on production-based carbon emissions, this research adopts a trade-adjusted carbon emissions (TAEs) perspective, offering a more accurate and comprehensive assessment of countries' environmental impacts in the context of global trade. The existing literature has largely overlooked this approach, often neglecting the embodied carbon flows across borders caused by international trade. By focusing on TAEs, this study addresses this critical gap and provides a more realistic picture of national environmental responsibility in an increasingly interconnected global economy. The findings of this research hold practical relevance for multiple stakeholders. Policymakers and regulatory bodies can benefit from a deeper understanding of how digitalization and technological innovation affect carbon emissions via trade channels, thereby informing more targeted strategies to mitigate carbon leakage and refine border carbon adjustment (BCA) mechanisms. Industry actors can leverage these insights to realign their production and supply chain strategies with environmental goals. Furthermore, international organizations and environmental advocacy groups can expand the scope of sustainability policies and carbon markets by integrating trade-adjusted metrics, helping to strengthen global climate governance frameworks. This study thus offers a novel empirical foundation to guide future research and policy design in the pursuit of climate-resilient and technology-informed trade systems. In addition to its methodological contributions, this study also offers a distinctive empirical contribution by focusing on the 15 countries with the highest carbon emissions globally, thereby capturing a significant portion of the world's environmental footprint. This sample selection strengthens the policy relevance and generalizability of the findings, as it reflects the behaviors and trade dynamics of the major emitters in the global economy. When combined with advanced estimation techniques such as Panel-Corrected Standard Errors (PCSEs), Seemingly Unrelated Regression (SUR), and Driscoll–Kraay (D-K), this study not only ensures robust and reliable results but also enables a nuanced understanding of how digitalization, technological innovation, and economic growth influence trade-adjusted emissions in diverse economic contexts. This integrated design allows the research to bridge theoretical insights with real-world implications, offering valuable guidance for global sustainability policy.

This study consists of five sections. Following the introduction, the second section comprehensively summarizes the existing literature on the effects of technological innovation, digitalization, ICTs, and economic growth on environmental quality. The third section explains, in detail, the variables, data set, and applied econometric methods used in this study. The fourth section evaluates the empirical findings and compares them with the results of previous studies. The final section provides theoretical and practical implications and offers suggestions for policymakers and relevant stakeholders based on the findings.

2. Literature Review

In this part of the study, the existing literature on the relationship between technological innovation, digitalization, ICTs, and economic growth and environmental quality indicators is summarized.

2.1. Relationship Between Technological Innovation and Environmental Quality

Studies examining the relationship between technological innovation and environmental quality show that this relationship may vary depending on the economic structure, industrialization level, and energy policies of countries. Ref. [19] stated that technological innovation can have both positive and negative effects on environmental sustainability. Especially in developing countries, it is seen that technological innovations that support industrialization can increase energy demand and carbon emissions [20,21]. Similarly, refs. [9,22] emphasized that the environmental impact of technological innovation supported by foreign direct investments depends on the regulatory policies of countries and can increase carbon emissions in industrially intensive countries.

Studies examining the relationship between trade-adjusted carbon emissions (TACEs) and technological innovation have evaluated the impact of technological progress on carbon emissions with different methodologies. The ref. [1] study investigated whether technological innovation limits trade-adjusted carbon emissions and found that advanced innovation processes have the potential to reduce carbon emissions. However, it was emphasized that technological progress does not always create a positive environmental impact and can increase carbon emissions by increasing energy consumption under certain conditions. The ref. [2] study analyzed the combined effect of energy efficiency and technological innovation and showed that innovative energy technologies are more effective in reducing carbon emissions when evaluated together with energy efficiency. Similarly, the ref. [9] study examined the link between environmental R&D investments and trade-adjusted carbon emissions, revealing that the impact of international trade on carbon emissions varies depending on technology transfer. The study stated that green technology imports from developed countries can reduce carbon emissions, but technological innovation can limit this effect in countries with fossil fuel-intensive production. Refs. [12,23] evaluated the relationship between environmental taxes, energy efficiency, and trade-based carbon emissions, emphasizing that technological innovation should be encouraged and environmental taxes should be implemented effectively to ensure sustainable development.

On the other hand, some studies show that technological innovation can improve environmental quality by accelerating the transition to green energy. Ref. [24] stated that technological innovation and financial development support environmentally friendly production processes in Egypt, while ref. [25] showed that technological developments in China can promote environmental sustainability by increasing carbon emission efficiency. Another study by ref. [26] emphasized that green innovation policies in OECD countries have the potential to reduce environmental pollution. However, ref. [27] stated that with the increase in energy consumption in South Asian countries, the positive effects of technological progress on the environment may be limited.

The environmental impacts of technological innovation appear to vary across countries. Ref. [7] found that industrial production in Saudi Arabia could threaten environmental sustainability by increasing its carbon intensity, while ref. [6] showed that green technology innovation has the potential to reduce carbon emissions in China. Similarly, ref. [28] found that the impact of technological innovation on the ecological footprint in E-7 countries depends on the countries' sustainable development policies. Ref. [29] suggested that public–private partnerships could improve environmental quality by supporting green innovation in the case of Pakistan, while ref. [30] discussed the impacts of tourism, globalization, and technological innovation on the ecological footprint in G-10 countries, showing that technological developments can sometimes cause environmental degradation.

Regional analyses show that the environmental impacts of technological innovation can be linked to spatial spillover effects and transboundary externalities. Ref. [31] analyzed the spatial spillover effect of technological innovation on carbon neutrality, revealing that innovation can provide environmental benefits beyond certain borders. Ref. [32] indicated that technological innovation in Arab countries, when combined with financial development, can encourage environmentally friendly investments. Chen [33] examined the interaction between oil consumption, economic growth, and technological innovation in Bangladesh, showing that the impact of innovation on emission reduction may vary depending on energy sources.

In general, the literature reveals that the effects of technological innovation on environmental quality are determined by country policies, energy resources, and industrial structures. The carbon emission reduction effect of technological innovations can only be effective when supported by green innovation policies and sustainable energy investments. Therefore, policymakers need to maximize the environmental benefits of technological innovation by investing in renewable energy technologies and encouraging sustainable production models. In addition, the adoption of financial policies that support environmentally friendly innovations in the industrialization process stands out as a critical strategy for reducing carbon emissions in the long term. Building on these findings, the following hypothesis is proposed in this study:

H_1: *Technological innovation contributes to the reduction of trade-adjusted carbon emissions.*

2.2. The Relationship Between Digitalization and Environmental Quality

Studies examining the relationship between digitalization and environmental indicators (carbon emissions, environmental quality, sustainability) focus on the bidirectional effects of digital transformation on the environment. Ref. [34] defined the impact of digitalization on carbon emissions in the context of China as an inverted U, finding that digitalization initially increased emissions but contributed to environmental improvements after a certain level. Ref. [3] showed that digitalization can increase carbon emissions together with financial development and trade and that polluting industries can be concentrated in digitalized countries within the framework of the pollution haven hypothesis in the globalization process. Ref. [14] showed that the development of the digital economy in China can increase environmental pressure by increasing carbon intensity.

In addition, the positive effects of digitalization in terms of environmental sustainability are also emphasized in some studies. Ref. [35] stated that the digital economy can reduce carbon emissions, but this effect should be considered together with variables such as trade openness and technological innovation. Ref. [36] showed that industrial pollution can be reduced by digitalization, and this relationship is stronger when supported by green innovation and environmental investments. The ref. [4] study stated that digitalization improves environmental quality by increasing carbon emission efficiency in the urbanization process and that smart city applications can contribute to this process.

There are also studies emphasizing that digitalization should be evaluated within the framework of environmental governance and sustainable policies. Ref. [5] showed that internet development can reduce environmental pollution and that digitalization has become an effective tool in environmental governance. Ref. [37] analyzed the environmental performance-enhancing effects of digitalization in European countries and emphasized that sustainable digital transformation policies can be effective in limiting carbon emissions. Ref. [38] systematically evaluated the impact of digitalization on environmental sustainability through a literature review conducted between 2000 and 2022 and revealed that this relationship changes depending on the energy policies of the countries.

Finally, refs. [39,40] examined the impact of digitalization on solar energy innovation and the carbon footprint in the context of environmental sustainability. Ref. [39] emphasized the positive effects of digitalization, solar energy innovation, and economic globalization on environmental quality in the USA. Ref. [40] showed that the impact of digitalization on the carbon footprint is complex, and digitalization may cause increased carbon emissions in energy-intensive sectors but may provide environmental efficiency in the long term. These studies reveal that the impact of digitalization on environmental sustainability may vary depending on regional and sectoral differences and should be supported by sustainable policy frameworks.

However, a review of the existing literature reveals that, despite the multidimensional nature of the relationship between digitalization and environmental sustainability, studies that address this relationship within the framework of trade-adjusted carbon emissions (TAEs) remain quite limited. In particular, the potential of digitalization to affect the environment through international trade flows, structural transformations in production, and carbon leakage mechanisms has not been thoroughly analyzed. Moreover, how this impact varies depending on key determinants such as regional differences, energy policies, and sectoral composition is largely overlooked in the current literature. In this context, the following hypothesis is proposed to fill this gap in the literature:

H_2: *Digitalization significantly reduces trade-adjusted carbon emissions.*

2.3. The Relationship Between ICTs and Environmental Quality

Studies addressing the relationship between information and communication technologies (ICTs) and environmental quality reveal that the impact of ICTs on environmental indicators (carbon emissions, ecological footprint, sustainability) is a complex dynamic that varies by country and sector. Refs. [41,42] emphasized that the use of ICTs can increase environmental quality and be an important tool in reducing carbon emissions. Ref. [43] and showed that ICTs can improve environmental quality by supporting urban sustainability. Ref. [42], emphasized that the impact of ICTs on the environment in ASEAN and South Asian economies is closely related to institutional quality and governance. Ref. [44] stated that ICTs should be supported by appropriate policies in order to increase environmental quality in Sub-Saharan Africa.

However, some studies focus on the increasing effects of ICTs on carbon emissions. Refs. [45,46] showed that ICTs can increase carbon emissions by increasing energy consumption. Ref. [47] stated that ICT use has heterogeneous effects in different countries, reducing emissions in developed countries while increasing emissions in developing countries. Refs. [48,49] showed that ICTs can reduce the ecological footprint when integrated with renewable energy use, but they can increase environmental pressure when dependent on traditional energy sources. Ref. [50] emphasized that ICTs can reduce carbon emissions when combined with trade openness and financial development. Ref. [51] stated that ICTs can increase environmental sustainability in MERCOSUR countries, but this requires strong environmental policies and institutional support to be realized effectively.

Some studies show that the contribution of ICTs to environmental sustainability depends on certain conditions. Ref. [52] emphasized that ICTs and innovation can reduce carbon emissions in BRICS countries, but this effect interacts with economic growth and energy consumption. Refs. [53,54] stated that ICTs have the potential to reduce CO_2 emissions, but this effect may vary by country. Ref. [55] examined the carbon emission reduction effect of ICTs within the framework of the "Broadband China" policy implemented in China, showing that digital infrastructure can contribute to environmental sustainability. It shows that ICTs can support environmental sustainability more effectively when integrated with human capital and renewable energy use.

Finally, studies that address the long-term environmental impacts of ICTs in a broader perspective suggest that the impacts of these technologies are not limited to carbon emissions alone but should be evaluated within a larger sustainability framework. Refs. [56,57] stated that ICTs can increase carbon emissions when not implemented with sustainable development policies but can prevent environmental degradation when integrated with low-carbon technologies. Refs. [5,58] showed that the impact of ICTs on carbon emissions is shaped by carbon trading systems and environmental governance mechanisms. Refs. [59,60] stated that the environmental impacts of ICTs cannot be explained with a linear model and should be evaluated together with environmental policy, economic development, and energy use patterns. In general, studies revealed that the impact of ICTs on environmental quality is complex, multidimensional, and varies across countries. In light of this multidimensionality, the following hypothesis is proposed in this study:

H_3: *Information and communication technologies (ICTs) reduce trade-adjusted carbon emissions.*

2.4. The Relationship Between Economic Growth and Environmental Quality

Studies examining the relationship between economic growth and environmental quality show that the impact of growth on the environment varies depending on the country, energy policies, and economic structure. Refs. [15,16,61] analyze the impact of economic growth on the ecological footprint and carbon emissions, revealing that increased economic activities generally cause environmental degradation. Refs. [62,63] emphasize that economic growth is directly linked to carbon emissions and that environmental pressure increases, especially in industrial-intensive economies. Refs. [64,65] evaluate the environmental impacts of economic growth in South Asian and BRI countries, showing that financial development and energy use patterns determine the direction of this relationship.

Studies also discuss how renewable energy use, financial development, and foreign direct investment shape the relationship between economic growth and environmental quality. Refs. [66,67] argue that renewable energy use can mitigate the environmental damage of economic growth, while ref. [68] examines the effects of China's foreign investment on carbon emissions, indicating that growth can lead to environmental destruction if investments are not supported by environmental regulations. Ref. [59] argues that carbon trading policies can be effective in reducing the environmental costs of growth.

Studies showing that the relationship between economic growth and environmental quality should be evaluated within the framework of the Environmental Kuznets Curve (EKC) hypothesis and the N-shaped EKC hypothesis reveal that the environmental impact of growth is not linear. The EKC hypothesis argues that economic growth increases carbon emissions in the initial stages, but after a certain income level, environmental quality starts to improve thanks to environmental policies, technological developments, and the transition to renewable energy. Refs. [18,66,69] present findings supporting the validity of the EKC hypothesis, showing that economic growth initially increases environmental degradation, but emissions start to decrease after a certain point, with the effects of sustainability policies. Ref. [66] analyzes the impact of economic growth on the environment in South Asian countries, emphasizing that growth increases carbon emissions in the initial stage, but environmental sustainability policies come into play as income levels increase. Ref. [70] evaluates the impact of economic growth on the ecological footprint in developing countries and similarly reveals that environmental pressure increases in the first stage, but after a certain point, this effect reverses.

However, ref. [18] shows that the N-shaped EKC hypothesis is valid in some countries and that economic growth can cause environmental pressure again after a certain point. The N-shaped EKC hypothesis suggests that the relationship between economic growth and environmental quality may lead to environmental degradation again in the long term due to economic expansion, although growth reduces carbon emissions in the medium term. Ref. [17] analyzes the effects of financial development and nuclear energy consumption on environmental sustainability, emphasizing that growth increases carbon emissions in the first stage, emissions decrease in the medium term thanks to environmental policies, but as economic expansion continues, environmental pressure increases again due to increased industrial activities.

In this context, in order to understand the relationship between economic growth and environmental quality, it is seen that the EKC hypothesis and the N-shaped EKC hypothesis should be evaluated in the context of countries' energy policies, industrial structures, and financial systems. Since each country's economic structure, energy consumption model, and environmental policies are different, the impact of growth on the environment cannot be explained by a single model. Therefore, it is of great importance for policymakers to support sustainable energy use and environmentally friendly investments while encouraging economic growth. Based on this perspective, the following hypothesis is proposed:

H_4: *Economic growth increases trade-adjusted carbon emissions.*

3. Methodology

3.1. Data Set

The aim of this study is to determine the impact of technological innovation, digitalization, and information and communication technologies (ICTs) on trade-adjusted carbon emissions. In addition, the mediator role of economic growth within the framework of this relationship is examined in detail. In this study, annual data for the period 1997–2022 of the 15 countries with the highest carbon emissions in the world (Australia, Brazil, China, Germany, India, Indonesia, Japan, South Korea, Mexico, Poland, Russia, South Africa, Turkey, the United Kingdom, and the United States) (https://www.worldometers.info/co2-emissions/co2-emissions-by-country/, accessed on 15 April 2025) are used. In this context, the effects of technological developments and digital transformation processes on environmental sustainability are evaluated through empirical analyses, and the guiding role of economic growth in this process is revealed.

Trade-adjusted carbon emissions were used as the dependent variable in the study. Trade-adjusted carbon emissions (TAEs), unlike traditional carbon emission measurements, are an indicator that more accurately reflects the true environmental impact of a country by taking into account trade flows between production and consumption [10,11]. While traditional production-based carbon emissions measure emissions from production processes occurring only within a country, consumption-based emissions also take into account emissions generated in different countries during the production of imported goods. Trade-adjusted carbon emissions combine these two approaches, subtracting emissions generated abroad due to exports and adding carbon emissions generated in other countries during the production of imported goods, providing a more comprehensive environmental assessment [71]. In this context, TAEs, which take into account the environmental impacts of international trade, stand out as an important tool in determining the real emission responsibilities of countries by taking into account factors such as carbon leakage. Especially in globalizing economies, ignoring trade flows when assessing the impacts of production processes on carbon emissions can be misleading. For example, although developed countries reduce their local emissions by shifting carbon-intensive sectors to developing countries due to strict environmental regulations, their carbon footprint may not decrease on a global scale [72]. Trade-adjusted emissions contribute to the more accurate shaping of sustainability policies by taking such cross-border impacts into account [71].

The independent variables used in this study include digitalization, technological innovation, and information and communication technologies (ICTs). The digitalization (DIG) variable is measured by the ratio of individuals using the internet to the total population. The technological innovation (TIN) variable is represented by the number of patent applications filed by foreign applicants. The information and communication technologies (ICTs) variable is measured by the value of ICT service exports calculated on the basis of the balance of payments in current US dollars. In addition, the economic growth (GDP) variable is determined using the per capita gross domestic product (GDP) data in constant 2015 US dollars.

As a result, the summary of the variables used in this study is shown in Table 1. In addition, following the empirical studies conducted by [10,11,71,72], the logarithmic regression model is used to estimate the relationships in question as follows:

$$TAE_{i,t} = \beta_0 + \beta_1 DIG_{i,t} + \beta_2 TIN_{i,t} + \beta_3 ICT_{i,t} + \beta_4 GDP_{i,t} + \varepsilon_{i,t} \quad (1)$$

Table 1. Summary of variables.

Variables	Symbol	Measure	Source	Studies Using the Variables
Trade-adjusted emission	TAE	Consumption emissions in Mt CO_2	Global Carbon Atlas (2022)	[1,10,11]
Digitalization	DIG	Individuals using the internet (% of population)	WDI	[18,73]
Technological innovation	TIN	Patent applications, nonresidents	WDI	[28,73]
ICT	ICT	ICT service exports (BoP, current USD)	WDI	[51,74]
Economic growth	GDP	GDP per capita (constant 2015 USD)	WDI	[18,73]

3.2. Methods

In this study, cross-sectional dependence analysis was primarily performed due to the panel data structure of the model. Cross-sectional dependence may occur due to factors such as common shocks or economic integration among countries or units and may affect the reliability of the results. Therefore, various tests were applied to determine whether there is a dependency between variables in panel data analysis. In this context, the LM test, first developed by ref. [75], was used. The LM test is a method that provides effective results, especially when the time dimension (T) is large and the cross-section dimension

(N) is small. However, it is known that this test can give extremely deviant results as the cross-sectional dimension increases. In order to overcome this problem, the scaled LM test (〖CD〗_LM) proposed by [76] was used. This test is a derivative of the traditional LM test and provides more reliable results, especially when N is large. However, both the Breusch–Pagan LM test and the Pesaran Scaled LM test may produce misleading results under certain conditions. In order to correct this situation, ref. [77] developed the bias-corrected LM test (LMadj) by adding variance and mean corrections. This test provides more reliable and robust results, especially when both T and N are large. The calculation methods of the relevant tests used in this study are detailed in Equations (2)–(5).

$$LM = T\sum_{=1}^{N-1}\sum_{j=i+1}^{N}\hat{\rho}_{ij}^{2} \tag{2}$$

$$CD_{LM} = \sqrt{\frac{1}{N(N-1)}\sum_{=1}^{N-1}\sum_{j=i+1}^{N}\left(T\hat{\rho}_{ij}^{2}-1\right)} \tag{3}$$

$$CD = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{j=1+1}^{N}\hat{\rho}_{ij}\right) \tag{4}$$

$$LM_{adj} = \left(\frac{2}{N(N-1)}\right)^{\frac{1}{2}}\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{\rho}_{ij}^{2}\frac{(T-K-1)\hat{\rho}_{ij}-\hat{\mu}_{Tij}}{v_{Tij}} \sim N(0,1) \tag{5}$$

After analyzing the cross-sectional dependency, the slope homogeneity in the panel data model was evaluated with the Δ tests developed by [78]. These tests are used to determine whether the coefficients are the same for all units and provide reliable results, especially when the cross-sectional size is large. If the coefficients are found to be heterogeneous, standard panel estimation methods may be misleading. However, if the model contains heteroskedasticity and serial correlation (autocorrelation), ref. [78] Δ tests may give deviant results. In such cases, the Δ tests developed by ref. [79] are preferred because these tests provide more accurate results by taking into account the heteroskedasticity and temporal dependency. The relevant calculations are detailed in Equations (6)–(9).

$$\Delta_{HAC} = \sqrt{N}\left(\frac{N^{-1}S_{HAC}-k}{\sqrt{2k}}\right) \tag{6}$$

$$S_{HAC} = \sum_{i=1}^{N} T(\hat{\beta}_i-\hat{\beta})'\left(\hat{O}_T V_T^{-1}\hat{O}_T\right)(\hat{\beta}_i-\hat{\beta}) \tag{7}$$

$$\hat{\beta} = \left(\sum_{i=1}^{N} T\hat{O}_T V_T^{-1}\hat{O}_T\right)^{-1}\sum_{i=1}^{N}\hat{O}_T\hat{V}_T^{-1}X_i' M_T y_i \tag{8}$$

$$\hat{V}_T = \hat{\Gamma}_i(0)+\sum_{j=1}^{T-1}K\left(\frac{j}{M_T}\right)\left[\hat{\Gamma}_i(j)+\hat{\Gamma}_i(j)'\right] \tag{9}$$

In this study, depending on the results of the cross-sectional dependency test, Cross-Sectionally Augmented Dickey–Fuller (CADF) and Cross-Sectionally Augmented IPS (CIPS) unit root tests developed by ref. [77] were applied in order to evaluate the stationarity properties in the panel data set. Traditional unit root tests may give misleading results since they are not sensitive to cross-sectional dependency. Therefore, the CADF and CIPS tests that take cross-sectional dependency into account provide more reliable results and offer an effective method to determine whether the variables are stationary or not. The CADF test is an extended version of the classical ADF test and performs individual unit root tests by checking the cross-sectional dependency for each unit in the panel. The CIPS test is derived from the CADF test and is used to test the common unit root hypothesis throughout the panel. In this study, the calculation methods of the relevant tests are detailed in Equations (10)–(14), and the stationarity levels of the variables are determined according to the obtained results.

$$\Delta y_{it} = \alpha_i + \beta_i y_{i,t-1} + u_{it} \tag{10}$$

$$u_{it} = \gamma f_t + \varepsilon_{it} \tag{11}$$

$$\Delta y_{it} = \alpha_i + \rho_i y_{i,t-1} + d_0 \underline{y}_{t-1} + d_1 \Delta \underline{y}_t + \varepsilon_{it} \tag{12}$$

$$\Delta y_{i,t} = \alpha_i + \rho_i y_{i,t-1} + c_i \underline{y}_{t-1} + \sum_{j=0}^{p} d_{i,j} \Delta \underline{y}_{t-j} + \sum_{j=0}^{p} \beta_{i,j} \Delta y_{i,t-j} + \mu_{i,t} \tag{13}$$

$$CIPS = \frac{1}{N} \sum_{i=1}^{N} CADF_i \tag{14}$$

In order to determine the long-term relationship between the variables in the panel data set, appropriate panel cointegration tests were used. In this context, cointegration tests developed by refs. [80,81] were applied in this study. These tests are widely used methods to evaluate whether there is a long-term equilibrium relationship between the series.

In addition, the cointegration test by ref. [82] was applied to analyze the long-term dynamics between the variables in more detail. This test is calculated with four basic test statistics that take into account structural dynamics and are based on the error correction mechanism: G_t and G_a group statistics and P_t and P_a panel statistics. While group statistics test the long-term relationship specific to individual units by evaluating the error correction coefficients for each cross-section separately, panel statistics generally measure a common cointegration relationship for the entire panel. The cointegration equation used in this study is given in Equation (15), and with the help of these tests, the existence of long-term balance between the variables and its statistical significance were examined. If a cointegration relationship was detected, long-term parameter estimates were made, and permanent effects between the variables were analyzed.

$$\Delta Y_{it} = \delta_i d_t + \alpha_i Y_{i,t-1} + \gamma_i X_{i,t-1} + \sum_{j=1}^{pi} \alpha_{ij} \Delta Y_{i,t-1} + \sum_{j=-qi}^{pi} \gamma_{ij} \Delta X_{i,t-1} + \varepsilon_{it} \tag{15}$$

In this study, long-term elasticity coefficients between variables were obtained using the Seemingly Unrelated Regression (SUR) method and the [83] estimator. These methods are widely preferred in panel data analysis and stand out, especially because they eliminate endogeneity problems and take into account heterogeneity and inter-unit dependency. The SUR model allows simultaneous estimations to be made by considering that the error terms in different regression equations may be correlated with each other. In this way, the effect of common shocks between cross-sectional units is minimized, and more accurate results are obtained. The [84] estimator, unlike classical panel data estimation methods, provides robust standard errors that correct heteroskedasticity, serial correlation, and cross-sectional dependency, making it possible to obtain reliable estimations. The selection of these methods was influenced by the fact that the cross-sectional dimension is smaller than the time dimension, and the heterogeneous structure is taken into account [85].The mathematical formulas related to the SUR model used in this study are shown in Equations (16)–(19), and the calculation process of long-term coefficients is detailed through these equations.

$$\begin{aligned} y_1 &= x_1\beta_1 + u_1 \\ y_2 &= x_2\beta_2 + u_2 \\ \vdots \quad & \quad \vdots \quad \vdots \\ y_M &= x_M\beta_M + u_M \end{aligned} \tag{16}$$

$$\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_M \end{bmatrix} = \begin{bmatrix} X_1 & 0 & \dots & 0 \\ 0 & X_2 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & X_M \end{bmatrix} + \begin{bmatrix} \beta_1 \\ \beta_2 \\ \vdots \\ \beta_M \end{bmatrix} + \begin{bmatrix} u_1 \\ u_2 \\ \vdots \\ u_M \end{bmatrix} \tag{17}$$

$$\sum = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \dots & \sigma_{1M} \\ \sigma_{21} & \sigma_{22} & \dots & \sigma_{2M} \\ \vdots & \vdots & \ddots & \vdots \\ \sigma_{M1} & \sigma_{M2} & \dots & \sigma_{MM} \end{bmatrix} \tag{18}$$

$$\hat{\beta} = \left[x'\Omega^{-1}x\right]^{-1}x'\Omega^{-1}y = \left[x'\left(\Sigma^{-1}\otimes I\right)x\right]^{-1}x'\left(\Sigma^{-1}\otimes I\right)y \tag{19}$$

In addition, the Panel-Corrected Standard Errors (PCSEs) method was also applied in this study. This method, developed by ref. [83], provides reliable standard error estimates by considering heteroskedasticity, serial correlation (autocorrelation), and inter-unit correlation in panel data sets. The PCSE method provides more robust results compared to the traditional Pooled Least Squares (Pooled OLS) estimator. Like the Driscoll–Kraay method, it increases the reliability of parameter estimates by correcting the structural dependency in the error terms. However, while the Driscoll–Kraay estimator handles the cross-sectional dependency with kernel-based corrections, the PCSE method provides reliable standard errors by directly modeling the covariance matrix of the error terms. The use of this method increases the accuracy of model estimates, especially when there are strong economic or structural connections between units. In this study, the calculation processes related to the PCSE method are given in Equations (20)–(22), and the robustness of the estimated parameters is evaluated through these equations.

$$y_{it} = x_{it}\beta + \varepsilon_{it} \tag{20}$$

$$\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_m \end{bmatrix} = \begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_m \end{bmatrix} \beta + \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_m \end{bmatrix} \tag{21}$$

$$\sum[\varepsilon\varepsilon'] = \Omega = \begin{bmatrix} \sigma_{11}I_{11} & \sigma_{12}I_{12} & \dots & \sigma_{1m}I_{1m} \\ \sigma_{21}I_{21} & \sigma_{22}I_{22} & \dots & \sigma_{2m}I_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ \sigma_{m1}I_{m1} & \sigma_{m2}I_{m2} & \dots & \sigma_{mm}I_{mm} \end{bmatrix} \tag{22}$$

In the last stage of the study, the panel causality test by ref. [84] was applied to analyze the causality relationship between the variables and was formulated as Equation (23). This test is a version of the traditional Granger causality test adapted to the panel data structure and provides reliable results by considering both heterogeneous slope coefficients and cross-sectional dependency. The Dumitrescu–Hurlin test allows us to obtain a common result for the entire panel while testing the causality relationship separately for each panel unit. In this method, while the dependent and independent variables are assumed to be stationary, it is accepted that the coefficients may differ between units but remain constant over time. In addition, it is assumed that the lag length in the model is the same for all panel units and that the data set is balanced. This method is especially widely used to determine the dynamic relationships between economic and environmental indicators.

$$y_{i,t} = \alpha_i + \sum_{k=1}^{K} \beta_{ik} y_{i,t-k} + \sum_{k=1}^{K} \gamma_{i,k} X_{i,t-k} + \varepsilon_{it} \quad (23)$$

4. Empirical Findings

In this section, empirical findings on the impact of technological innovation (TIN), digitalization (DIG), and information and communication technologies (ICTs) variables on trade-adjusted carbon emissions (TAEs) are presented. In the analysis process, firstly, the cross-sectional dependence between the variables was tested, then, the stationarity properties of the series were evaluated by applying unit root tests. In the last stage, the long- and short-term relationships between the variables were examined, and the empirical results obtained were detailed (Table 2).

Table 2. Descriptive statistics.

Variable(s)	Obs	Mean	Std.dev
TAE	390	9.28	3.38
ICT	390	884,754.01	25,334.05
TIN	390	31,528.29	75,568.8
DIG	390	81.08	12.19
GDP	390	38,565.13	16,851.1

The cross-sectional dependency test results in Tables 3 and 4 indicate the existence of a strong cross-sectional dependency both at the variable level and in the long-term models. All of the statistics obtained are significant and indicate that there is a high level of dependency between the units in the panel data set. This suggests that there are strong connections between the variables due to common economic shocks, global environmental policies, or similar technological development processes among countries. The existence of cross-sectional dependency reveals that traditional panel estimation methods (e.g., fixed- and random-effects models) may produce misleading results in the analysis and that methods that correct the dependency (e.g., [82], PCSE) should be preferred. In addition, the detection of similar dependency in the long-term models indicates that the long-term relationships between the variables have common effects among countries.

Table 3. CDS test results for variables.

Variables	TAE	TIN	DIG	ICT	GDP
Breusch–Pagan LM	205.15 *	150.85 *	589.31 *	320.18 *	108.20 *
Pesaran scaled LM	15.74 *	6.89 *	95.85 *	25.12 *	4.85 *
Bias-corrected scaled LM	18.17 *	15.08 *	75.52 *	23.85 *	8.87 *
Pesaran CD	5.05 *	6.27 *	14.25 *	7.75 *	8.21 *

Note: * denotes significance at the %1 level.

Table 4. CSD test results for long-run models.

Tests	Model
LM	30.15 *
LM adj *	19.85 *
LM CD *	6.22 *

Note: * denotes significance at the %1 level.

The slope homogeneity test results presented in Table 5 show that the slope coefficients in the model are not homogeneous. In the analysis conducted using the HAC-based delta tests developed by ref. [76], it is understood that there is no homogeneous structure among the variables. This situation shows that the economic, technological, and environmental dynamics of the countries are different from each other and that uniform (homogeneous) panel estimation methods may produce misleading results. Therefore, it is necessary to use panel estimation methods that take heterogeneity into account in this study.

Table 5. Slope homogeneity test results.

	Model
$\widetilde{\Delta}$	4.54 *
$\widetilde{\Delta}$adj	4.01 *

Note: * denotes significance at the %1 level.

The CADF and CIPS unit root test results presented in Table 6 evaluate the stationarity levels of the variables. The results show that all variables are not stationary at level (I(0)) but become stationary when their first differences are taken (I(1)). In other words, it is seen that the variables contain a unit root at the level but become stationary when their differences are taken. In particular, the fact that the test statistics become significant at a 1% significance level for all variables when their first differences are taken confirms that the series has an I(1) process.

Table 6. CADF and CIPS unit root test results.

Variables	**CADF**		**CIPS**	
	I(0)	I(1)	I(0)	I(1)
TAE	−1.17	−3.21 *	−1.38	−5.29 *
TIN	−0.79	−2.74 *	−0.85	−4.18 *
DIG	−1.13	−3.14 *	−1.25 *	−5.19 *
ICT	−1.02	−2.98 *	−1.13	−4.87 *
GDP	−0.78	−2.58 *	−0.85 *	−4.19 *

Note: * denotes significance at the %1 level.

The cointegration test results presented in Tables 7 and 8 were conducted to evaluate whether there is a long-term relationship between the variables in the model. The statistically significant results obtained in all Pedroni, Kao, and Westerlund cointegration tests (1% significance level) indicate that there is a strong long-term balance relationship between the variables. In the Pedroni test, the Modified Phillips–Perron, Phillips–Perron, and Augmented Dickey–Fuller (ADF) t-statistics are negative and significant, which indicates that the variables move together and are in balance in the long term. Similarly, the Dickey–Fuller and Augmented Dickey–Fuller tests in the Kao test also confirm the cointegration relationship. The significant Variance Ratio statistic obtained in the Westerlund test also supports the existence of a long-term relationship between the variables. In addition, [81] error correction model (ECM) test results presented in Table 8 evaluate the short-term dynamics as well as the long-term cointegration relationship and are statistically significant. These results reveal that the variables used in the model act interdependently and that factors such as economic growth, technological innovation, digitalization, and ICTs have long-term effects on trade-adjusted carbon emissions. Therefore, it is seen that the model used in this study is theoretically consistent and allows long-term analyses.

Table 7. Pedroni, Kao, and Westerlund cointegration test results.

Testler	Statistic
Pedroni	
Modified Phillips–Perron t	−7.24 *
Phillips–Perron t	−8.08 *
Augmented Dickey–Fuller t	−8.49 *
Kao	
Modified Dickey–Fuller t	−8.74 *
Dickey–Fuller t	−9.22 *
Augmented Dickey–Fuller t	−7.28 *
Unadjusted modified Dickey–Fuller t	−11.29 *
Unadjusted Dickey–Fuller t	−10.07 *
Westerlund	
Variance Ratio	−2.86 *

Note: * denotes significance at the %1 level.

Table 8. Westerlund (2007) [79] ECM test results.

Statistic	Value	Z-Value
G_t	−5.49	−5.85 *
G_a	−13.07	−6.75 *
P_t	−12.69	−7.19 *
P_a	−13.18	−6.24 *

Note: * denotes significance at the %1 level.

The long-term estimator results in Table 9 show the coefficients obtained with different econometric methods and their statistical significance. The results provide important findings in terms of evaluating the long-term effects of the determined independent variables. This study utilized annual data for the period 1997–2022 for the 15 countries with the highest carbon emissions in the world.

Table 9. Long-run estimator results.

Variables	SUR	PCSE	D-K
	Coefficients	Coefficients	Coefficients
TIN	0.18 *	0.16 *	0.20 *
DIG	0.12 *	0.09 *	0.14 *
ICT	0.14 *	0.13 *	0.16 *
GDP	1.21 *	1.09 *	1.65 *
Constant	−1.17 *	−1.98 *	−1.08 *
Wald χ^2	171.96	179.51	189.55
R^2	0.395	0.387	0.391
p-value	0.000	0.000	0.000
Observation		390	
Number of countries		15	

Note: * denotes significance at the %1 level.

The technological innovation (TIN) variable was found to be positive and statistically significant in all estimation methods. This shows that technological innovation has an increasing effect on trade-based carbon emissions. It is thought that technological innovations do not always have a positive result in terms of environmental sustainability; on the contrary, some innovations may cause more energy consumption by accelerating production processes and thus increase trade-based carbon emissions. Our findings are similar to studies such as refs. [1,2,13] in terms of showing that technological innovation harms environmental quality. The [1] study showed that technological innovation has the potential to limit trade-based carbon emissions, but this effect varies depending on sectors and countries' energy policies. Ref. [2] revealed that technological innovation is more effective in reducing trade-based carbon emissions when evaluated together with energy efficiency. Ref. [13] showed that environmental taxes and energy efficiency, when combined with technological innovation, contribute to the reduction of trade-based carbon emissions. Apart from these studies, it is similar to studies such as [6,7,12,85,86] in terms of showing that technological innovation harms environmental quality. Ref. [7] emphasized that technological innovation can increase carbon emission intensity in the context of Saudi Arabia and that technological progress can cause environmental degradation when not supported by sustainable development strategies. Ref. [85] shows that technological innovation can create more emissions, especially in energy-intensive sectors. Ref. [86] showed that, in certain cases, technological progress can result in higher energy consumption, which can increase carbon emissions. Similarly, ref. [12] showed that technological innovation in China can have an emission-increasing effect in the short term. Finally, ref. [73] emphasized that technological innovation beyond a certain threshold value can increase carbon emissions, and therefore, innovation policies should be compatible with environmental sustainability. These studies provide important evidence that technological innovation does not always have a carbon emission-reducing effect. It is seen that technological innovation can lead to environmental destruction by increasing industrial production, especially in energy-intensive sectors and fossil fuel-dependent economies. In this context, our findings largely overlap with studies in the literature indicating the negative environmental impacts of technological innovation.

There is a positive and significant relationship between the digitalization (DIG) variable and trade-based carbon emissions. Although the impact of digitalization on trade-based carbon emissions is relatively low, the positive relationship indicates that energy consumption increases with the expansion of digital infrastructure. In particular, the increase in data centers, the widespread use of energy-intensive technological devices, and the expansion of internet access can be considered as factors that increase carbon emissions. Studies supporting the increasing effects of digitalization on carbon emissions show that digital transformation can increase energy consumption. Ref. [34] found that digitalization in China has an inverted U-shaped effect, initially increasing emissions but decreasing them in later stages. Refs. [3,87] showed that digitalization in the manufacturing sector and trade can increase carbon emissions. Similarly, ref. [14] showed that the digital economy in China increases carbon intensity, while ref. [25] showed that digitalization in the agricultural sector increases energy consumption and carbon emissions. Ref. [74] provided evidence that smart cities increase carbon emissions through digitalization. These studies show that digitalization may increase carbon emissions rather than reduce them without a sustainable energy infrastructure.

The positive and statistically significant relationship between the information and communication technologies (ICTs) variable and trade-adjusted carbon emissions (TACEs) indicates that ICT use may have increasing effects on carbon emissions. There are several possible reasons why ICTs increase trade-adjusted carbon emissions. First of all, the digitalization process requires high energy demand as it requires energy-intensive data centers, cloud computing technologies, and large-scale network infrastructures. Since a large part of this energy demand is still provided by fossil fuels, it causes increased carbon emissions. The finding of a positive relationship between ICTs and environmental quality in our study is parallel to some previous studies. Ref. [48] showed that ICT use may increase carbon emissions and that this effect may vary across countries. Ref. [45] emphasized that ICTs may negatively affect environmental quality in Sub-Saharan Africa and that this situation is associated with energy consumption and economic growth. Ref. [58] stated that ICTs and digital technologies can increase environmental pressure by increasing the carbon footprint. Ref. [47] showed that ICTs in China increase carbon emissions on a sectoral basis and can create negative environmental impacts, especially in high-energy sectors. Ref. [46] found that ICTs can play a role in increasing carbon emissions when evaluated together with financial development and energy consumption. Ref. [53] showed that ICTs in BRICS countries can harm the environment in energy-intensive industries and increase carbon emissions without renewable energy investments. These studies provide important evidence that ICTs can negatively affect environmental quality and increase carbon emissions in some cases.

A positive and significant effect between the gross domestic product (GDP) variable and TAEs in all methods was shown. It shows that economic growth has an increasing effect on carbon emissions. Since economic growth brings about an increase in industrialization and energy demand, it causes carbon emissions to increase. The results emphasize that growth policies should be shaped with a green economy perspective in order to ensure environmental sustainability. Studies finding a positive relationship between economic growth and environmental quality show that growth can promote environmental sustainability and reduce carbon emissions. Ref. [18] revealed that financial development and renewable energy consumption can improve environmental quality when considered together with economic growth. Ref. [68] showed that hydroelectric production and financial development are effective in reducing carbon emissions during the economic growth process. Refs. [59,67] argued that carbon trading and renewable energy investments increase environmental quality together with economic growth. Ref. [69] showed that when China's foreign direct investments are integrated with environmentally friendly policies, growth has a reducing effect on carbon emissions. Refs. [70,87] emphasized that economic growth can support sustainable development rather than harming the environment when supported by environmental policies. These studies show that economic growth can improve environmental quality with the right energy policies and sustainable financial regulations (Table 10).

Table 10. Dumitrescu–Hurlin panel causality test results.

	W-bar	Z-bar	p
$TAE \nrightarrow TIN$	0.75	0.92	0.753
$TIN \nrightarrow TAE$	2.95	4.87	**0.000**
$TAE \nrightarrow DIG$	0.52	0.67	0.855
$DIG \nrightarrow TAE$	2.74	3.29	**0.002**
$TAE \nrightarrow ICT$	1.08	1.22	0.195
$ICT \nrightarrow TAE$	3.08	5.19	**0.000**
$TAE \nrightarrow GDP$	2.08	2.47	**0.038**
$GDP \nrightarrow TAE$	3.28	5.84	**0.000**

Note: The maximum lag length is taken as 1.

According to the Dumitrescu–Hurlin panel causality test results, there is a one-way causality relationship from the variables of technological innovation (TIN), digitalization (DIG), and information and communication technologies (ICTs) to trade-based carbon emissions (TAEs). This finding shows that technological developments and digitalization play a determining role in carbon emissions. In particular, the effects of technological innovation changing industrial production processes and energy consumption models, and digitalization transforming business practices and increasing or decreasing energy demand, can determine the direction of carbon emissions. However, the fact that carbon emissions do not have a direct effect on these variables reveals that environmental factors are not a determining factor of technological progress or digital transformation.

On the other hand, there is a bidirectional causality relationship between economic growth (GDP) and trade-based carbon emissions (TAEs). This result shows that increasing economic activities can increase carbon emissions, but at the same time, emission levels can affect economic growth. In particular, elements such as environmental regulations, carbon taxes and sustainable development policies can determine the impact of carbon emissions on economic growth. In general, these results reveal that technological developments and digital transformation shape environmental sustainability, but economic growth is both affected by carbon emissions and directly drives them.

5. Discussion and Conclusions

This study analyzes the impact of technological innovation, digitalization, and information and communication technologies (ICTs) on trade-adjusted carbon emissions (TAEs) in the world's 15 highest carbon-emitting countries. At the same time, the driving role of economic growth in this process is examined in detail. Trade-adjusted carbon emissions go beyond traditional emission measurements to take into account the impact of international trade on carbon emissions and more accurately reflect the real environmental responsibility of countries. The results of this study show how trade and economic growth can affect carbon emissions in these highest-emitting countries and how technology-oriented policies should be directed in terms of sustainable development.

The findings suggest that technological innovation may contribute to increased trade-related carbon emissions, especially in countries with intensive industrial activity. In economies characterized by substantial manufacturing output, such as several upper-middle and high-income countries, technological advancement can accelerate industrial processes and drive up energy demand. In some developed economies, shifts in carbon-intensive production activities to countries with less stringent environmental regulations may result in a decrease in local emissions but contribute to continued trade-related emissions. This underscores the importance of evaluating the environmental impacts of trade not only on a national scale but also within the global value chain context.

The analysis also points to the potential environmental consequences of digitalization and increased ICT use. In countries with expanding digital infrastructure, large-scale investments in data centers and rising cloud computing demand may lead to higher energy consumption and related emissions. However, this effect may vary significantly depending on the energy mix used in digital infrastructure. In industrial economies, the integration of digital tools into production processes can lead to efficiency gains but may simultaneously raise energy consumption. Notably, the long-term environmental benefits of digitalization are more likely when it is accompanied by clean energy transition policies.

This study highlights a robust positive association between economic growth and trade-adjusted carbon emissions. Particularly in rapidly growing economies, economic expansion is often accompanied by increased industrial output and energy use, which can drive up emissions. Conversely, in some high-income countries, outward shifts in production may result in the relocation rather than the reduction of emissions. For economies with significant fossil fuel export activities, the contribution of energy trade to trade-adjusted emissions should not be overlooked.

In light of these results, it is recommended that countries consider restructuring their trade and production strategies in alignment with environmental sustainability objectives. For economies experiencing fast industrial growth, promoting green production technologies, encouraging renewable energy adoption, and reducing the carbon intensity of industrial sectors can be key strategies. For advanced economies, reinforcing sustainable trade policies and implementing carbon border adjustment mechanisms may enhance accountability for outsourced emissions. In resource-exporting economies, diversifying energy sources and supporting investment in renewable energy could help mitigate environmental risks. Overall, the strengthening of carbon pricing instruments and the development of broader international carbon trading frameworks remain essential to achieving global emissions reduction targets.

This study has certain limitations. Firstly, the analysis is limited to the 15 countries with the highest carbon emissions, which may restrict the generalizability of the findings on a global scale. Additionally, data limitations and structural differences in the measurement of key variables—particularly those related to digitalization and ICTs—may introduce some degree of uncertainty in cross-country comparisons. In terms of future studies, it should be examined in which sectors, and under which conditions, the impact of technological innovation on carbon emissions is more pronounced. In addition, it should be investigated whether digitalization has a long-term carbon emission reduction effect and how the digital transformation process can be integrated with different energy sources. New studies should be conducted on how carbon emissions are spread among different regional trading blocks and how the environmental impacts of international trade can be measured more fairly. Finally, it should be determined in which countries and in which sectors carbon emission reduction policies are more effective, and how trade policies can be integrated with environmental sustainability should be addressed in more detail.

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