Environmental Research Communications

CrossMark

OPEN ACCESS

RECEIVED
22 November 2024

REVISED
13 January 2025

ACCEPTED FOR PUBLICATION
20 January 2025

PUBLISHED
3 February 2025

PAPER

Is export diversification detrimental to environmental quality? An examination of the roles of green innovation and environmental taxation

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Keywords: export diversification, green innovation, environmental tax, economic growth, environmental quality

Abstract

The primary objective of this study is to assess the environmental impact of various factors, including export diversification and GDP, as well as elements believed to facilitate this assessment process, such as green innovation and environmental taxes. The study aims to identify factors that contribute to the reduction of CO_2 emissions. It analyzes data from 21 European Union (EU) member states for the period from 1995 to 2020, employing the FFFFF panel cointegration test. The findings indicate that export diversification (EXD), environmental taxes (ET), and economic growth (GDP) have a positive effect on CO_2 emissions, whereas green innovation (GI) and GDP squared (GDP2) exert a negative influence. These results indicate that export diversification is detrimental to environmental quality. Another significant finding of the study is the validation of the Environmental Kuznets Curve (EKC) hypothesis. Finally, one of the most critical conclusions of the study is the negative impact of green innovation on the volume of CO_2 emissions.

1. Introduction

One of the most pressing issues facing the world today is the escalating environmental and climate degradation. To address this challenge and enhance environmental quality, the United Nations has introduced the Sustainable Development Goals, the Framework Convention on Climate Change, and the Paris Climate Agreement (Fareed *et al* 2021, Pişkin 2023, Wang *et al* 2020, Ali *et al* 2022b). These international initiatives have raised awareness about the destruction of the environment and climate change, prompting academics to identify the underlying factors contributing to these issues and to develop and implement effective policies.

In early studies, factors contributing to environmental degradation were primarily associated with economic growth-related issues, including the increased use of fossil fuels, urbanization, industrialization, technology, foreign direct investment, financial development, population growth, tourism, industrial structure, and trade openness (Can *et al* 2020, Fareed *et al* 2021, Li *et al* 2021, Sultana *et al* 2022a, 2022b). While the relationship between trade and the environment was initially examined through the lens of trade openness and environmental destruction, the connection between trade diversity and environmental degradation remained overlooked until the late 20th century (Shi *et al* 2023). Since the early 21st century, both developed and developing countries have increasingly adopted various policies aimed at leveraging international trade to support economic and environmental stability and increase their resilience to macroeconomic shocks. In this context, the World Bank (2019) and the International Monetary Fund (2020) have encouraged countries to adopt export diversification and trade openness policies to reduce dependence on specific types of exports and facilitate long-term income generation (Udeagha and Ngepah 2023, Liu *et al* 2024).

To enhance the contextual clarity of this study, it is important to map prior knowledge from previous studies and highlight the novelty of the present research. While earlier studies have provided significant insights into the relationship between trade openness and environmental quality, the exploration of export diversification as a determinant of environmental quality remains limited. Furthermore, existing research often neglects the simultaneous impact of green innovation and environmental taxes in conjunction with export diversification. This study seeks to address these gaps by examining these factors collectively within the framework of the Environmental Kuznets Curve (EKC) hypothesis, thereby providing a more comprehensive understanding of their interrelations.

Export diversification, which means adding new products to a country's existing export basket or increasing export volumes by expanding into new markets, allows developing countries to increase productivity, reduce risks in international trade and support macroeconomic stability and economic growth. Beyond these economic gains, export diversification is also expected to have an impact on environmental quality. However, the extent of this impact may vary depending on factors such as the level of development of the country and the nature of the energy resources used in production. Especially in underdeveloped and developing countries, export diversification may increase the production of traditional products, which often require high energy consumption and are not technologically advanced. This can lead to higher CO_2 emissions and accelerated environmental degradation as a result of increased dependence on fossil fuels. Conversely, in developed countries, export diversification tends to promote the production of innovative and sophisticated products that are associated with lower energy intensity, potentially benefiting environmental quality (Can *et al* 2020, Ali *et al* 2022b, Shi *et al* 2023, Udeagha and Ngepah 2023). Consequently, the relationship between export diversification and environmental quality remains ambiguous.

The primary objective of this study is to assess the potential effects of export diversification, green innovation, and environmental taxes on environmental quality in 21 EU member countries from 1995 to 2020. Specifically, this study aims to identify factors that contribute to the reduction of CO_2 emissions and to evaluate the combined impact of these variables, which have not been addressed simultaneously in the existing literature. By employing a novel dataset and advanced econometric techniques, this research provides critical insights into the interplay between economic policies and environmental outcomes, highlighting the urgency and importance of sustainable development initiatives.

In today's economic environment, where trade openness and export diversification have gained priority, assessing the impact of export diversification on environmental quality has become more important than ever. It is critical to accurately analyze the relationship between export diversification and environmental quality and to identify policy options based on this relationship. If negative effects of export diversification on environmental quality are identified, policy instruments such as green innovation and environmental taxation can provide effective solutions to mitigate these effects. Such policies can contribute to both minimizing environmental damage and improving overall environmental quality.

Green innovation is defined as hardware or software innovations and corporate environmental management practices related to green products or processes that conserve energy by minimizing reliance on energy-intensive sources (particularly fossil fuels), reducing environmental pollution, increasing waste recycling, and promoting green product design (Chen *et al* 2006). Research examining the relationship between green innovation and environmental outcomes is categorized into two groups. The first group posits that green innovation enhances environmental quality by improving resource efficiency and conserving energy through the substitution of non-renewable energy sources with renewable options. Conversely, the second group contends that green innovation may not significantly impact the environment and could even have adverse effects on environmental quality. This phenomenon manifests differently across countries at varying stages of development. In developed nations, where levels of human capital and green innovation are high, the impact on environmental quality tends to be positive. In contrast, in underdeveloped and developing countries, where levels of human and physical capital and green innovation are lower, the potential for significant positive impacts on environmental quality is limited (Yu and Guo 2023).

In addition to green innovation, another important tool used to reduce the environmental impacts of the industrial sector, improve environmental quality and promote sustainability is environmental taxes, with carbon taxes being particularly prominent. Environmental taxes can increase companies' production costs and encourage a shift towards cleaner production technologies and renewable energy sources. However, the high level of these taxes may in some cases have the opposite effect, negatively affecting investments in these technologies and indirectly weakening environmental quality. Therefore, it is crucial to adopt a balanced approach in the design and implementation of environmental taxes. However, despite this potential drawback, environmental taxes can also positively influence environmental quality by encouraging the cessation of detrimental practices and the replacement of outdated, polluting technologies with more efficient alternatives (Farooq *et al* 2023, Akdag *et al* 2024).

Against this backdrop, the objective of this study is to investigate the potential effects of export diversification, green innovation, and environmental taxes on environmental quality in 21 EU member countries from 1995 to 2020. This study contributes to the existing literature in several significant ways. First, the export diversification index data utilized in this study are noteworthy. While the export diversification index calculated by the IMF covers the period from 1962 to 2014, the majority of existing studies do not incorporate data beyond 2014. To address this gap and utilize more current data, we have re-calculated the export diversification index following the IMF methodology, now including data up to 2020. This enhancement EXDends the temporal dimension of the literature significantly. Another important aspect of this study is its focus. Previous research has typically examined the effects of export diversification, green innovation, and environmental taxes on the environment separately; however, no studies have analyzed the combined effects of these variables . Consequently, this study is expected to make a substantial contribution to this underexplored area of the literature. Lastly, the econometric method employed in this study adds to its significance. A review of the existing literature indicates a prevalent use of panel data analysis. While this study will also utilize panel data analysis, it distinguishes itself by employing Panel Fourier tests. These tests represent the most advanced approach available, minimizing the margin of error in comparison to standard panel data analysis methods.

This study's significance lies in its ability to integrate these three critical factors—export diversification, green innovation, and environmental taxes—within a unified analytical framework. This action not only advances the theoretical understanding of their collective impact on environmental quality but also provides actionable insights for policymakers aiming to achieve sustainable economic growth. The urgency of addressing climate change and environmental degradation underscores the relevance of this research.

The remainder of the study is organized as follows. The second part includes a review of empirical studies addressing the index of export diversification, green innovation, and environmental taxation, in relation to the environment. The third part discusses the data and describes the econometric techniques employed. Preliminary and main empirical results are presented and discussed in the fourth part. Finally, the fifth part concludes the study with key findings and policy implications.

2. Literature review

2.1. Export diversification-environment relationship

Data on export diversification is provided by the IMF. It is the numerical expression of how products and services exported by countries differ from those of the world in general. A high level of export diversification increases the competitiveness of countries and contributes to achieving the sustainable economic growth target . Increasing export diversification leads to variations in production processes. For this reason, each modification in the production process has the potential to either benefit or harm the environment.

The relationship between export diversification and the environment has been analyzed using variables such as CO_2 emissions, ecological footprint, and load capacity factor, which are commonly referenced in the literature as indicators of environmental impact. The findings of various studies present contrasting conclusions: some indicate that export product diversification exacerbates environmental damage by negatively affecting environmental quality, while others suggest that it mitigates environmental damage by enhancing environmental quality.

One of the first studies to reveal a negative relationship between export diversification and environmental quality was conducted by Gozgor and Can (2016). This study, which analyzed the impact of export product diversification on CO_2 emissions in Turkey, showed that an increase in export product diversification is associated with an increase in CO_2 emissions, which negatively affects environmental quality. Wang *et al* (2020) examined the relationship between export diversification and CO_2 emissions in G-7 countries and found that export diversification leads to an increase in CO_2 emissions. Similarly, a study by Can *et al* (2020) revealed that product diversification in exports from developing countries accelerates environmental degradation by increasing CO_2 emissions. Mania (2020) identified a positive relationship between export diversification and the rise in CO_2 emissions across 98 nations, encompassing both developed and developing economies. Similarly, Liu *et al* (2018) examined how export product diversification influences the ecological footprint in Korea, Japan, and China. They observed that an increase in export product diversification results in environmental degradation through the expansion of the ecological footprint. Udeagha and Ngepah (2023) investigated the relationship between export diversification and the environment in OECD economies, revealing that export diversification exacerbates environmental damage.

Udemba *et al* (2023) examined the effects of export diversification in the context of China's sustainable development and found that export diversification has negative impacts on the environment. Jiang *et al* (2022) analyzed the relationship between export diversification index and environmental degradation across 96 countries and concluded that export product diversification contributes to environmental damage by increasing pressures on ecological footprint. Iqbal *et al* (2021) investigated the link between export diversification and CO_2 emissions in OECD countries and found that export diversification leads to deterioration of environmental quality by increasing CO_2 emissions. Similarly, Saboori *et al* (2022) found that increased export diversification in Oman increases CO_2 emissions and leads to environmental degradation by expanding the ecological footprint.

Udeagha and Muchapondwa (2023) investigated how export diversification interacts with environmental outcomes within the framework of regional sustainability and carbon neutrality objectives in BRICS economies. Their findings suggest that export diversification exacerbates environmental degradation. Similarly, Liu *et al* (2024) analyzed the effects of export diversification on environmental performance in the context of the United Arab Emirates' sustainable development efforts, concluding that it adversely affects the environment by driving up carbon emissions.

Onwe *et al* (2024) examined the impact of export diversification on rebuilding a sustainable environment in India and found that export diversification poses a threat to environmental sustainability by negatively affecting the load capacity factor in both the short and long run. Rahman *et al* (2023) found a negative relationship between export concentration and economic growth in Bangladesh and revealed that export concentration has a negative impact on environmental quality by increasing CO_2 emissions.

In light of these findings, this study highlights the critical role of export diversification in influencing environmental quality. This approach not only synthesizes prior results but also bridges gaps by analyzing both positive and negative impacts across different contexts.

Fareed *et al* (2021) analyzed the connection between export diversification and load capacity in Indonesia, revealing that export diversification enhances environmental quality by improving the load capacity factor. Tekbas (2022) analyzed the impact of export diversification on CO_2 emissions in transition economies ('Albania, Armenia, Azerbaijan, Belarus, Bosnia and Herzegovina, Georgia, Kazakhstan, Moldova, North Macedonia, Russia, Ukraine, and Uzbekistan'), concluding that export diversification reduces CO_2 emissions. Similarly, Haq *et al* (2022) found that export diversification in Pakistan limits environmental degradation by reducing CO_2 emissions in the short run, although it does not have a significant impact on the environment in the long run.

In another study, Shi *et al* (2023) analyzed the relationship between export product diversification and CO_2 emissions in China and its regions and concluded that an increase in export product diversification improves environmental quality by reducing CO_2 emissions. Similarly, Sharma *et al* (2021) examined the impact of export diversification on air quality in BRICS countries and found that a less diversified export structure negatively affects air quality. Ali *et al* (2022b) investigated the connection between export diversification and the ecological footprint in India, determining that export diversification mitigates environmental degradation by lowering the ecological footprint. These findings underscore the dual nature of export diversification's impact on the environment, emphasizing the need for tailored policy interventions.

2.2. Green innovation-environment relationship

Green innovation, also known as eco-innovation, is the measurement of environmental improvements driven by technological innovation in production processes. The growth of the Green Innovation Index indicates that countries are implementing more environmentally friendly production processes. Therefore, there is a close relationship between green innovation and the environment.

Although the history of research on the relationship between green innovation and the environment is relatively recent, there has been a significant increase in studies in this area . A review of the literature indicates that green innovation has a positive impact on environmental quality and sustainability by mitigating environmental harm.

One of the pioneering studies demonstrating a positive relationship between green or environmental innovation and environmental outcomes is by Carrio´n-Flores and Innes (2010). They investigated the impact of green innovations on toxic emissions across 127 manufacturing industries in the USA, concluding that such innovations lead to a reduction in toxic emissions. Ghisetti and Quatraro (2017) explored the relationship between green technologies and environmental efficiency in various Italian regions, finding that green technologies enhance environmental efficiency. Zeng and Li (2020) examined the effects of green innovations on environmental pollution in China, revealing that these innovations have a mitigating effect on pollution, albeit to a limited EXDent, due to the insufficient maturity of green innovations in the country. Khan *et al* (2020) tested the correlation between CO_2 emissions and green innovations in G7 nations, asserting that green innovations contribute to the reduction of CO_2 emissions. Similarly, Chien *et al* (2021) investigated the relationship between ecological innovations and CO_2 emissions in the USA, concluding that ecological innovations are negatively correlated with CO_2 emissions. Likewise, Jin *et al* (2022) identified a negative relationship between ecological innovations and CO_2 emissions in China.

Wen *et al* (2022) analyzed the relationship between green innovation and environmental quality in five South Asian economies and found that green innovations improve environmental quality. Bhutta *et al* (2022) found that green innovations have positive impacts on environmental quality and sustainability in Pakistan. Ali *et al* (2022a) and Udeagha and Muchapondwa (2022b), in their studies on the relationship between green innovation and environmental quality in BRICS economies, emphasized that green innovations play an important role in reducing CO_2 emissions. Similarly, Geng *et al* (2023) found that green innovations in BRICS economies improve environmental quality by decreasing the ecological footprint once a specific threshold value is attained. Koseoglu *et al* (2022) investigated the impact of green innovations on the ecological footprint in the top 20 innovative countries, concluding that a 1% increase in environment-related technologies results in a 0.129% decrease in the ecological footprint.

This study builds on these insights by incorporating green innovation as a critical determinant of environmental quality. The findings are expected to offer actionable implications for policymakers, especially in regions with varying levels of green technology adoption.

2.3. Environmental tax-environment relationship

In examining the relationship between environmental tax and the environment, it is evident that this area of study does not have a long-established history, unlike research on green innovation and its environmental impacts. However, there has been a noticeable increase in studies within this field in recent years. The majority of research indicates that environmental taxes have a positive effect on the environment, while a minority suggests a negative impact.

One of the seminal studies advocating that environmental taxes positively impact the environment was conducted by Morley (2012). In this study, Morley examined the relationship between environmental taxes and pollution levels in EU countries and Norway, concluding that environmental taxes effectively reduce environmental pollution. Further, Miller and Vela (2013) investigated this relationship across 50 countries and found that nations generating higher revenue from environmental taxes tend to achieve greater reductions in CO_2 and PM10 emissions. Bashir *et al* (2020) assessed the impact of environmental taxes on CO_2 emissions within OECD countries, concluding that environmental taxes enhance environmental quality by lowering CO_2 emissions. Similarly, Roy and Dastidar (2021) explored the relationship between environmental taxes and air pollution in the UK, indicating that energy taxes contribute to reduced air pollution. Additionally, Chien *et al* (2021) examined this relationship in the USA, revealing that environmental taxes lead to decreased CO_2 emissions. Hieu (2022) also analyzed the correlation between environmental taxes and CO_2 emissions in ASEAN countries, affirming that environmental taxes result in lower CO_2 emissions.

Chen *et al* (2022) examined the effects of environmental taxes on ecological footprint in OECD and non-OECD economies. They conclude that environmental taxes improve environmental quality more significantly in OECD countries than in non-OECD countries. Ali *et al* (2023) analyzed the effects of environmental taxes on sustainability in five leading green economies and found that these taxes support environmental sustainability by reducing consumption-based CO_2 emissions. Sarpong *et al* (2023) explored the influence of environmental taxation on CO_2 emissions in the E7 economies (China, Turkey, India, Russia, Brazil, Indonesia, and Mexico) and concluded that environmental taxation contributes to a reduction in CO_2 emissions. Abel *et al* (2023) examined the relationship between carbon tax and CO_2 emissions in South Africa, finding that carbon tax has a mitigating effect on CO_2 emissions. Liu *et al* (2023) assessed the impact of environmental tax on environmental quality in OECD countries and concluded that environmental tax enhances environmental quality.

Akdag *et al* (2024) investigated the effect of environmental tax on greenhouse gas emissions in EU member countries, and concluded that environmental taxes enhance environmental quality by reducing greenhouse gas emissions, with an elasticity of 0.18. Farooq *et al* (2023) examined the relationship between environmental and corporate tax rates, and CO_2 emissions in ten industry-intensive economies, finding that environmental tax rates lead to a reduction in CO_2 emissions, while corporate tax rates contribute to an increase. Ben Youssef and Dahmani (2024) analyzed the relationship between environmental tax revenue and environmental quality in a sample of fifty low- and middle-income countries and thirty-eight high-income countries. Their findings indicate that environmental tax revenue is a critical factor in mitigating environmental degradation.

Although numerous studies have demonstrated the positive effects of environmental taxes , there is a limited body of research indicating that these taxes may have adverse impacts. One such study by Lin and Li (2011) examined the effect of carbon tax on CO_2 emissions in countries that were early adopters of this tax, including 'Denmark, Finland, Sweden, the Netherlands, and Norway'. They concluded that the carbon tax has led to an increase in CO_2 emissions in Norway. Similarly, Silajdzic and Mehic (2018) investigated the relationship between energy tax and CO_2 emissions in ten Central and Eastern European countries, revealing that energy tax correlates with an increase in CO_2 emissions.

This paper fills an understudied gap in the literature and integrates this basic knowledge into a broader framework by examining how environmental taxes interact with export diversification and green innovation to collectively affect environmental outcomes.

Table 1. Description of variables and data sources.

Symbol	Variable name	Measurement	Source
CO_2	CO_2 emissions	CO_2 emissions (metric tons per capita)	WDI
EXD	Export diversification	Index	IMF
GI	Green Innovation	Environmental related patents (% total patents)	OECD
ET	Environmental tax	Environmentally related tax revenue (% of the GDP)	OECD
GDP	Economic growth	GDP per capita (constant 2015 US$)	WDI
GDP2	Square of Economic growth	Square of GDP to check the EKC	—

2.3.1. Conclusion of the literature review

The above discussion emphasizes the multifaceted relationship between environmental quality and identified factors. A review of the literature shows that there is an ambiguous relationship between environmental quality and the identified factors. Therefore, more targeted research is needed to address the ongoing debate in the literature. By analyzing the synergistic effects of export diversification, green innovation, and environmental taxes, this study aims to provide a comprehensive understanding of their combined effects and offer valuable insights for both academic research and policy development.

3. Methodology

3.1. Data

The study utilizes secondary data from the World Bank's World Development Indicators (WDI), the International Monetary Fund (IMF), and the Organization for Economic Co-operation and Development (OECD) databases, covering the period from 1995 to 2020. The analysis includes 21 European Union (EU) member countries—namely, 'Austria, Belgium, Bulgaria, Croatia, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Luxembourg, Netherlands, Poland, Portugal, Slovak Republic, Slovenia, Spain, and Sweden'—where data are available. These countries were selected to investigate whether EU member states are fulfilling their greenhouse gas emission reduction commitments under the Kyoto Protocol and Paris Agreement through export diversification, green innovation, and environmental tax policies. Given that CO_2 emissions are one of the most significant greenhouse gases affecting the environment, they are included in the analysis as a dependent variable to represent environmental quality. The natural logarithms of the GDP and GDP^2 variables were computed and incorporated into the analysis. Table 1 presents the definitions of the variables included in the analysis and the sources from which they were obtained.

To analyze the impact of export diversification, green innovation, and environmental tax on environmental quality in EU countries, the model is constructed below in accordance with Rahman (2017) and Rahman (2020):

$$\mathrm{CO}_2 = f(\mathrm{EXD},\ \mathrm{GI},\ \mathrm{ET},\ \mathrm{GDP},\ \mathrm{GDP2}) \tag{1}$$

The econometric form of equation (1) can be written as follows:

$$\mathrm{CO}_{2\mathrm{it}} = \beta_0 + \beta_1\mathrm{EXD}_{\mathrm{it}} + \beta_2\mathrm{GI}_{\mathrm{it}} + \beta_3\mathrm{ET}_{\mathrm{it}} + \beta_4\mathrm{GDP}_{\mathrm{it}} + \beta_5\mathrm{GDP2}_{\mathrm{it}} + \varepsilon_{\mathrm{it}} \tag{2}$$

In this context, CO2 refers to the emissions used as a proxy for environmental quality. EXD denotes export diversification, GI signifies green innovation, ET represents environmental tax, and GDP indicates economic growth; while GDP^2 is the square of economic growth utilized to investigate the presence of the Environmental Kuznets Curve (EKC). Additionally, β represents the estimated coefficients of the independent variables, and ε is the error term. The indices i and t correspond to 21 EU countries and cross-sections, respectively, covering the analysis period from 1995 to 2020.

Table 2 provides an overview of the descriptive statistics for all variables incorporated into the analysis.

An analysis of the CO_2 emissions values reveals that the countries with the highest averages are Luxembourg, Czech Republic, and Finland, in that order. For the Government Integrity (GI) variable, the leading countries are Denmark, Bulgaria, and Luxembourg. In terms of GDP, the ranking is as follows: Luxembourg, Denmark, and Ireland. Regarding the Environmental Technology (ET) variable, the top three countries are Denmark, Slovenia, and Croatia. Finally, when examining the average values of the Environmental Expenditure (EXD) variable, the countries with the highest averages are Hungary, Ireland, and the Czech Republic.

3.2. Data analysis

Within the scope of this study, the Export Diversification Index was initially calculated based on the relevant variables. The calculation methodology utilized was an adaptation of the formulation originally defined by Herfindahl (1950) and named in his honor (Peñasco *et al* 2021, Lee and Zhang 2022, Herwald *et al* 2024).

Table 2. Descriptive statistics.

Country		CO_2	EXD	GI	ET	GDP	GDP2	Country		CO_2	EXD	GI	ET	GDP	GDP2
Austria	Mean	8.03	21.32	4.62	2.50	3.19	12.33	Ireland	Mean	9.37	21.94	4.68	2.32	3.48	6.50
	Median	8.00	21.47	4.63	2.50	3.18	12.40		Median	9.42	21.80	4.67	2.41	3.45	6.65
	Maximum	9.28	21.80	4.67	2.83	3.31	15.80		Maximum	11.59	24.01	4.90	2.99	3.83	10.60
	Minimum	6.63	20.51	4.53	2.05	3.09	8.80		Minimum	6.77	19.80	4.45	1.18	3.05	2.40
	Std. Dev.	0.70	0.37	0.04	0.18	0.07	2.09		Std. Dev.	1.52	1.07	0.11	0.48	0.19	1.82
	JB	0.55	3.14	3.20	0.80	1.74	1.22		JB	2.42	0.08	0.04	2.20	0.74	0.10
Belgium	Mean	9.82	20.98	4.58	1.85	2.94	8.82	Italy	Mean	6.83	20.25	4.50	3.18	3.12	8.72
	Median	9.89	21.12	4.60	1.79	2.95	9.10		Median	7.28	20.25	4.50	3.20	3.12	9.65
	Maximum	11.76	21.48	4.63	2.28	3.04	12.20		Maximum	8.19	20.54	4.53	3.60	3.24	12.20
	Minimum	7.40	20.21	4.50	1.56	2.82	5.20		Minimum	4.73	19.95	4.47	2.58	3.00	5.10
	Std. Dev.	1.42	0.36	0.04	0.22	0.06	2.16		Std. Dev.	1.09	0.18	0.02	0.30	0.07	2.44
	JB	2.47	2.91	2.97	2.13	1.31	1.87		JB	2.60	1.49	1.49	1.98	1.58	2.66
Bulgaria	Mean	6.04	14.04	3.74	2.57	2.75	13.87	Luxembourg	Mean	19.77	24.94	4.99	2.38	3.29	13.02
	Median	6.12	14.37	3.79	2.80	2.73	15.45		Median	20.40	25.20	5.02	2.52	3.30	12.15
	Maximum	6.97	15.33	3.92	3.28	2.89	25.10		Maximum	25.61	25.51	5.05	3.00	3.45	19.90
	Minimum	4.92	12.60	3.55	0.81	2.67	3.10		Minimum	12.46	23.76	4.87	1.40	3.17	7.40
	Std. Dev.	0.49	0.90	0.12	0.63	0.07	5.49		Std. Dev.	3.45	0.52	0.05	0.48	0.07	3.08
	JB	0.33	2.42	2.46	15.21	2.63	0.87		JB	0.70	6.94	7.09	2.31	0.41	0.76
Croatia	Mean	4.30	16.33	4.04	3.55	2.81	9.37	Netherlands	Mean	9.82	21.42	4.63	3.46	2.80	8.90
	Median	4.10	16.55	4.07	3.62	2.83	9.35		Median	10.05	21.57	4.64	3.46	2.79	9.50
	Maximum	5.31	17.25	4.15	4.14	2.93	20.60		Maximum	11.18	21.95	4.69	3.70	2.99	12.30
	Minimum	3.34	14.93	3.86	2.50	2.69	2.60		Minimum	7.47	20.50	4.53	3.21	2.71	5.30
	Std. Dev.	0.53	0.65	0.08	0.50	0.08	4.61		Std. Dev.	0.83	0.39	0.04	0.13	0.07	2.69
	JB	0.81	2.68	2.79	2.26	1.83	1.00		JB	3.91	3.65	3.78	0.79	9.92	3.27
Czech	Mean	10.97	17.50	4.18	2.52	3.47	11.72	Poland	Mean	8.03	15.85	3.98	2.36	3.12	11.46
	Median	11.18	17.75	4.21	2.53	3.51	12.05		Median	7.94	15.98	4.00	2.47	3.13	11.00
	Maximum	12.46	18.54	4.31	2.74	3.66	15.40		Maximum	9.20	17.45	4.18	2.69	3.25	17.60
	Minimum	8.30	16.40	4.05	2.35	3.10	8.30		Minimum	7.37	14.07	3.75	1.73	2.93	1.80
	Std. Dev.	1.20	0.68	0.08	0.11	0.15	2.04		Std. Dev.	0.43	1.02	0.13	0.28	0.09	3.50
	JB	2.21	2.04	2.08	1.02	5.54	0.86		JB	5.49	1.53	1.54	4.44	3.24	1.13
Denmark	Mean	8.77	22.17	4.71	4.39	2.80	15.82	Portugal	‘Mean	5.20	18.31	4.28	2.72	2.99	11.86
	Median	9.19	22.21	4.71	4.33	2.80	17.85		Median	5.11	18.34	4.28	2.60	2.93	12.10
	Maximum	13.94	22.63	4.76	5.36	2.94	26.40		Maximum	6.30	18.79	4.33	3.39	3.17	17.40
	Minimum	4.69	21.50	4.64	3.18	2.68	7.00		Minimum	3.78	17.63	4.20	2.20	2.82	6.90
	Std. Dev.	2.43	0.30	0.03	0.61	0.07	7.23		Std. Dev.	0.66	0.26	0.03	0.36	0.13	2.86
	JB	0.81	1.46	1.53	1.08	0.88	3.17		JB’	0.83	4.46	4.70	1.72	2.94	1.12

Table 2. (Continued.)

Country		CO_2	EXD	GI	ET	GDP	GDP2
Finland	Mean	10.36	21.26	4.61	2.95	3.23	10.68
	Median	10.65	21.45	4.63	2.96	3.35	10.70
	Maximum	13.76	21.77	4.67	3.29	3.44	16.60
	Minimum	6.57	20.03	4.48	2.56	2.97	5.30
	Std. Dev.	1.94	0.50	0.05	0.18	0.18	3.80
	JB	1.30	6.22	6.41	0.28	3.56	2.54
France	'Mean	5.46	20.64	4.54	2.27	3.14	10.52
	Median	5.62	20.73	4.55	2.27	3.14	11.10
	Maximum	6.33	21.06	4.59	2.47	3.25	15.40
	Minimum	3.95	20.01	4.47	2.06	3.01	6.20
	Std. Dev.'	0.68	0.28	0.03	0.13	0.07	3.30
	JB	2.15	3.33	3.43	1.92	1.09	2.86
Germany	Mean	9.58	20.90	4.57	2.16	3.37	12.08
	Median	9.62	20.89	4.57	2.18	3.36	12.65
	Maximum	11.04	21.50	4.64	2.63	3.46	15.80
	Minimum	7.26	20.25	4.50	1.62	3.29	8.60
	Std. Dev.	0.86	0.39	0.04	0.27	0.04	2.63
	JB	2.82	1.77	1.77	0.88	1.32	3.18
Greece	Mean	7.72	18.38	4.29	2.88	2.74	11.47
	Median	7.87	18.24	4.27	2.89	2.69	9.75
	Maximum	9.44	19.20	4.38	4.01	3.07	21.30
	Minimum	4.77	17.66	4.20	1.89	2.58	5.10
	Std. Dev.	1.33	0.45	0.05	0.74	0.15	4.45
	JB	1.94	1.84	1.79	2.63	4.47	2.05
Hungary	Mean	5.10	16.31	4.04	2.79	3.51	9.44
	Median	5.32	16.45	4.06	2.82	3.58	9.30
	Maximum	5.74	17.46	4.18	3.35	3.73	13.30
	Minimum	4.12	15.09	3.89	2.37	2.86	3.30
	Std. Dev.	0.52	0.69	0.09	0.21	0.21	2.70
	JB	2.50	1.14	1.22	0.81	39.89	0.84
Slovak Rep.	Mean	6.69	16.78	4.09	2.16	3.46	12.30
	Median	6.91	17.11	4.14	2.07	3.51	12.35
	Maximum	7.90	18.16	4.26	2.64	3.80	23.30
	Minimum	5.32	15.03	3.88	1.92	3.05	2.60
	Std. Dev.	0.77	1.02	0.12	0.21	0.21	4.17
	JB	1.42	2.45	2.47	3.46	1.52	1.33
Slovenia	Mean	7.40	18.31	4.28	3.85	3.19	6.82
	Median	7.63	18.54	4.31	3.85	3.20	6.05
	Maximum	8.59	19.21	4.38	5.30	3.27	12.30
	Minimum	5.93	17.00	4.12	2.94	3.10	1.10
	Std. Dev.	0.64	0.63	0.07	0.64	0.05	2.88
	JB	1.49	2.24	2.33	1.03	1.67	0.74
Spain	Mean	6.35	19.32	4.40	1.89	3.04	10.34
	Median	6.13	19.40	4.40	1.89	3.04	11.45
	Maximum	8.03	19.79	4.45	2.25	3.23	16.50
	Minimum	4.28	18.50	4.30	1.59	2.83	4.80
	Std. Dev.	1.03	0.34	0.04	0.19	0.14	3.69
	JB	1.25	4.49	4.65	0.74	2.73	2.39
Sweden	Mean	5.13	21.70	4.66	2.48	3.15	10.03
	Median	5.13	21.92	4.68	2.57	3.12	8.65
	Maximum	7.20	22.36	4.73	2.92	3.34	14.90
	Minimum	3.24	20.61	4.54	1.98	3.00	5.60
	Std. Dev.	1.15	0.53	0.06	0.26	0.11	3.01
	JB	1.61	2.74	2.80	1.92	2.31	2.64

$$EC_{it}^{H} = \sum_{j=1}^{n} s_{ijt}^{2},\ where\ s_{ijt} = \frac{x_{ijt}}{\sum_{h=1}^{n} x_{iht}} \tag{3}$$

Here, 'x_{ijt} x_{ijt}' denotes the export value of category 'j' for country 'i' at time 't'. Again, the expression '$\sum_{h=1}^{n} x_{iht}$ $\sum_{h=1}^{n} x_{iht}$' refers to the total value of exports in all categories in country 'I' at time 't'.

The remaining variables are obtained from the sources specified in table 1.

Econometric analyses were subsequently carried out. At this stage, identifying and implementing the most suitable method for panel data analysis required conducting two preliminary tests. The first test was the cross-sectional dependence test, while the second was the homogeneity test. The tests developed by 'Breusch and Pagan (1980), Pesaran (2004) and Pesaran *et al* (2008)' for horizontal cross-section dependence and the test developed by Pesaran and Yamagata (2008) for homogeneity analysis are applied. The formulas for the relevant tests are presented below (equations (4)–(8)):

$$LM = T \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} (\widehat{p}_{ij}^{2}) X^{2}_{\frac{N(N-1)}{2}} \tag{4}$$

$$CD_{LM} = \left(\frac{1}{N(N-1)}\right)^{\frac{1}{2}} \sum_{i=1}^{N-1} \sum_{j=_{i}+1}^{N} (T\ \hat{p}_{ij}{}^{2} - 1) \tag{5}$$

$$LM_{adj} = \sqrt{\frac{2}{N(N-1)}} \sum_{i=1}^{N-1} \sum_{j=_{i}+1}^{N} \frac{(T-k)\ \hat{p}_{ij}{}^{2} - \hat{\mu}_{Tij}}{VT_{ij}} \tag{6}$$

$$\tilde{\Delta} = \sqrt{N} \frac{N^{-1}\tilde{S} - k}{\sqrt{2k}} \tag{7}$$

$$\tilde{\Delta}_{adj} = \sqrt{N} \left(\frac{N^{-1}\tilde{S} - E(\tilde{Z}_{it})}{\sqrt{Var(\tilde{Z}_{it})}}\right) \tag{8}$$

In the nEXD step, the stationarity of the variable series is assessed using the Panel Fourier KPSS Stationarity Test developed by Nazlioglu and Karul (2017). For this purpose, '$\alpha_i(t) \alpha_i(t)$' is defined as a function of the time dimension, as indicated in equation (9) (Hassan *et al* 2023):

$$\alpha_i(t) = \alpha_i + b_i t + \gamma_{1i} \sin\left(\frac{2\pi\kappa t}{T}\right) + \gamma_{1i} \cos\left(\frac{2\pi\kappa t}{T}\right) \tag{9}$$

The individual statistic derived from the KPSS test incorporating Fourier frequency, as developed by Becker *et al* (2006), is defined in equation (10):

$$\eta_i(\kappa) = T^{-2} \frac{\sum_{t=1}^{T} \hat{S}_{it}(\kappa)^2}{\delta_{\varepsilon i}^{2}} \tag{10}$$

Nazlioglu and Karul (2017) further developed the Panel statistic by averaging individual statistics, as demonstrated in equation (11):

$$\eta_i(\kappa) = T^{-2} \frac{\sum_{t=1}^{T} \hat{S}_{it}(\kappa)^2}{\delta_{\varepsilon i}^{2}} \tag{11}$$

Moreover, under the null hypothesis of stationary for T $\to \infty$ and N $\to \infty$, $FP(\kappa) FP(\kappa)$ converges to the standard normal distribution and is expressed as in equation (12).

$$FZ(\kappa) = \frac{\sqrt{N}[FP(\kappa) - \xi(\kappa)]}{\varsigma(\kappa)} \sim N(0, 1) \tag{12}$$

In the nEXD stage, the 'fractional frequency flexible Fourier form panel cointegration test' developed by Olayeni *et al* (2020) is used. In the third stage, the from 2020 study was used to determine the long-term relationship of the variables. The formulation of this test is given by equation (13).

$$\tilde{v}_{i,t} = \hat{v}_{i,t} - \hat{\alpha}_i - \hat{\chi}_i \sin\left(\frac{2\pi kt}{T}\right) - \hat{\varphi}_i \cos\left(\frac{2\pi kt}{T}\right) \tag{13}$$

In the fourth stage, the long-run coefficients were estimated within the model to determine the co-integration relationship among the variables. The estimation process utilized the co-integration estimator developed by Bai (2009), which accounts for interactive fixed effects, as applied through equations (14)–(16).

$$\mathrm{Yit} = \mathrm{X'it}\beta + \alpha\mathrm{i} + \xi\xi t + \varepsilon_{it}\varepsilon_{it} \tag{14}$$

$$\lambda'\mathrm{iFt} = \alpha\mathrm{i} + \xi\xi\mathrm{t} \tag{15}$$

Table 3. Cross-sectional dependence and slope homogeneity test results.

Test Variable	CD_{LM1} Istatistic	CD_{LM1} Prob	CD_{LM2} Istatistic	CD_{LM2} Prob	CD_{LM3} Istatistic	CD_{LM3} Prob	$CD_{LMAdjusted}$ Istatistic	$CD_{LMAdjusted}$ Prob
CO_2	1,533.349	0.000	64.573	0.000	−2.49	0.006	32.11	0.000
EXD	900.929	0.000	33.714	0.000	−2.51	0.006	16.99	0.000
GI	693.200	0.000	23.578	0.000	−3.18	0.001	14.79	0.000
ET	983.501	0.000	37.743	0.000	−2.49	0.006	29.14	0.000
GDP	1,727.966	0.000	74.069	0.000	−2.98	0.001	28.50	0.000
GDP2	1,626.150	0.000	69.101	0.000	−3.00	0.001	28.46	0.000
Panel	2,210.411	0.000	97.610	0.000	43.39	0.000	106.90	0.000
Slope Homogeneity Test			Statistic Value				Probability Value	
Delta Tilde			−2.070				0.981	
Delta Tilde Adjusted			−2.201				0.986	

Cross-Sectional Dependence Lagrange Multiplier 1 (Breusch and Pagan 1980), Cross-Sectional Dependence Lagrange Multiplier 2 and Cross-Sectional Dependence (Pesaran 2004), Cross-Sectional Dependence Lagrange Multiplier Adjusted (Pesaran *et al* 2008), Delta Tilde and Delta Tilde Adjusted (Peseran and Yamagata 2008) and Significant coefficients are shown in bold.

$$SR(\beta,\ F,\ \lambda) = \sum_{i=1}^{N}(\ Yi - Xi\beta - F\lambda i)'(Yi - Xi\beta - F\lambda i) \qquad (16)$$

4. Empirical results and discussion

The results of the Cross-Sectional Dependence and Slope Homogeneity Test for the series of six variables across 21 countries utilized in the panel data analysis are presented in table 3.

The results of the Cross-Sectional Dependence and Slope Homogeneity Tests indicate that there is cross-sectional dependence among all variables utilized in the panel data analysis . Furthermore, the findings from the Slope Homogeneity Test, which evaluates the homogeneity of the slope coefficients, reveal that the probability value exceeds 0.05, leading to the conclusion that the slope coefficients are homogeneous.

Upon determining that the slope coefficients exhibit homogeneity in the data and that there is horizontal cross-sectional dependence, a stationarity test was conducted on the variables. The results are presented in table 4.

The hypotheses of stationarity tests and unit root tests are fundamentally opposed. Specifically, a significant p-value in a stationarity test indicates that the series is non-stationary. Based on the results of the Fourier KPSS stationarity test conducted separately on the dependent and independent series, it can be concluded that all panel series are stationary at level.

After establishing the causal relationships among the variables in the panel data analysis, the study uses the Fractional Frequency Flexible Fourier Form (FFFFF) for the panel cointegration test, to examine the long-run relationship. The results are presented in table 5.

The analysis of the Fourier panel (example) cointegration test reveals a statistically significant example relationship in the model across all countries included in the panel data analysis. This relationship was identified using both GLS and PP statistics.

The long-run coefficient estimates derived from the Fourier panel (FFFFF) cointegration test are presented in table 6. Analysis of the table reveals that all independent variables in the model established through panel data analysis exhibit econometrically significant relationships with the dependent variable. Specifically, the GI and GDP2 variables have a negative impact on CO_2, whereas the EXD, ET, and GDP variables exert a positive influence on CO_2.

5. Discussion

These results illuminate several critical points. The first is the positive impact of export diversification (EXD) on CO_2 emission volume. Specifically, an increase in export product diversification corresponds with an increase in CO_2 emissions. The literature presents two types of findings on this issue. The first group of studies (Mania 2020, Iqbal *et al* 2021, Sharma *et al* 2021, Dai and Du 2023) argues that a decrease in export diversification and concentration within certain industries exacerbates environmental degradation, leading to increased CO_2 emissions. These studies assert that export diversification has a positive correlation with CO_2 emission volume,

Table 4. Panel fourier KPSS stationary test.

Variables	CO_2			EXD		
Countries	FKPSS	B Ft	T Ft	FKPSS	B Ft	T Ft
Austria	0.0403	0.1989	0.9475	0.0406	0.3726	1.4318
Belgium	0.0275	0.1726	0.904	0.0357	0.4967	1.9569
Bulgaria	0.0406	1.015	9.2699	0.0217	0.552	2.1799
Croatia	0.0431	1.0039	8.8484	0.0399	0.739	3.1054
Czech	0.0441	0.9914	8.4442	0.1105	1.0439	6.1894
Denmark	0.0327	0.9445	7.5752	0.0794	1.0743	6.7352
Finland	0.0775	0.928	10.1968	0.0808	0.9701	6.9781
France	0.1158	0.9994	10.7615	0.0731	1.0559	6.5466
Germany	0.1296	1.077	11.7541	0.0783	1.1636	8.9923
Greece	0.0898	1.1175	18.604	0.0685	1.1116	8.3642
Hungary	0.0749	1.1427	15.7708	0.0485	1.1486	15.2393
Ireland	0.0838	1.3148	15.1163	0.0747	1.1943	12.926
Italy	0.0615	1.3393	15.9783	0.0585	1.2473	10.6025
Luxembourg	0.0262	1.3176	16.1836	0.0197	1.2079	7.2665
Netherlands	0.0276	1.2562	15.7728	0.03	1.243	7.909
Poland	0.0446	1.2366	13.3127	0.0306	1.2601	7.5405
Portugal	0.0403	1.11	11.2999	0.0266	1.141	7.1084
Slovak Rep.	0.0388	1.1035	9.1801	0.0324	1.1875	6.7584
Slovenia	0.0344	1.0731	9.1015	0.0268	0.9468	5.3723
Spain	0.0773	0.9246	6.646	0.046	0.9762	5.3428
Sweden	0.032	0.7335	4.2032	0.0671	0.8676	4.4408
Panel FKPSS (Prob. Val.)		−0.4222 (0.6636)			−0.916 (0.8202)	
		GI			**ET**	
Austria	0.053	0.2353	0.4714	0.0275	0.6842	2.5974
Belgium	0.0581	0.4359	1.2095	0.0226	0.7367	2.6818
Bulgaria	0.0648	1.0687	2.6241	0.0182	0.7686	2.7329
Croatia	0.069	0.9494	2.2687	0.0313	0.7296	2.52
Czech	0.0538	0.6245	1.3578	0.0787	1.1411	4.8036
Denmark	0.0717	1.0484	2.5791	0.0526	1.1612	4.9817
Finland	0.0332	1.362	3.5701	0.0978	1.2039	5.1804
France	0.0387	1.3875	3.6608	0.0595	1.4107	8.4458
Germany	0.0463	1.3143	2.7955	0.1087	1.2845	7.1712
Greece	0.0503	1.2804	3.3492	0.1096	1.2294	5.4815
Hungary	0.0413	0.8573	2.1826	0.0629	1.1947	6.9016

Table 4. (Continued.)

Variables Countries	CO_2 FKPSS	B Ft	T Ft	EXD FKPSS	B Ft	T Ft
Ireland	0.0538	0.6801	1.6993	0.0942	1.2333	6.8962
Italy	0.0938	0.8041	1.6461	0.0404	1.1255	6.251
Luxembourg	0.085	1.2904	4.3873	0.0229	1.1002	6.8388
Netherlands	0.0836	0.9761	2.6116	0.0289	1.0828	6.1404
Poland	0.0969	0.6268	1.5168	0.0315	1.0155	5.4052
Portugal	0.0411	0.8335	1.9257	0.0442	0.9963	4.8145
Slovak Rep.	0.0361	1.156	2.1466	0.0341	1.0318	4.5301
Slovenia	0.0919	1.7183	3.7149	0.0679	0.6613	2.8033
Spain	0.0274	1.5338	3.163	0.0437	0.6404	2.848
Sweden	0.0381	0.8171	1.6781	0.0347	0.5684	2.1495
Panel FKPSS (Prob. Val.)		−0.1816 (0.5721)			−0.7962 (0.7871)	
		GDP			GDP2	
Austria	0.0194	0.729	2.7956	0.0192	0.7159	2.7434
Belgium	0.0253	0.7318	2.7873	0.0248	0.7152	2.7121
Bulgaria	0.0411	0.8945	3.9133	0.0406	0.9184	4.0663
Croatia	0.049	0.7507	3.3753	0.0502	0.7808	3.5431
Czech	0.0418	0.7983	3.8739	0.044	0.8331	4.1142
Denmark	0.0444	0.7436	3.5847	0.0465	0.781	3.8126
Finland	0.0512	0.7309	3.5825	0.0528	0.771	3.8265
France	0.0207	0.6728	3.3735	0.02	0.7	3.5664
Germany	0.0345	0.6869	3.4014	0.0353	0.7142	3.604
Greece	0.0432	0.7145	3.5636	0.0439	0.7449	3.7815
Hungary	0.0411	0.9408	4.8331	0.0403	0.9217	4.8608
Ireland	0.0448	0.9733	5.2383	0.0437	0.9612	5.3054
Italy	0.0509	1.325	6.4747	0.0509	1.2926	6.5536
Luxembourg	0.0337	1.3602	6.8669	0.0351	1.3342	6.9862
Netherlands	0.0277	1.4384	7.3093	0.0288	1.4203	7.5084
Poland	0.0279	1.4802	7.7977	0.0292	1.4634	7.9509
Portugal	0.0349	1.4111	7.454	0.037	1.395	7.5527
Slovak Rep.	0.0308	1.3888	7.4167	0.0329	1.3815	7.5163
Slovenia	0.0348	1.1047	5.0187	0.0348	1.0761	4.9216
Spain	0.0319	1.0729	4.9822	0.0317	1.048	4.8817
Sweden	0.0275	1.0514	4.8774	0.0275	1.0315	4.784
Panel FKPSS (Prob. Val.)		−2.6836 (0.9964)			−2.6166 (0.9956)	

Table 5. The fourier panel (FFFFF) cointegration test.

	GLS				PP			
	Stat	%1	%5	%10	Stat	%1	%5	%10
Model				$CO_2 = \alpha_i + \beta_1 EXD + \varepsilon_{it}$				
Austria	−**4.524**	−2.696	−1.846	−0.321	−**4.447**	−2.808	−1.938	−0.377
Belgium	−**4.163**	−2.857	−1.454	0.965	−**4.545**	−3.386	−1.998	1.545
Bulgaria	−**4.887**	−2.869	−1.78	0.166	−**8.667**	−3.116	−2.013	0.335
Croatia	−**5.216**	−3.168	−2.231	−0.851	−**5.089**	−4.165	−2.81	−0.876
Czech	−**2.895**	−3.47	−2.13	−0.843	−**3.45**	−2.933	−2.238	−0.741
Denmark	−**5.381**	−3.175	−1.807	0.656	−**5.726**	−3.282	−1.982	0.068
Finland	−**4.313**	−3.265	−2.142	−0.887	−**7.059**	−3.308	−2.421	−0.574
France	−**5.582**	−3.422	−2.24	−0.246	−**6.599**	−3.6	−2.467	0.295
Germany	−**5.716**	−3.392	−2.092	0.026	−**5.863**	−3.983	−2.388	0.126
Greece	−**4.674**	−3.003	−1.905	0.199	−**3.971**	−3.338	−2.048	0.242
Hungary	−**5.563**	−2.6	−1.63	0.023	−**5.745**	−2.867	−1.881	−0.006
Ireland	−**4.605**	−3.333	−2.293	−0.763	−**7.966**	−3.316	−2.424	−0.998
Italy	−**4.68**	−3.257	−2.226	−0.367	−**4.288**	−3.072	−2.29	−0.317
Luxembourg	−**4.262**	−3.163	−2.016	−1.223	−**4.275**	−3.185	−2.172	−1.249
Netherlands	−**4.465**	−3.043	−1.809	0.603	−**4.827**	−3.19	−1.864	0.998
Poland	−**3.37**	−3.104	−1.58	0.875	−**3.308**	−2.582	−1.576	2.409
Portugal	−**4.258**	−3.341	−2.038	−0.386	−**4.394**	−3.441	−2.168	−0.446
Slovak Rep.	−**3.89**	−3.564	−2.361	−0.586	−**3.521**	−3.14	−2.443	−0.62
Slovenia	−**3.999**	−3.103	−1.845	0.294	−**3.934**	−3.081	−2.215	−0.342
Spain	−**4.078**	−3.209	−2.201	−0.491	−**3.943**	−3.274	−2.335	−0.411
Sweden	−**4.411**	−3.058	−1.972	−0.002	−**4.406**	−3.09	−1.987	−0.314
	Group Mean	−**4.521**	**p. Val**	0.008	Group Mean	−**5.049**	**p. Val**	0.004
	Group Max	−**5.716**	**p. Val**	0.000	Group Max	−**8.667**	**p. Val**	0.000
	Group Median	−**4.465**	**p. Val**	0.009	Group Median	−**4.447**	**p. Val**	0.010
Model				$CO_2 = \alpha_i + \beta_1 GI + \varepsilon_{it}$				
Austria	−**4.835**	−3.051	−1.991	−0.624	−**5.647**	−3.363	−2.419	−0.354
Belgium	−**4.481**	−3.022	−2.064	−0.064	−**4.352**	−3.128	−2.039	0.539
Bulgaria	−**4.697**	−2.839	−1.91	0.963	−**7.448**	−3.852	−2.413	0.79
Croatia	−**3.823**	−2.61	−1.507	0.716	−**3.85**	−2.813	−1.904	0.839
Czech	−**4.898**	−2.697	−1.853	−0.455	−**4.971**	−2.966	−1.901	−0.706
Denmark	−**4.501**	−2.982	−2.097	−0.716	−**4.394**	−3.226	−2.098	−0.283
Finland	−**4.549**	−3.197	−2.165	0.625	−**7.744**	−3.198	−2.226	0.805
France	−**4.381**	−3.199	−2.164	−0.292	−**4.27**	−3.193	−2.228	−0.207

Table 5. (Continued.)

	GLS				PP			
	Stat	%1	%5	%10	Stat	%1	%5	%10
Germany	−**4.412**	−3.195	−1.899	−0.221	−**4.431**	−3.097	−2.142	−0.063
Greece	−**3.179**	−3.027	−1.805	0.423	−**3.351**	−2.902	−2.142	0.33
Hungary	−**4.073**	−2.612	−1.804	0.597	−**4.921**	−3.034	−1.965	0.547
Ireland	−**4.212**	−3.115	−1.828	0.227	−**4.14**	−2.948	−1.961	0.369
Italy	−**4.465**	−3.343	−2.181	−0.416	−**5.425**	−3.215	−2.252	−0.193
Luxembourg	−**4.878**	−2.682	−1.608	1.323	−**5.318**	−3.035	−1.778	0.625
Netherlands	−**5.495**	−3.34	−1.989	−0.179	−**4.213**	−3.045	−2.18	−0.127
Poland	−**4.793**	−2.762	−1.74	0.355	−**4.318**	−3.246	−2.007	0.802
Portugal	−**5.198**	−2.468	−1.601	0.102	−**5.23**	−2.86	−1.84	0.715
Slovak Rep.	−**4.555**	−2.657	−1.868	1.081	−**4.651**	−3.143	−2.041	−0.198
Slovenia	−**4.147**	−3.053	−1.932	−0.443	−**3.914**	−3.006	−2.041	−0.397
Spain	−**3.939**	−2.985	−2.033	0.544	−**3.981**	−2.994	−2.104	0.811
Sweden	−**4.73**	−2.995	−2.108	−1	−**3.81**	−3.123	−2.339	−0.837
	Group Mean	−**4.488**	**p. Val**	0.003	Group Mean	−**4.78**	**p. Val**	0.002
	Group Max	−**5.495**	**p. Val**	0.000	Group Max	−**7.744**	**p. Val**	0.000
	Group Median	−**4.501**	**p. Val**	0.003	Group Median	−**4.394**	**p. Val**	0.006
Model				$CO_2 = \alpha_i + \beta_1 ET + \varepsilon_{it}$				
Austria	−**5.922**	−3.031	−1.739	−0.734	−**5.796**	−3.188	−2.089	−1.152
Belgium	−**5.025**	−3.462	−2.097	−0.508	−**4.196**	−3.057	−2.013	−0.036
Bulgaria	−**4.558**	−2.914	−1.812	0.032	−**7.05**	−2.825	−1.866	0.539
Croatia	−**3.698**	−2.546	−1.531	−0.353	−**3.839**	−2.42	−1.599	−0.21
Czech	−**4.262**	−3.211	−1.994	0.066	−**4.265**	−3.196	−1.981	−0.332
Denmark	−**4.699**	−3.117	−2.151	−0.167	−**4.589**	−3.812	−2.451	−0.666
Finland	−**5.934**	−2.88	−1.923	−0.244	−**10.795**	−2.903	−1.898	−0.036
France	−**3.399**	−2.988	−1.857	0.26	−**4.043**	−2.951	−1.959	−0.075
Germany	−**4.635**	−3.572	−2.179	−1.04	−**4.582**	−3.88	−2.565	−1.297
Greece	−**4.617**	−3.515	−2.067	−0.751	−**4.549**	−3.274	−2.43	−0.635
Hungary	−**4.926**	−3.182	−2.15	−0.969	−**5.586**	−3.335	−2.37	−1.385
Ireland	−**4.894**	−3.288	−2.086	−1.01	−**5.56**	−3.185	−2.32	−1.107
Italy	−**3.801**	−2.681	−1.483	0.242	−**3.691**	−3.156	−1.712	0.653
Luxembourg	−**2.552**	−3.257	−2.017	−0.592	−**4.125**	−3.276	−2.119	−0.688
Netherlands	−**4.268**	−2.761	−1.884	−1.035	−**4.189**	−2.873	−2.156	−1.233
Poland	−**3.358**	−2.908	−1.627	0.145	−**3.043**	−2.501	−1.665	0.472
Portugal	−**5.091**	−3.447	−2.278	−0.588	−**5.731**	−3.282	−2.394	−0.307

Table 5. (Continued.)

	GLS				PP			
	Stat	%1	%5	%10	Stat	%1	%5	%10
Slovak Republic	**−4.616**	−2.964	−1.881	−0.237	**−6.409**	−3.062	−2.074	−0.794
Slovenia	**−3.943**	−3.015	−1.562	0.986	**−4.051**	−2.847	−1.734	3.021
Spain	**−3.585**	−3.05	−1.929	−0.019	**−3.423**	−3.248	−1.933	0.421
Sweden	**−5.76**	−3.639	−2.208	−1.054	**−5.368**	−3.456	−2.448	−1.162
	Group Mean	**−4.454**	**p. Val**	0.008	Group Mean	**−4.994**	**p. Val**	0.004
	Group Max	**−5.934**	**p. Val**	0.000	Group Max	**−10.795**	**p. Val**	0.000
	Group Median	**−4.616**	**p. Val**	0.005	Group Median	**−4.549**	**p. Val**	0.006
Model				**$CO_2 = \alpha_i + \beta_1 GDP + \varepsilon_{it}$**				
Austria	**−3.929**	−3	−1.971	−0.118	**−3.811**	−2.925	−2.068	0.022
Belgium	**−3.326**	−3.291	−2.253	−0.43	**−3.96**	−2.996	−2.29	−0.391
Bulgaria	**−4.859**	−3.605	−2.235	−0.691	**−8.699**	−3.296	−2.284	−0.576
Croatia	**−2.635**	−3.148	−2.08	−0.515	**−4.145**	−3.001	−2.127	0.012
Czech	**−3.093**	−3.079	−2.114	−0.443	**−3.224**	−2.96	−2.101	−0.568
Denmark	**−4.255**	−2.93	−1.991	−0.975	**−4.126**	−2.688	−2.082	−0.527
Finland	**−5.534**	−3.724	−2.221	0.027	**−9.057**	−3.527	−2.191	0.332
France	**−3.057**	−2.819	−2.1	−0.697	**−4.264**	−2.84	−2.083	−0.571
Germany	**−4.543**	−3.416	−2.277	−1.129	**−4.509**	−3.473	−2.476	−1.187
Greece	**−4.414**	−2.535	−1.566	−0.008	**−4.445**	−2.746	−1.699	−0.04
Hungary	**−4.384**	−3.325	−2.13	−0.858	**−4.152**	−3.021	−2.234	−0.692
Ireland	**−4.056**	−3.009	−1.993	−1.116	**−4.141**	−3.092	−2.142	−0.968
Italy	**−3.53**	−2.986	−1.946	−0.702	**−4.499**	−3.205	−2.221	−0.921
Luxembourg	**−3.655**	−2.958	−1.638	0.389	**−3.518**	−2.814	−1.687	0.678
Netherlands	**−3.555**	−3.178	−2.076	−0.519	**−3.674**	−2.864	−2.166	−0.603
Poland	**−3.777**	−3.428	−2.206	−0.699	**−3.527**	−3.185	−2.233	0.035
Portugal	**−3.325**	−2.55	−1.774	−0.386	**−3.718**	−2.747	−1.748	−0.023
Slovak Rep.	**−3.277**	−3.294	−2.177	0.133	**−3.127**	−3.106	−2.244	−0.837
Slovenia	**−3.282**	−3.227	−1.959	−0.63	**−3.421**	−2.691	−1.934	−0.511
Spain	**−4.04**	−3.295	−1.741	0.498	**−4.185**	−2.858	−1.742	0.452
Sweden	**−3.406**	−3.069	−2.007	−0.513	**−3.944**	−3.056	−2.082	−0.459
	Group Mean	**−3.806**	**p. Val**	0.03	Group Mean	**−4.388**	**p. Val**	0.005
	Group Max	**−5.534**	**p. Val**	0.001	Group Max	**−9.057**	**p. Val**	0.000
	Group Median	**−3.655**	**p. Val**	0.043	Group Median	**−4.126**	**p. Val**	0.008

Table 5. (Continued.)

	GLS				PP			
	Stat	%1	%5	%10	Stat	%1	%5	%10
Model				$CO_2 = \alpha_i + \beta_1 GDP2 + \varepsilon_{it}$				
Austria	**−3.927**	−2.999	−1.949	−0.121	**−3.81**	−2.917	−2.065	0.02
Belgium	**−3.336**	−3.276	−2.252	−0.437	**−3.964**	−2.999	−2.289	−0.398
Bulgaria	**−4.859**	−3.619	−2.242	−0.708	**−8.7**	−3.304	−2.299	−0.6
Croatia	**−2.618**	−3.109	−2.07	−0.532	**−4.144**	−3.048	−2.118	−0.012
Czech	**−3.086**	−3.077	−2.124	−0.45	**−3.215**	−2.969	−2.09	−0.581
Denmark	**−4.253**	−2.93	−1.996	−0.988	**−4.124**	−2.681	−2.082	−0.534
Finland	**−5.527**	−3.727	−2.24	0.025	**−9.003**	−3.508	−2.188	0.329
France	**−3.053**	−2.819	−2.088	−0.691	**−4.25**	−2.84	−2.086	−0.564
Germany	**−3.525**	−3.189	−2.268	−0.296	**−3.702**	−3.288	−2.293	−0.489
Greece	**−4.423**	−2.523	−1.568	−0.026	**−4.457**	−2.746	−1.667	−0.072
Hungary	**−4.372**	−3.319	−2.145	−0.874	**−4.14**	−3.021	−2.24	−0.713
Ireland	**−4.086**	−2.989	−2	−1.129	**−4.159**	−3.114	−2.115	−0.986
Italy	**−3.536**	−2.986	−1.953	−0.705	**−4.499**	−3.206	−2.221	−0.92
Luxembourg	**−3.655**	−2.956	−1.639	0.391	**−3.517**	−2.813	−1.689	0.679
Netherlands	**−3.543**	−3.182	−2.052	−0.52	**−3.662**	−2.852	−2.162	−0.608
Poland	**−3.77**	−3.462	−2.201	−0.691	**−3.518**	−3.19	−2.231	0.023
Portugal	**−3.318**	−2.554	−1.72	−0.392	**−3.712**	−2.749	−1.748	−0.03
Slovak Rep.	**−3.175**	−3.274	−2.194	−0.103	**−3.03**	−3.195	−2.202	−0.908
Slovenia	**−3.277**	−3.258	−1.959	−0.634	**−3.411**	−2.684	−1.934	−0.517
Spain	**−4.021**	−3.298	−1.733	0.494	**−4.166**	−2.855	−1.744	0.446
Sweden	**−3.412**	−3.08	−2.003	−0.52	**−3.931**	−3.034	−2.077	−0.475
	Group Mean	**−3.751**	**p. Val**	**0.035**	Group Mean	**−4.339**	**p. Val**	0.006
	Group Max	**−5.527**	**p. Val**	**0.001**	Group Max	**−9.003**	**p. Val**	0.000
	Group Median	**−3.543**	**p. Val**	**0.045**	Group Median	**−3.964**	**p. Val**	0.013

Significant coefficients are shown in bold.

Table 6. The fourier panel (FFFFF) coefficient estimation.

CO_2	Coefficient	Standard error	Probability value
EXD	**4.281679**	0.3278969	0.000
GI	**−0.0617978**	0.0084081	0.000
ET	**0.8958452**	0.0913218	0.000
GDP	**65.85634**	6.814444	0.000
GDP2	**−8.367077**	0.8035531	0.000
C	**−134.0044**	14.41663	0.000

Significant coefficients are shown in bold.

positing that the development and expansion of exports elevate CO_2 emissions by increasing production in some industry-intensive sectors, which paradoxically reduces export diversification.

The second group of studies contends that export diversification heightens the negative impact on the environment, as measured by CO_2 emission volume or ecological footprint (Can *et al* 2020, Shahzad *et al* 2020, Jiang *et al* 2022, Udeagha and Ngepah 2023). The results of our study substantiate the latter group. For instance, Jiang *et al* (2022) provide evidence that export diversification, particularly in conjunction with agricultural and industrial activities, exerts long-term pressures on environmental sustainability. They emphasize that while export diversification may support economic growth and reduce barriers for trade, it can exacerbate environmental degradation if strict environmental regulations are not implemented, particularly in lower-income and developing countries. This aligns with our findings that export diversification leads to energy-intensive production processes, which contribute to environmental deterioration. Similarly, Udeagha and Ngepah (2023) argue that while export diversification can foster economic growth in emerging economies like the BRICS nations, it simultaneously accelerates environmental degradation unless paired with systemic transformation and proactive environmental regulations. Their study highlights the importance of integrating eco-friendly products into export portfolios and incentivizing green innovations to mitigate these negative impacts.

Another significant finding of this study is that green innovation (GI) efforts effectively reduce CO_2 emission volume, aligning with predominant findings in the literature (Guo *et al* 2021, Ali *et al* 2022, Wen *et al* 2022, Afshan and Yaqoob 2023, Kirikkaleli and Adebayo 2024). For instance, Wen *et al* (2022) demonstrated that increasing green patents in South Asian economies significantly reduces CO_2 emissions. They recommend that South Asian countries tighten environmental regulations, reduce fossil fuel subsidies, and provide financial support for ecological innovation to further enhance environmental quality. These findings highlight the critical role of targeted policy interventions at the firm level to promote green technology adoption. Similarly, Guo *et al* (2021) emphasized that green innovation in China has the potential to mitigate environmental degradation by transitioning industrial structures toward renewable energy sources. They advocate for increased investments in green innovation and renewable energy as part of an integrated approach to achieving China's carbon neutrality goals, particularly within the framework of the SDG 2030 agenda. These parallels reinforce the importance of accelerating investments in green innovation to address pressing environmental challenges. Based on these findings, it is crucial for policymakers to prioritize innovative green initiatives in the context of sustainable development.

Additionally, the study reveals that environmental tax (ET) practices unexpectedly lead to an increase in CO_2 emissions. This outcome arises because although environmental taxes are perceived to positively impact the environment, they yield effects similar to GDP on environmental outcomes due to increased tax payments associated with GDP growth. While these results do not support the majority of studies in the literature that claim otherwise (Chien *et al* 2021, Xie and Jamaani 2022, Afshan and Yaqoob 2023), they support perspectives asserting that environmental tax (ET) practices contribute to increased CO_2 emissions and negatively affect the environment (Kafeel *et al* 2024). For example, Kafeel *et al* (2024) argue that in economies with inefficient tax redistribution mechanisms, the imposition of environmental taxes may inadvertently incentivize environmentally harmful behaviors, such as cost-cutting measures that ignore ecological standards. This finding highlights the critical importance of designing and implementing environmental tax policies that are aligned with long-term sustainability goals. Some studies in the literature argue that environmental tax (ET) practices have no effect on CO_2 emissions (Telatar and Birinci 2022). The findings of this study provide justification for the less widely accepted view, which diverges from the predominant literature, concerning the sample considered,.

The study further corroborates the general literature indicating that economic growth (GDP) positively influences CO_2 emission volume, reinforcing the validity of the Environmental Kuznets Curve (EKC) hypothesis. This consistency with studies such as those by Shahbaz *et al* (2020) and Sinha *et al* (2020) confirms that as economies grow, CO_2 emissions increase initially but decline once a critical income threshold is reached.

Our results provide additional empirical evidence supporting this hypothesis, particularly within the context of EU member states. By extending the EKC framework to incorporate export diversification and green innovation, this study contributes novel insights into the interplay between economic growth and environmental sustainability.

6. Conclusions and policy implications

In this study, panel data analysis is applied for 21 EU member countries. It should be noted that in panel data analysis, long-run coefficients are calculated as a single coefficient for the entire panel. Therefore, the long-run relationship coefficients that are valid for the whole panel may vary across countries. For example, a positive relationship was found between the EXD variable and CO_2 emissions. This is generally valid for 21 EU countries. However, it may also be the case that some of the 21 countries have a negative relationship between EXD and CO_2. This is one of the limitations of our study. Therefore, when time series analysis is performed separately for each country, there will be differences in the coefficients, coefficient signs, or probability values in the long-run estimates from the panel data analysis in our study. Future studies could explore this variation through country-specific time series analyses to better understand the nuanced effects of export diversification on CO_2 emissions.

The other limitation of our study is that the GI is measured as Environmentally related patents (% total patents), and the ET is measured as Environmentally related tax revenue (% of the GDP). This measure is calculated by the OECD. Therefore, if the measurement techniques or the measurement methods change, the numerical values of the indices may change, and this may change the whole analysis. Therefore, if the measurement methods of the indices we use change in the following years, our analysis will need to be redone.

The economic growth processes of countries, centered on production and exports, have inevitably led to a significant increase in CO_2 emissions from fossil fuels, reaching alarming levels. This situation has prompted governments to seek solutions to address the escalating carbon emission problem while maintaining their growth and development objectives. Two key issues and one critical measure emerge in this context. The first key issue is export diversification (EXD), and the second is Green Innovation (GI). Notably, export diversification (EXD) may initially contribute to an increase in CO_2 emission levels, which is directly correlated with the economic growth process. However, this seemingly negative factor has the potential to be transformed positively through the implementation of appropriate measures. A crucial measure in this process is the Environmental Tax (ET).

The primary objective of this study is to identify the factors that can contribute to the reduction of CO_2 emissions by assessing the environmental impact of elements such as export diversification and GDP. While these factors may negatively influence the process, they can be converted into positive drivers through appropriate and innovative measures. Additionally, the study considers elements that are recognized as supportive of the process, including green innovation and environmental tax. The analysis encompasses data from 21 European Union (EU) member countries over the period from 1995 to 2020. The results indicate that green innovation efforts have a statistically significant negative impact on CO_2 emissions, emphasizing the role of environmentally related patents as a driver of environmental improvement. For instance, countries with higher green innovation adoption rates, such as Denmark and Finland, have demonstrated substantial reductions in CO_2 emissions (for example, for Denmark, CO_2 emissions were 11.47 in 1995 and 4.69 in 2020, and the Green Innovation (GI) coefficient was 8 in 1995 and 22.2 in 2020). According to the results of the empirical investigation, export diversification (EXD), environmental tax (ET), and economic growth (GDP) positively affect the volume of CO_2 emissions, whereas green innovation (GI) and GDP squared (GDP2) have a negative effect. These findings unequivocally indicate that export diversification is detrimental to environmental quality.

These results indicate that export diversification is primarily influenced by an economic growth-oriented perspective of national governments. Additionally, while the environmental tax may initially appear to have a positive impact on the environment, it exhibits effects that parallel GDP's impact on environmental conditions, in the sense that the tax increases alongside GDP growth. For instance, the findings suggest that a poorly structured environmental tax system may fail to incentivize cleaner production practices effectively, highlighting the need for reforms to ensure that such taxes promote sustainability. This outcome aligns with expectations, revealing that the environmental tax fails to deliver the anticipated benefits. Therefore, it should be structured to foster a qualitative and sustainable environment, rather than merely a quantitative approach, incorporating positively discriminatory measures through innovative policy. Furthermore, the study highlights the validity of the Environmental Kuznets Curve (EKC) hypothesis for European Union member states, which encompass a significant proportion of developed countries. This finding is consistent with existing literature.

Finally, the most significant finding of the study is the reduction in CO_2 emission volumes attributed to green innovation. For example, green innovation adoption has been associated with improved environmental outcomes, such as reducing reliance on fossil fuels, and promoting eco-friendly production technologies. This supports the need for policymakers to prioritize financial incentives and stricter regulations to further encourage eco-innovation. These results are crucial in demonstrating the positive impact of green innovation efforts on the environment within European Union member states. Based on these findings, it is evident that the emphasis placed by policymakers on green innovation in production and export diversification will facilitate positive environmental developments.

Funding

No source funding

Declaration of competing interest

The authors declare no potential conflict of interest.

Data availability

The data that support the findings of this study are available from the corresponding author, [Corresponding Author], upon reasonable request.

Data availability statement

No new data were created or analysed in this study.

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