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Navigating sustainability: how export diversification influences ecological footprints in developed and developing countries

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Abstract
Environmental sustainability has become a critical global challenge, driving researchers and policymakers to explore solutions that balance economic growth with ecological preservation. As nations strive to achieve the United Nations Sustainable Development Goals (SDGs), understanding the relationship between trade structures and environmental impact is more crucial than ever. To do so, this paper intends to examine the effect of export diversification on the ecological footprint in 87 countries, utilizing annual data from 1995 to 2014. Since per capita ecological footprint of consumption is considered as a thorough indicator of environmental degradation, it has been used as the dependent variable (Ulucak and Bilgili in J Clean Prod 188:144–157, 2018). Additionally, export diversification is measured using the Theil entropy index, along with its intensive and extensive margins, based on data from the IMF. The intensive, extensive, and overall Theil indices were calculated according to the definitions and methods outlined by (Cadot et al. in Rev Econ Stat 93:590–605, 2011). Using a panel Autoregressive Distributed Lag (ARDL) model, the findings indicate that both the intensive and extensive margins of export diversification contribute to reducing the ecological footprint. Specifically, in developing economies, diversification in the intensive margin positively impacts the environment. Conversely, in developed economies, export concentration in the intensive margin is linked with a decrease in the ecological footprint. These findings underscore the importance of effective export diversification strategies for sustainable economic development in developing economies, while encouraging developed countries to prioritize the export of green technologies and investments to aid in addressing global environmental challenges. Policies aligned with the United Nations Sustainable Development Goals (SDGs) are essential in both developed and developing economies to address the interconnections among various SDGs and, in turn, enhance ecosystem sustainability.

Article highlights

- Export diversification can improve environmental quality globally.
- Developing nations can lessen their ecological footprint through export diversification.
- Export concentration contributes to environmental sustainability in developed economies.

Keywords Ecological footprint · Export diversification · Theil index · Fossil fuel energy consumption · Renewable electricity output · Environmental Kuznets curve hypothesis

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1 Introduction

The challenges that are attributed to environmental degradation have played a significant role in centralizing the sustainability topic into global priorities. Also, the 17 United Nations Sustainable Development Goals (SDGs) have emphasized this importance of environmental sustainability across multiple objectives. SDGs 3, 6, 7, 13, 14, and 15 underline that the vital role of environmental factors such as air and water quality, as well as the health of ecosystems on land and in the oceans, in fostering overall well-being and achieving sustainable development.

To achieve sustainability, the concept of a green economy has gained significant global attention with a particular emphasis on the need to increase competitiveness, promote low-carbon production, and foster eco-efficient practices across various sectors [25]. This focus on green economic principles has become crucial in addressing the mounting global issue of environmental degradation [48].

Among the numerous environmental challenges, carbon dioxide (CO2) emissions have drawn significant attention for their critical role in global warming [47]. The surge in CO2 emissions is largely driven by the energy consumption necessary for economic growth. Although energy is essential for different nations, it poses a substantial environmental threat due to the excessive buildup of carbon dioxide [46]. CO2 is considered a primary greenhouse gas. It contributes to rising global temperatures and climate change by trapping heat in Earth's atmosphere. This heat-trapping effect occurs because CO2 molecules absorb and re-emit infrared radiation, which would otherwise escape into space [47]. Consequently, managing CO2 levels has become a major global priority [80].

Yet, the emissions of CO2 are primarily driven by the combustion of the different resources of energy, representing just one aspect of the broader issue of greenhouse gas emissions, which also involve other gases [2, 48]. Therefore, focusing solely on CO2 does not fully capture the multidimensional nature of environmental degradation [50].

To assess environmental deterioration more accurately, the ecological footprint (EF) is recognized as a suitable measure. Ahmad et al. [1] explain that EF integrates information on human impacts on soil, air, and water, offering a broader perspective. It accounts not only for emissions but also for the effects of resource consumption across various types of land use [42]. Consequently, researchers have endeavored to identify the factors influencing ecological footprint levels globally [45]. Notably, human-related factors such as energy use and international trade have been identified as key contributors to environmental degradation [49].

On the light of the above, while international trade fosters economic growth, its environmental consequences can differ markedly across countries. Murshed et al. [45] suggests that its environmental impacts can vary significantly from one country to another due to differences in trade policies, economic compositions, and the extent of environmental regulations. In line with the perspective of the Pollution Haven Hypothesis (PHH), trade liberalization may exacerbate environmental deterioration as firms relocate pollution-intensive industries to countries with lax environmental regulations [20]. This phenomenon suggests that in the absence of stringent regulatory frameworks, trade openness could lead to increased carbon emissions and ecological strain, particularly in developing economies [64]. Conversely, the Porter Hypothesis posits that strict environmental regulations can drive innovation and efficiency, ultimately enhancing both trade competitiveness and environmental quality [59]. In this regard, the relationship between trade openness and environmental sustainability is highly context-dependent, shaped by regulatory stringency and the capacity of economies to integrate cleaner technologies into their industrial frameworks [7].

To empirically investigate trade-environment dynamics, several studies have used trade openness, calculated as the ratio of total exports and imports to the gross value added, to examine environmental quality [61]. Others have focused on the composition of international trade, such as export diversification, to assess environmental impact [43].[1]

However, the relationship between export diversification and environmental degradation remains inconclusive. Some researchers argue that export diversification exacerbates environmental deterioration [18, 44], while others find that it enhances environmental quality [5, 40, 89]. Therefore, this study aims to explore the impact of export diversification on the ecological footprint in 87 countries from 1995 to 2014.

This study makes a significant contribution to academic literature by exploring the link between export diversification and environmental pollution through a novel approach. It specifically assesses how export diversification influences the ecological footprint, both at a global level and within the contexts of developing and developed nations (as classified by the IMF) between 1995 and 2014, while aligning with the Environmental Kuznets Curve (EKC) hypothesis. The analysis

[1] Export diversification refers to the expansion of a country's export mix [24], which significantly influences economic growth by boosting productivity, enhancing macroeconomic stability, and fostering economic development [29].

focuses on the two components of the Theil index—the intensive and extensive margins of export diversification—and their respective effects on the ecological footprint, using the Pooled Mean Group (PMG) model. Additionally, to enhance the robustness and credibility of the findings, the fully modified ordinary least squares (FMOLS) method was applied; the export product concentration index was incorporated into the estimated equation as a key explanatory factor, and the carbon emissions per capita were used as a dependent variable.

The novelty of this study lies in its context-specific analysis, which distinguishes the impact of export diversification on environmental sustainability in developed and developing countries—an area that remains insufficiently explored in the literature. By utilizing disaggregated country- and sector-level data, this research enhances the precision of estimates and offers a deeper insight into how trade structures shape ecological footprints. Additionally, the study employs advanced econometric techniques, including the Pooled Mean Group (PMG) and Fully Modified Ordinary Least Squares (FMOLS) models, ensuring the robustness of the findings. The inclusion of the export product concentration index as a key explanatory variable further enriches the analysis, providing new perspectives on the trade-environmental relationship. These contributions position the study as a significant addition to the discourse on sustainable trade policies, offering practical insights for policymakers aiming to reconcile economic expansion with environmental sustainability.

The paper is organized as follows: Sect. 2 offers an in-depth review of relevant literature, while Sect. 3 describes the model and data construction. Section 4 explains the econometric techniques used in the analysis. The findings are presented and discussed in Sect. 5, followed by a robustness check in Sect. 6. The final section, Sect. 7, concludes the study and offers recommendations based on the results.

2 Literature review

2.1 Export diversification and environmental quality

In recent years, academic literature on export diversification has increasingly focused on analyzing its impact on environmental sustainability in countries. Over the past five years, numerous studies have examined the relationship between export diversification and various environmental indicators, such as carbon dioxide emissions, opportunities for achieving hydrocarbon neutrality, the use of renewable energy sources, and overall environmental pollution. The main findings of these studies are summarized in Table 1.

These studies have explored how a country's shift towards a more diversified export portfolio, moving away from heavy reliance on a few primary export products, can impact its environmental performance and sustainability efforts. A significant body of research suggests that export diversification is linked to a rise in environmental degradation, as evidenced by the works of [17, 18, 31, 33]. However, the literature also presents opposing viewpoints, including those by [6, 40, 66].

Using the approach of the Generalized Method of Moments (GMM) and other analytical techniques, Mania [44] finds that export diversification has a statistically significant positive impact on per capita CO2 emissions. The results reveal that in developing countries, increasing export diversification tends to elevate CO2 emissions, while in developed nations, export concentration is linked to a reduction in emissions. Based on these findings, the author recommends that developing countries should implement stringent environmental policies in tandem with their export diversification strategies. For advanced economies, the focus should be on promoting and facilitating the transfer of green technologies to emerging markets. Additionally, investments in human capital and technological innovation are highlighted as crucial for reducing environmental pollution globally.

In a similar analysis conducted by Liu, Kim, and Choe [43], the impact of horizontal and vertical export diversification on carbon dioxide emissions has been examined using data from 125 countries from 2000 to 2014. According to their study, diversification of export geography can lead to increased CO2 emissions due to increased cargo transportation volumes. Horizontal export diversification can also increase carbon dioxide emissions, while vertical export diversification can lead to decreased emissions. The panel data analysis showed that diversification of export geography and structure helped reduce CO2 emissions in 125 countries. The authors explain this by saying that countries are likely to focus on exporting more environmentally friendly goods, following global trends. However, to obtain more accurate results, the authors suggest that this effect should be assessed separately for specific groups of countries ranked by per capita income.

In their article, Wang et al. [79] examine the impact of export diversification and environmental innovation on carbon dioxide emissions in G7 countries from 1990 to 2017. Their analysis reveals that while export diversification contributes to increased CO2 emissions, ecological innovation and renewable energy consumption play a significant role in

Table 1 Selected literature on the effects of export diversification, economic growth, and energy consumption on environmental quality

Authors	Country(s)	Period	Method	Finding
Export diversification and environmental quality				
Ali et al. (2022)	India	1965–2016	ARDL model	Export diversification reduces EFP in the long run
Bake et al. (2024)	The European Union countries	1995–2018	Pooled mean group/autoregressive distributed lag approach (ARDL)	Export concentration has a negative impact on the EFP
Iqbal et al. (2021)	37 OECD countries	1970–2019	The augmented mean group (AMG) approach	Export diversification positively impacts CO_2 emissions
Liu et al. (2019)	125 countries	2000–2014	Fixed effects model with Driscoll and Kraay standard errors	Diversification of markets and horizontal export diversification increases CO_2 emissions, while vertical diversification decreases CO_2 emissions
Mania (2020)	98 developed and developing countries	1995–2013	Generalized Method of Moment (GMM), Pooled Mean Group estimations	Export diversification is positively associated with CO_2 emissions
Wang et al. (2021)	G7 countries	1990–2017	CS-ARDL approach	Export diversification contributes to increased CO_2 emissions
Zafar et al. (2022)	22 major remittance recipient countries	1986–2017	CupFM and CUP-BC and generalized quantile regression methods	Export diversification decreases CO_2 emissions
Ximei et al. (2025)	Asia–Pacific Economic Cooperation (APEC)	1991–2002	Panel Cointegration, CS- ARDL	Industrialization has ultimate damaging impact on environmental sustainability
Export diversification and energy consumption				
Lee and Ho (2022)	121 Countries	1990—2014	Panel OLS and fixed effect model	Export diversification leads to more energy intensity
Olasehinde-Williams, Lee, and Folorunsho (2023)	30 countries	1980—2014	Non-parametric time varying approach	Export diversification lowers overall energy demand
Shahbaz, Gozgor, and Hammoudeh (2019)	USA	1975—2016	Bootstrapping ARDL and VECM	Export diversification causes energy demand Economic growth increase energy consumption
Sharma et al. (2021b)	BRICS	1990—2108	Cross-sectional ARDL	Reduction in export diversification worsened the air quality in the BRICS
Economic growth, energy consumption, and environmental quality				
Ahmad et al. (2020)	22 emerging economies	1984–2016	The second-generation panel cointegration methodologies	The EKC hypothesis is confirmed
Ahmed and Wang (2019)	India	1971–2014	ARDL, VECM	The EKC hypothesis is confirmed
Alaali and Naser (2020)	Bahrain	1980- 2014	ARDL model	The EKC hypothesis is confirmed
Aşıcı & Acar (2016)	116 countries	2004–2008	Fixed effects panel data model	The EKC-type relationship revealed only between per capita income and footprint of domestic production
Awosusi et al. (2022)	BRICS economies	1990–2017	Panel quantile regression	Economic growth and non-renewable energy consumption increases the EFP

Table 1 (continued)

Authors	Country(s)	Period	Method	Finding
Boukhelkhal (2022)	Algeria	1980–2017	ARDL	Economic growth and energy consumption, and exports, contribute to environmental degradation
Bulut (2020)	Türkiye	1970–2016	DOLS estimator	The EKC hypothesis is confirmed Renewable energy consumption decreases the EFP
Charfeddine and Mrabet (2017)	15 MENA (Middle East and North African) countries	1975–2007	FMOLS and DOLS estimations	The EKC hypothesis is confirmed
Danish et al. (2020)	BRICS countries	1992–2016	Fully modified ordinary least squares (FMOLS) and dynamic ordinary least squares (DOLS) long-run estimators	The EKC hypothesis is confirmed Renewable energy decreases the EFP
Destek et al. (2018)	EU countries	1980–2013	The second generation panel data methodologies	The EKC hypothesis is confirmed
Kızılgöl and Öndes (2022)	31 OECD countries	1995–2017	The second-generation panel data methodologies	The EKC hypothesis is confirmed
Kirikkaleli et al. (2021)	Türkiye	1985–2017	Dual adjustment approach, FMOLS and DOLS methods	GDP growth decreases the EFP
Shayanmehr et al. (2023)	Top renewable energy consumption countries	1994–2018	The method of moment quantile regression (MMQR)	GDP growth and non-renewable energy consumption increases the EFP
Sogut et al. (2024)	10 European Union countries	1996–2020	The CCE and the rCCE estimators	The EKC hypothesis is confirmed
Wang et al. (2013)	150 nations	2005	Spatial econometric approach	The EKC hypothesis is not confirmed
Li et al. (2024)	BRICS	January 2000-January 2021	cross-sectional autoregressive distributed lag (CS-ARDL), augmented mean group (AMG), and common correlated effects mean group (CCEMG)	EPU increases environmental degradation by discouraging green investments and delaying sustainable development initiatives
Wang et al. (2023a)	BRICS	2000–2021	FMOLS, DOLS, AMG	EPU and economic growth increase carbon emissions, GPR reduces them by slowing economic activity
Information Technology, Artificial Intelligence, and Environmental Quality				
Sibt-e-Ali et al. (2024	Emerging Economies	1990–2021	DOLS, FMOLS, and MMQR models	technological innovation and renewable energy reduce ecological footprint, while financial globalization, economic growth, and urbanization worsen environmental degradation
Wang et al. (2023)	69 countries	1993–2019	STIRPAT modeling, mediation effect analysis, and panel threshold techniques	AI significantly reduces carbon emissions when trade openness surpasses a critical threshold
Wang et al. (2025a)	11 coastal provinces in China	2009–2020	fixed effects models, moderation effect models, and panel threshold models	AI enhances green economic efficiency, with green finance, trade openness, and R&D investment

Table 1 (continued)

Authors	Country(s)	Period	Method	Finding
Wang et al. (2025b)	67 countries	1993—2019	SYS-GMM and DPTM	AI significantly reduces ecological footprints and carbon emissions while accelerating energy transitions
Wang et al. (2025c)	51 countries	2010–1019		AI significantly promotes sustainable development

reducing these emissions. The detrimental effects of CO2 emissions in developed countries diminish as the adoption of environmental innovations rises. Consequently, the authors recommend that G7 countries enhance their use of renewable energy and implement environmentally friendly technologies. Additionally, the findings indicate that the effects of government policies on export diversification, environmental innovation, and renewable energy consumption typically become apparent approximately one year after their implementation.

Iqbal et al. [31] examined the role of export diversification, environmentally related technological innovation, and fiscal decentralization in achieving hydrocarbon neutrality in 37 OECD countries from 1970 to 2019. According to the results, export diversification and fiscal decentralization, accompanied by GDP growth, positively impact carbon dioxide emissions. At the same time, renewable energy consumption and environmentally related technological innovations help move closer to hydrocarbon neutrality. The authors recommend that OECD countries increase their share of energy consumption from renewable sources and make greater use of environmentally friendly technological innovations.

However, in the article by Zafar et al. [89], an inverse impact of export diversification on CO2 emissions was found. The authors' work examines the relationship between remittances, export diversification, education, and CO2 emissions in 22 major remittance recipient countries from 1986 to 2017. According to the obtained results, in addition to export diversification, the reduction of CO2 emissions is positively influenced by remittances and energy consumption from renewable sources. In contrast, economic growth and education promote environmental degradation. The authors explain this by the fact that the analyzed countries have yet to reach a level of education that allows for a qualitative transition from the use of energy from fossil fuels to green energy technologies.

Ali et al. [6] argue that carbon dioxide emissions alone do not provide a comprehensive measure of environmental degradation. To fully understand the ecological impacts of export diversification, research must also examine its contribution to the ecological footprint. Using Indian data from 1965 to 2017 and applying the ARDL model, the authors suggest that environmental degradation can decrease if a country diversifies its exports by producing less resource-intensive, innovative, and sophisticated products. Their findings indicate that, in the long run, export diversification reduces India's ecological footprint and helps establish an inverted U-shaped relationship among ecological footprint and economic growth. The key findings of the study highlights that more diversification in the basket of exports plays a vital role in promoting sustainable economic growth in India.

In line with [6], Bake et al. [78] utilized pooled mean ARDL approach to examine the impact of export concentration on the ecological footprint in the European Union from 1995–2018. Key findings reveal that while energy consumption increases the ecological footprint, export concentration can significantly improve the quality of the environment by having a negative impact on the ecological footprint.

In a more recent study conducted by Ximei et al. [88], the effects of information and communication technology (ICT) and economic globalization (ECG) on environmental sustainability (ENS) has been examined considering three environmental sustainability measure including: carbon dioxide emissions (CO2), ecological footprint (EFP), and load capacity factor (LCF). Using panel data analysis for Asia–Pacific Economic Cooperation (APEC) from 1991–2002, results of long-run estimation reveal that information communication technology, economic globalization, renewable energy consumption, and green financial development have the potential to enhance environmental sustainability. However, industrialization has ultimate damaging impact.

2.2 Export diversification and energy consumption

As explained above, the existing economic literature remains divided on the impact of export diversification on carbon dioxide emissions. Such a result could be derived from the sample of countries, the specification of the econometric model, and the inclusion of other independent variables that influence CO2 emissions. The negative effect of export diversification on CO2 emissions found in some studies can be explained by the inverse impact of export diversification on energy consumption found in some empirical studies. In particular, Shahbaz, Gozgor, and Hammoudeh [63] showed that other things being equal, an increase in the export diversification index by 1 percent leads to a decrease in energy consumption in the U.S. economy by 0.4692 percent. According to the authors, this is because the U.S. is focused on producing products that increase energy efficiency through a process of diversification, which in turn reduces energy demand. Thus, the authors conclude that export diversification, in the long run, leads to lower energy consumption in the United States.

A comparable result was found by Olasehinde-Williams, Lee, and Folorunsho [52], who investigated how export diversification influences energy consumption across 30 countries in the global North from 1980 to 2014. Their findings indicate that export diversification plays a significant role in reducing overall energy consumption in these developed nations, highlighting it as an effective approach for managing energy use and minimizing environmental impact. This outcome is mainly due to the widespread adoption of energy-efficient technologies in advanced economies with sophisticated production systems, along with the relocation of energy-intensive manufacturing to developing countries in the global South. As a result, developed countries benefit from reduced domestic energy demands, while shifting the environmental burden elsewhere.

Sharma et al. [68] examined the relationship between export diversification and renewable energy consumption and found that a broader export diversification margin decreases renewable energy use, whereas a more concentrated diversification margin increases renewable energy consumption in BRICS countries over the long term. Moreover, once export diversification reaches a certain threshold, further expansion leads to a reduction in the use of cleaner energy sources.

The inverse effect of export diversification on energy consumption from renewable sources was also revealed in [38] as a result of panel data analysis for 121 countries from 1990 to 2014. This effect is especially evident in countries with high technological and economic development and in European countries.

2.3 Economic growth, energy consumption, and environmental quality

Over the past decade, the relationship between economic growth and environmental quality has received considerable attention. Yielding mixed results, many researchers have not only shed light on this relationship, but also examined the Environmental Kuznets Curve (EKC) hypothesis, which proposes an inverted U-shape relationship between economic growth and environmental degradation.

Ahmad et al. [1] conducted a thorough investigation into the Environmental Kuznets Curve (EKC) hypothesis across 22 emerging economies over a 32-year period, from 1984 to 2016. By employing advanced second-generation panel cointegration methodologies, they provided robust evidence supporting the EKC hypothesis, suggesting that as these economies grew, environmental degradation initially increased but eventually began to decline as per capita income reached higher levels.

In a more focused study on India, Ahmed and Wang [2] examined data from 1971 to 2014. They used the Autoregressive Distributed Lag (ARDL) and Vector Error Correction Model (VECM) techniques to investigate the income-environment relationship. Their results aligned with the EKC hypothesis, showing that India's environmental impact first increased with economic growth, then decreased as income continued to rise, pointing toward a turning point in pollution levels as economic prosperity deepened.

Turning to Bahrain, Alaali and Naser [4] also confirmed the EKC hypothesis. They analyzed the period from 1980 to 2014 using the ARDL model, finding that Bahrain's economic growth initially contributed to environmental degradation. However, as the country developed further, the pollution levels stabilized and then showed a decline, indicating an EKC-like curve for Bahrain's development pattern.

Aşıcı and Acar [10] expanded their scope significantly by examining 116 countries from 2004 to 2008, applying a fixed-effects panel data model to assess the EKC hypothesis. They discovered an EKC-type relationship specifically between per capita income and the ecological footprint related to domestic production, illustrating that economic growth impacted the ecological footprint in a pattern consistent with the EKC hypothesis across diverse countries.

In Turkey, Bulut [15] focused on the years 1970 to 2016 and employed the Dynamic Ordinary Least Squares (DOLS) estimator. His findings reinforced the EKC hypothesis, indicating that Turkey experienced an initial increase in environmental degradation followed by a decline as income rose, affirming the EKC hypothesis within the Turkish context.

Charfeddine and Mrabet [19] explored this relationship among 15 Middle Eastern and North African (MENA) countries, using data from 1975 to 2007. Their analysis utilized Fully Modified Ordinary Least Squares (FMOLS) and DOLS estimation methods, both of which validated the EKC hypothesis across these MENA nations, suggesting that as incomes improved, environmental degradation eventually slowed and began to reverse.

Danish et al. [23] examined the BRICS countries, analyzing data from 1992 to 2016. Applying FMOLS and DOLS long-run estimators, they confirmed the EKC hypothesis, illustrating that the BRICS economies followed the EKC pattern with initial increases in environmental degradation that subsequently decreased as economic growth advanced.

In a European Union-focused study, Destek et al. [26] evaluated 28 EU countries from 1980 to 2013, using second-generation panel data methodologies. Their findings again supported the EKC hypothesis, indicating that environmental degradation in the EU countries initially increased but later showed reductions as these economies matured.

Further examining developed nations, Kızılgöl and Öndes [35] looked at 31 OECD countries from 1995 to 2017. Through second-generation panel data methodologies, they confirmed the EKC hypothesis, providing evidence that the EKC relationship held across high-income countries, where initial environmental degradation leveled off and began to decline as income rose.

A recent study by Sogut et al. [72] focused on 10 European Union countries from 1996 to 2020, using the Common Correlated Effects (CCE) and Robust Common Correlated Effects (rCCE) estimators. Their analysis confirmed the EKC hypothesis, reinforcing the finding that economic growth in these EU countries followed a path where initial increases in pollution eventually tapered and decreased as income levels climbed.

In contrast, Wang et al. [86] took a different approach, analyzing data from 150 countries in 2005 using spatial econometric techniques. Their study did not confirm the EKC hypothesis, suggesting that the relationship between income and environmental degradation is not universally consistent across all nations and may vary significantly depending on regional and spatial factors.

Shayanmehr et al. [69] conducted a focused study on countries with high renewable energy consumption between 1994 and 2018, investigating the relationship between economic growth and environmental impact. Using the method of moment quantile regression (MMQR), they explored how GDP growth influences the ecological footprint (EFP) across various quantiles of the data. Their findings suggested that in these top renewable energy-consuming countries, an increase in GDP growth still led to a rise in the ecological footprint, implying that even with a strong renewable energy presence, economic expansion continued to place pressure on the environment. This study presents a unique perspective on the Environmental Kuznets Curve (EKC) hypothesis, as it highlights the challenges in achieving environmental sustainability solely through economic growth and renewable energy consumption.

Kirikkaleli et al. [34] examined the relationship between economic growth and environmental footprint in Türkiye over the period from 1985 to 2017. Using a dual adjustment approach alongside Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares (DOLS) methods, the researchers found that GDP growth in Türkiye has a negative impact on the environmental footprint, suggesting that increases in economic growth correlate with a reduction in environmental pressure during this time frame.

Boukhelkhal [14] explores the factors influencing Algeria's ecological footprint, serving as a proxy for environmental quality, over the period from 1980 to 2017, using various economic indicators. The study also aims to assess the impact of social indicators—specifically, education and life expectancy—on environmental quality. Employing the autoregressive distributed lags (ARDL) method, the study estimates models of environmental degradation. Results indicate that imports significantly reduce the ecological footprint in both the short and long term, contrasting with economic growth, energy consumption, exports, and natural resource rents, all of which contribute to environmental degradation. Additionally, the findings reveal that in the short term, education and life expectancy increase environmental degradation. Over the long term, however, education begins to reduce environmental degradation, while life expectancy continues to increase it. Based on these insights, the study offers recommendations for enhanced management of Algeria's natural and human resources, providing guidance for policymakers on advancing sustainable development.

Li et al. [39] examines the impact of geopolitical risk and economic policy uncertainty on environmental sustainability in BRICS countries. Using panel data from January 2000-January 2021, advanced econometric models such as the cross-sectional autoregressive distributed lag (CS-ARDL), augmented mean group (AMG), and common correlated effects mean group (CCEMG) have been employed. Key results show that EPU exacerbates environmental degradation by discouraging green investments and delaying sustainable development initiatives. Conversely, GPR is associated with a reduction in ecological footprint, likely due to economic slowdowns that temporarily curb energy consumption and industrial activity. The findings highlight the need for policy interventions that mitigate the negative environmental consequences of economic uncertainty, including strengthening governance structures, stabilizing economic policies, and fostering international cooperation to achieve sustainability goals.

Jiatong et al. [32] examine the impact of economic policy uncertainty (EPU) and geopolitical risk (GPR) on environmental pollution, assessing whether renewable energy consumption (REC) mitigates these effects. Using panel data from 2000–2021 and econometric models (FMOLS, DOLS, AMG), the study finds that EPU and economic growth drive carbon emissions, while GPR reduces them by slowing economic activity. REC plays a crucial role in offsetting environmental damage, and well-managed urbanization can support sustainability. The study underscores the need for stable policies, international cooperation, and green energy investments to counteract environmental risks.

2.4 Information technology, artificial intelligence, and environmental quality

Technological advancements, particularly in information technology (IT) and artificial intelligence (AI), have increasingly been explored for their role in shaping environmental quality, energy transitions, and carbon emission reductions. The integration of these technologies into sustainability efforts offers both opportunities and challenges, requiring nuanced policy approaches to maximize their benefits while mitigating their potential drawbacks.

Sibt-e-Ali et al. [70] examine the impact of technological innovation, climate technology, energy transition, financial globalization, and economic growth on ecological footprint in emerging economies (1990–2021). Using Dynamic Ordinary Least Squares (DOLS), Fully Modified Ordinary Least Squares (FMOLS), and Method of Moments Quantile Regression (MMQR) models, the study finds that technological innovation and renewable energy reduce ecological footprint, while financial globalization, economic growth, and urbanization worsen environmental degradation. The results highlight the need for policies that promote green technology and sustainable energy transitions to balance economic growth with environmental sustainability.

Building on this, AI has emerged as a powerful tool for enhancing energy efficiency, reducing carbon emissions, and facilitating sustainable economic growth. Wang et al. [85] investigate AI's role in energy transition and carbon emissions reduction using panel data from 69 countries from 1993 to 2019. Applying STIRPAT modeling, mediation effect analysis, and panel threshold techniques, the study finds that trade openness mediates AI's environmental impact—AI only significantly reduces carbon emissions when trade openness surpasses a critical threshold. Similarly, AI's effectiveness in accelerating energy transitions is amplified under higher levels of trade openness, emphasizing the importance of economic integration in maximizing AI's environmental benefits. However, concerns persist regarding AI's high energy consumption, particularly in data storage and cooling systems, which could offset its sustainability advantages.

Further, Wang et al. [83] explore AI's impact on green economic efficiency, specifically in marine fisheries, using panel data from 11 coastal provinces in China from 2009 to 2020. Employing fixed effects models, moderation effect models, and panel threshold models, the study finds that AI enhances green economic efficiency, with green finance, trade openness, and R&D investment playing critical roles in strengthening its effects. However, regional disparities exist, highlighting the need for targeted policies that account for differences in technological readiness and economic structures across countries.

Expanding on AI's transformative potential, Wang et al. [82] provide a comprehensive review of AI's role in energy transition, highlighting its contributions to renewable energy deployment, energy efficiency, and smart grid stability. AI enhances photovoltaic array optimization, demand-side energy management, and energy distribution through smart grids and vehicle-to-grid systems. Additionally, AI fosters advancements in blockchain, IoT-based energy solutions, and predictive energy analytics, reinforcing its pivotal role in driving global decarbonization and net-zero targets. Nonetheless, challenges remain, including data security risks, interoperability issues, and ethical concerns, necessitating carefully designed regulatory frameworks and global cooperation to ensure sustainable AI-driven energy transitions.

Beyond energy and emissions, Wang et al. [81] examine AI's influence on ecological footprints, carbon emissions, and energy transitions in 67 countries (1993 -2019) using System Generalized Method of Moments (SYS-GMM) and Dynamic Panel Threshold Models (DPTM). The findings confirm that AI significantly reduces ecological footprints and carbon emissions while accelerating energy transitions, with the strongest effect observed in energy transitions. The study's nonlinear analysis provides key insights: (i) industrial sector expansion weakens AI's ability to reduce ecological footprints and carbon emissions but strengthens its role in energy transitions; (ii) higher trade openness enhances AI's impact on carbon reduction and energy transitions; (iii) the environmental benefits of AI are most pronounced in highly AI-developed economies; and (iv) as the energy transition deepens, AI's effectiveness in reducing ecological footprints and carbon emissions increases, while its role in further advancing energy transitions diminishes.

Finally, Wang et al. [84] explore AI's role in sustainable development during urbanization across 51 countries, focusing on AI R&D innovation, infrastructure, and market advantage. Using panel data for the period from 2020 to 2019 and threshold modeling, the study finds that AI significantly promotes sustainable development, with AI R&D innovation having the strongest effect, followed by AI infrastructure, while AI market advantage has the smallest impact. The study also identifies a threshold effect of urbanization: when urbanization is low, AI R&D innovation and infrastructure promote sustainability, while AI market advantage inhibits it. However, when urbanization surpasses a critical level, AI infrastructure begins to hinder sustainable development, the impact of AI R&D innovation diminishes, and AI market advantage turns positive. These findings emphasize the importance of aligning AI-driven sustainability policies with urbanization levels to optimize AI's contribution to sustainable development goals (SDGs).

3 Research gap and contributions

Despite extensive research on the relationship between export diversification and environmental sustainability, findings remain inconclusive. Some studies suggest that export diversification exacerbates environmental degradation, while others argue it mitigates pollution. However, the impact of export diversification on ecological footprint is still underexplored, particularly when disaggregated by country groups and industries. Existing research lacks a nuanced approach that accounts for the varying effects in developed and developing economies.

To address this gap, this study investigates the role of export diversification in shaping environmental sustainability using the Theil index as a measure of export concentration. By analyzing its impact on the ecological footprint globally, in developing countries, and in developed countries, this research contributes to the existing literature in threefold. First, it provides a context-specific analysis by distinguishing the impact of export diversification on the ecological footprint across developed and developing countries, addressing inconsistencies in previous studies and offering a nuanced understanding of trade-environment dynamics. Second, it enhances the accuracy of estimates through the use of disaggregated data, incorporating country- and sector-specific information to offer a more detailed perspective on how export structures influence environmental sustainability. Finally, it provides policy implications by offering targeted recommendations that help policymakers design sustainable trade strategies that balance economic growth with environmental protection. To be precise, this study aims to examine the following hypotheses:

H_1: The Theil index has a significant positive impact on the long-term ecological footprint globally (because a higher value of the Theil index indicates a higher degree of export concentration, the hypothesis means that export diversification has a significant negative impact on the ecological footprint in the long term).

H_2: In developing countries, the Theil index has a significant positive impact on the ecological footprint in the long term (export diversification has a significant negative impact on the ecological footprint in developing countries).

H_3: In developed countries, the Theil index has a significant negative impact on the ecological footprint in the long term (export concentration has a significant negative impact on the ecological footprint in developed countries).

4 Data and model construction

The study utilizes data from 87 countries from 1995 to 2014 to investigate export diversification's effect on ecological footprint. In our analysis, the dependent variable is the ecological footprint of consumption per person. This indicator is a comprehensive measurement of environmental deterioration [74]. The ecological footprint measures "the ecological assets that a given population or product requires to produce the natural resources it consumes (including plant-based food and fiber products, livestock and fish products, timber, and other forest products, space for urban infrastructure) and to absorb its waste, especially carbon emissions." [28]. The Ecological Footprint is the only measurement that compares individuals', governments', and businesses' resource demands with the Earth's biological regeneration capacity [28].

According to our hypothesis, export diversification can mitigate the ecological footprint. Including innovative green products in the export structure will favor the environment [6]. We employ the Theil entropy index and its intensive and extensive margins to measure export diversification. The data for this index is derived from the IMF database. The intensive, extensive, and overall Theil indices were calculated according to the explanations and techniques employed by [16]. The intensive margin assesses changes in export values associated with established export products. In contrast, the extensive margin indicates changes in the number of new export commodities or new destinations for existing exports [16].

Following the IMF methodology, before constructing the overall Theil Index and its components, each product in the export structure of the country was specified as "traditional," "new," or "non-traded." Commodities exported at the sample's beginning were defined as "traditional" goods, whereas items with zero exports for the whole sample were determined as "non-traded" goods. The dummy values for these categories of goods remained consistent throughout all years in the sample. Products classified as "new" were absent from the export portfolio for at least the preceding two years and subsequently exported during the following two years. The dummy values associated with new commodities can fluctuate over time. The extensive Theil index is computed for each country/year combination using the following formula:

$$T_B = \sum_{k=0}^{K} \frac{N_k}{N} \frac{\mu_k}{\mu} \ln(\frac{\mu_k}{\mu}) \quad (1)$$

where k stands for each group of products (traditional, non-traded, new), N_k is the total number of products exported in each group, and $\frac{\mu_k}{\mu}$ is the relative mean of exports in each group.

The following formula calculates the intensive Theil index for each country/year combination:

$$T_w = \sum_{k=0}^{K} \frac{N_k}{N}\frac{\mu_k}{\mu}\left[\frac{1}{N_k}\sum_{i\in I_k}\frac{x_i}{\mu_k}\ln\left(\frac{x_i}{\mu_k}\right)\right] \quad (2)$$

where x denotes export value.

The total Theil index is the combination of extensive and intensive margins. An economy with a smaller Theil index has a more diversified export composition [30].

The advantage of the Theil index over other measurements of export diversification, like the Herfindahl–Hirschman Index (HHI), is that it can be decomposed into within-group (intensive margin) and between-group (extensive margin) components. This decomposition helps to identify the impact of structural sources of diversification (changes in shares of established products in total exports or entering new export product categories). The analysis with intensive and extensive margins is particularly valuable in understanding the effects of specific drivers of export diversification on the ecological footprint in developed and developing economies and in elaborating actionable policy recommendations for improving environmental quality.

In our study, we included three control variables that have been empirically shown to be crucial factors influencing the ecological footprint. Economic growth, a factor widely acknowledged to contribute to environmental degradation [1, 3, 23, 35], was a key consideration. We also incorporated GDP per capita and its quadratic terms to explore the possibility of a hump-shaped relationship between economic growth and ecological footprint, in line with the theoretical framework of the Environmental Kuznets Curve (EKC) hypothesis. Moreover, we took into account the adverse effect of fossil fuel energy consumption on the ecological footprint [51, 62], and the direct impact of renewables on the environment [23, 26, 41, 67, 77] based on robust empirical evidence.

The relationship between export diversification and ecological footprint is estimated using the following equation:

$$ln(EFP)_{it} = \alpha_0 + \alpha_1 GDPpc_{it} + \alpha_2 (GDPpc_{it})^2 + \alpha_3 DIV_{it} + \alpha_4 X'_{it} + \varepsilon_{it} \quad (3)$$

In this equation, $ln(EFP)_{it}$ is the natural logarithm of the ecological footprint of consumption per person; $GDPpc_{it}$ denotes GDP per capita; $(GDPpc_{it})^2$ is the quadratic term of GDP per capita; DIV_{it} stands for the Theil index or its components (extensive margin (DIV_EM_{it}) and intensive margin (DIV_IM_{it})); X'_{it} indicates the vector of control variables; α_0 is a constant; ε_{it} refers to the error term; $\alpha_1, \alpha_2, \alpha_3, \alpha_4$ are estimated coefficients (α_4– vector of coefficients); i denotes countries ($i = 1 \ldots N$); t represents years ($t = 1 \ldots T$).

The descriptions of variables employed in the investigation and their data sources are presented in Table 2. The data for the ecological footprint per capita comes from the Global Footprint Network website. The overall, extensive, and intensive Theil indices are sourced from the IMF statistics database. For GDP per capita (adjusted to constant 2015 US dollars), fossil fuel energy consumption (as a percentage of total), and renewable electricity production (as a percentage of total), we refer to the World Bank's World Development Indicators (WDI) database. This study draws on annual data from 87 countries from 1995 to 2014. The inclusion of countries in the sample depended on data availability. The data set is restricted to 2015 because information on the Theil index became unavailable after 2014.

We divided our general sample into two sub-samples according to the IMF country classification. The first sub-sample includes 59 emerging market and middle-income economies and low-income developing countries (developing countries). The second sub-sample consists of 28 advanced economies (developed countries). The sub-samples were defined to investigate and compare the impact of export diversification on the ecological footprint in developed and developing economies separately.

As developed and developing countries have structural economic differences due to their distinct sectoral composition, productivity levels, integration into global markets, and institutional frameworks, the impact of export diversification on environmental sustainability may vary between these groups. Developed economies are characterized by the prevalence of the tertiary sector and knowledge-based industries with a large share of high-value-added products and services in total exports. In contrast, many developing countries still rely heavily on primary industries and exhibit limited diversification into manufacturing or modern services. Differences in technological advancement and innovations cause a gap in productivity levels in developed and developing countries, explaining the dominance of advanced economies in high-technology exports and the prevalence of many developing economies in labor-intensive industries and low-value

Table 2 Variables and data sources. Source: Authors

Variable used	Descriptions	Data source
Ecological footprint per person (LnEFP)	It is expressed in global hectares per person	Global Footprint Network
GDP per capita (GDPpc)	GDP per capita (in constant 2015 US dollar)	World Development Indicators
Quadratic term of GDP per capita ($GDPpc^2$)	Quadratic term of GDP per capita (in constant 2015 US dollar)	World Development Indicators
Theil Index (DIV)	Overall measure of export diversification. Higher values indicate lower diversification	International Monetary Fund
Intensive Margin (DIV_IM)	Reflects the concentration in the export volumes across active products	International Monetary Fund
Extensive margin (DIV_EM)	Indicates the concentration in the number of products by country	International Monetary Fund
Fossil fuel energy consumption (FFEC)	Consumption of energy generated from fossil fuel (coal, oil, petroleum, and natural gas products), % of total energy consumption	World Development Indicators
Renewable electricity output (REO)	Electricity generated by renewable power plants (% of total electricity generated by all types of plants)	World Development Indicators

exports. Therefore, economic diversification is crucial for developing economies to reduce their dependence on commodity exports, promote structural transformation, and ensure sustainable long-term economic growth [30].

The relative dominance of primary, secondary, and tertiary sectors significantly influences the environmental impact of economic activities. The primary and secondary sectors, particularly heavy industries, are characterized by high resource utilization, substantial energy consumption, and a larger ecological footprint [90]. Transitioning from resource-intensive sectors to lighter manufacturing and service industries may lead to reduced ecological impacts. Economies that shift towards service-based sectors can experience adverse spatial spillover effects on their ecological footprints [8]. Our analysis aims to investigate the varied impacts of export diversification and sectoral transitions on ecological footprints in both advanced and developing economies.

5 Econometric methodology

The effect of export diversification on the ecological footprint was explored using the panel autoregressive distributed lag (panel ARDL) approach. Figure 1 illustrates the particular stages of the study, which will be elaborated on in detail below.

First, we tested our panel data for cross-sectional dependence, reflecting interdependence among the countries. Given the limited duration of the study period (20 years) and the relatively large number of countries in the panel (87), Pesaran's cross-sectional dependence (CD) test is deemed more robust [67]. The null hypothesis for the Pesaran [55] CD test posits cross-section independence, which cannot be rejected if the p-values are above 0.01, 0.05, or 0.1. It means the presence of cross-sectional association due to global shocks with heterogeneous impacts on individual countries or spillover effects between countries [44]. The formula for computing the inter-country dependency is as follows:

$$CD = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\rho_{ij}\right) \rightarrow N(0,1) \tag{4}$$

where ρ_{ij} is the estimated pairwise correlation coefficient between the time series for country i and j.

Second, we applied the second-generation unit root tests to check the unit root properties of our variables. Considering the possibility of cross-sectional dependence, we verified the stationarity of the variables with the Pesaran unit root tests [56], which allows for the presence of inter-country dependency in the panel. The test's null hypothesis is homogeneous non-stationary. Rejection of the null hypothesis reveals the stationarity of panels.

Third, we applied Pedroni [53] and Westerlund [87] tests to identify a cointegration between variables. If panels are cointegrated, we can estimate a long-run relationship between variables. Pedroni [53] and Westerlund [87] tests operate under the assumption of a panel-specific cointegrating vector, allowing for individual slope coefficients across the panels. Pedroni's approach examines unit roots in the estimated residuals, and panel cointegration tests are derived using Augmented Dickey-Fuller (ADF) regression. Conversely, Westerlund's methodology generates AR test statistics by assessing unit roots in the predicted residuals through Dickey-Fuller (DF) regression. Both techniques yield test statistics based on a model where the autoregressive (AR) parameter may be specific to each panel or uniform across them. The panel-specific AR test statistic evaluates the null hypothesis of no cointegration among the panels against the alternative hypothesis that all panels exhibit cointegration.

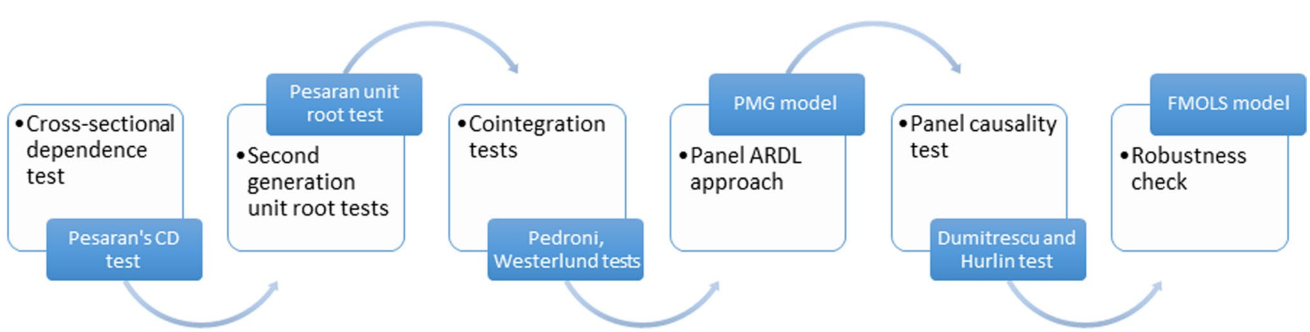

Fig. 1 Flow of empirical analysis. Source: Authors

Fourth, upon confirming cointegration among the panels, we utilized the Pooled Mean-Group (PMG) model [58] to investigate the effects of the regressors on the ecological footprint in the short-run and long-run perspective. This approach, a variant of the panel Autoregressive Distributed Lag (ARDL) method, enables the estimation of variable coefficients in the long run when cointegration is established. In the PMG model, while the long-run coefficients are consistent across the panel, the short-run coefficients are tailored to each specific group [44]. PMG combines pooled estimation for long-run parameters with averaging for short-rum parameters.

PMG model is specified using the following equation:

$$\Delta y_{it} = \theta_i\left(y_{i,t-1} - \beta\prime x_{i,t-1}\right) + \sum_{j=1}^{p-1} \gamma_{ij}\Delta y_{i,t-j} + \sum_{j=1}^{q-1} \gamma\prime_{ij}\Delta x_{i,t-j} + \mu_i + \varepsilon_{it} \quad (5)$$

where θ_i is the error correction speed of the adjustment parameter; $x_{i,t-1}$ are the explanatory variables; $\beta\prime$ represent the estimated parameter in the long run; $\gamma_{ij}, \gamma\prime_{ij}$ are the estimated coefficients in the short run; μ_i denote fixed effects; ε_{it} refer to the error terms.

The basic assumptions of the PMG estimator are as follows: (1) the error terms are serially uncorrelated and are distributed independently of the regressors; (2) there exists a long-run relationship between the dependent and explanatory variables; and (3) the long-run parameters are the same across the groups [58].

One notable advantage of the Pooled Mean-Group (PMG) model is its ability to accommodate distinct short-run dynamic specifications across different countries while maintaining uniformity in the long-run coefficients [58]. Additionally, in contrast to Dynamic Ordinary Least Squares (DOLS) and Fully Modified Ordinary Least Squares (FMOLS), the PMG estimator places greater emphasis on the dynamic relationship between short-run adjustments and long-run equilibrium. The rationale for assuming that short-run dynamics and error variances are identical is less compelling. Given that short-run slope coefficients need not be equal, the dynamic specifications can differ among countries [12].

The PMG method is more efficient than the Mean Group (MG) estimator if long-run homogeneity is maintained. It is also less restrictive than the Dynamic Fixed Effects (DFE) model, which requires homogeneity of all parameters. According to Pesaran and Smith [57], fixed effects, instrumental variables, and Generalized Method of Moments (GMM) estimators may yield inconsistent and potentially misleading estimates of average parameter values in dynamic panel data models when the slope coefficients vary significantly across groups. In such cases, it is more appropriate to use an estimator that imposes weaker homogeneity assumptions [58]. The PMG estimator is a hybrid approach that provides consistent long-run estimates while capturing the diversity in short-run adjustments across different groups. For example, in panels of countries with similar economic structures, PMG captures cross-country similarities in long-term trends while accounting for short-term differences.

The PMG model is applicable in analyzing cross-country growth drivers and is suitable for testing hypotheses about long-run equilibrium relationships under heterogeneous short-run dynamics [71].

Fifth, we performed a Granger non-causality test on heterogeneous panel data models using the methods described by Dumitrescu and Hurlin [27]. This test accounts for cross-sectional dependence by employing bootstrapped critical values instead of asymptotic ones. It is suitable for unbalanced panels or panels with different lag orders for each variable.

The Granger causality test is based on the following equation:

$$Y_{it} = \sigma_i + \sum_{k=1}^{K} \varphi_i^{(k)} y_{i,t-k} + \sum_{k=1}^{K} \gamma_i^{(k)} x_{i,t-k} + \varepsilon_{it} \quad (6)$$

where x and y—stationary variables observed for N individuals (i = 1,…,N) on T periods (t = 1,…,T), σ_i—individual effects, K—lag orders, $\varphi_i^{(k)}$—autoregressive parameters, $\gamma_i^{(k)}$– slopes of regression coefficients, ε_{it}—error term.

The null hypothesis for the test asserts that no cross-sectional units in the panel have a causal relationship. The alternative hypothesis indicates the presence of heterogeneous causality.

Finally, we checked the robustness of the PMG estimation results by incorporating another proxy for export diversification, namely UNCTAD's product concentration index of exports, into Eq. (3) instead of the overall Theil index. We also applied a panel fully modified ordinary least squares (FMOLS) method to assess the reliability of the study's findings. FMOLS is a nonparametric approach for dealing with serial correlation. A panel FMOLS model is applied to correct both endogeneity bias and serial correlation problems in the panel data [54]. FMOLS is considered an appropriate technique to examine long-run relationships in the case of cointegrated panels. We also checked the robustness of our findings by using CO2 emissions per capita as a dependent variable in the Eq. (3).

6 Results and discussion

Table 3 presents the descriptive statistics for the variables used in the study covering the years 1995 to 2014. EFP per person ranges from 0.490 to 8.970, with a mean of 3.311 global hectares (Gha). The ecological footprint significantly varied in the selected countries during the period analyzed. The mean ecological footprint is notably higher in developed countries (5.666 Gha) compared to developing countries (2.194 Gha), confirming the opinion that advanced economies contribute the most to climate change. The average Theil index (DIV) stands at 2.881. The lowest recorded value is 1.147, indicating a low degree of export concentration, while the highest value of 6.417 signifies a high degree of export concentration. The mean of DIV in developed countries (2.084) is lower than in developing countries (3.259), indicating that advanced economies have a more diversified export portfolio. The intensive margin component of export diversification dominates the overall Theil index, demonstrating that export diversification occurs mainly due to the convergence in export volumes across active products.

GDP per capita ranges from 217.6 USD in low-income developing countries to 83,394 USD in advanced economies, with a mean of 13,055 USD. The GDP per capita series has shown a significant standard deviation in the general sample and two sub-samples during the study period. FFEC ranges from 3.226% to 99.804%, with a mean of 66.314%. The mean of REO constitutes 34.485%. The mean of FFEC is larger in advanced nations, whereas the mean of REO is higher in developing countries over the analysis period.

We created scatter plots to investigate the presence of an inverted U-shaped relationship between income per capita and the ecological footprint, which aligns with the EKC. In these plots, GDP per capita values are represented on the X-axis, while the ecological footprint of consumption per person is shown on the Y-axis. Figures 2, 3 and 4

Table 3 Descriptive statistics. Source: Authors

Variables	Obs	Mean	Std. Dev	Min	Max
General sample					
EFP	1740	3.311	2.023	0.490	8.970
DIV	1740	2.881	1.089	1.174	6.417
DIV_IM	1740	2.586	0.892	1.134	5.258
DIV_EM	1740	0.295	0.421	-0.043	2.399
GDPpc	1740	13,055	16,705	217.6	83,394
$GDPpc^2$ (mln. USD)	1740	449.3	994.4	0.047	6955
FFEC	1739	66.314	26.710	3.226	99.804
REO	1740	34.485	31.854	0	100
Developing countries					
EFP	1180	2.194	1.242	0.490	7.038
DIV	1180	3.259	1.082	1.597	6.417
DIV_IM	1180	2.880	0.885	1.379	5.258
DIV_EM	1180	0.380	0.480	-0.043	2.399
GDPpc	1180	3920	3196	217.6	15,649.4
$GDPpc^2$ (mln. USD)	1180	25.577	37.712	0.047	244.90
FFEC	1179	62.649	29.073	3.226	99.804
REO	1180	38.239	33.494	0	100
Developed countries					
EFP	560	5.666	1.138	2.535	8.971
DIV	560	2.084	0.531	1.174	3.881
DIV_IM	560	1.968	0.505	1.134	3.705
DIV_EM	560	0.117	0.131	– 0.022	0.565
GDPpc	560	32,303	17,299.6	4936	83,394
$GDPpc^2$ (mln. USD)	560	1342	1377	24.364	6955
FFEC	560	74.030	18.680	14.490	99.085
REO	560	26.573	26.418	0.045	99.715

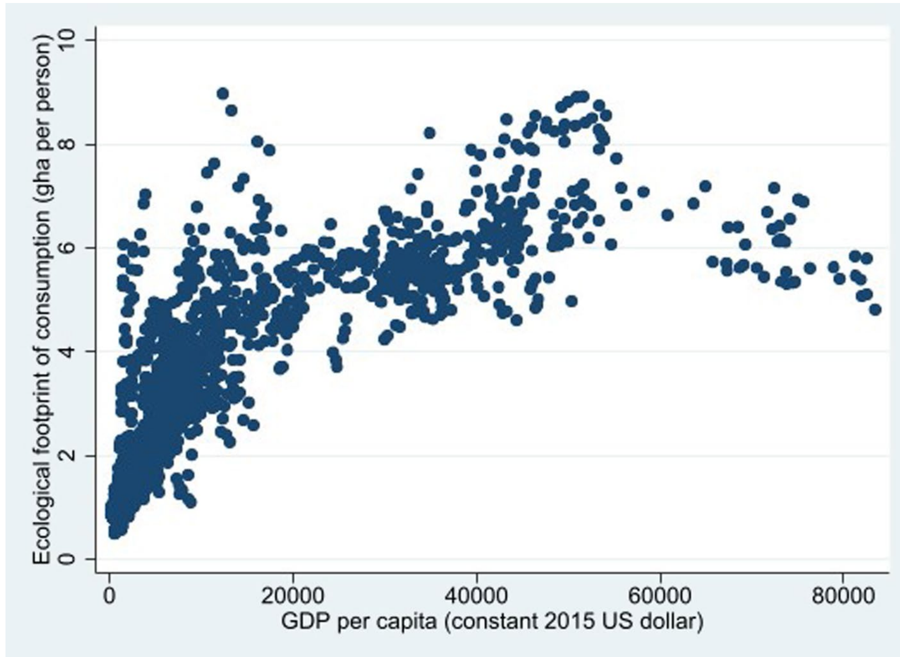

Fig. 2 Relationship between GDP per capita and ecological footprint (general sample, 1995–2014). Source: Authors

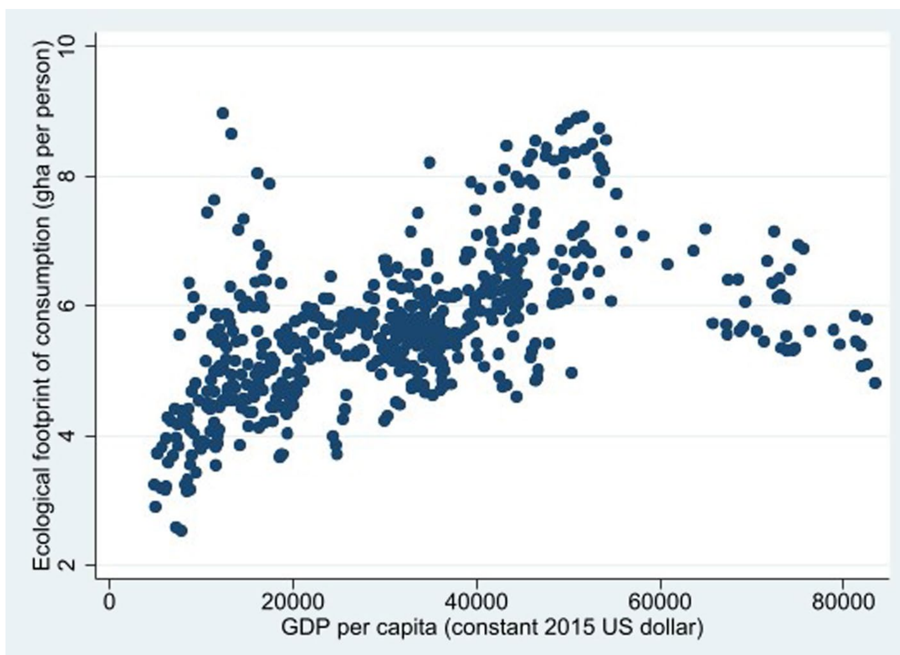

Fig. 3 Relationship between GDP per capita and ecological footprint (developed countries, 1995–2014). Source: Authors

illustrate a hump-shaped association between per capita GDP and ecofootprint for the global sample and the groups of developed and developing countries.

According to the EKC hypothesis, the initial stages of economic development are associated with an increase in the ecological footprint. However, the ecological footprint decreases as income rises and reaches a certain GDP per capita threshold. In our analyzed sample, the turning point for the overall group and developed countries occurs at an income level between USD 40,000 and USD 60,000, while for developing economies, this threshold is above USD 10,000. The scatter plots seem to be compatible with the EKC hypothesis.

Table 4 presents the findings from the cross-sectional dependence test. Pesaran's test results reveal that the data series exhibits cross-sectional dependence. The null hypothesis of cross-section independence is rejected for all variables

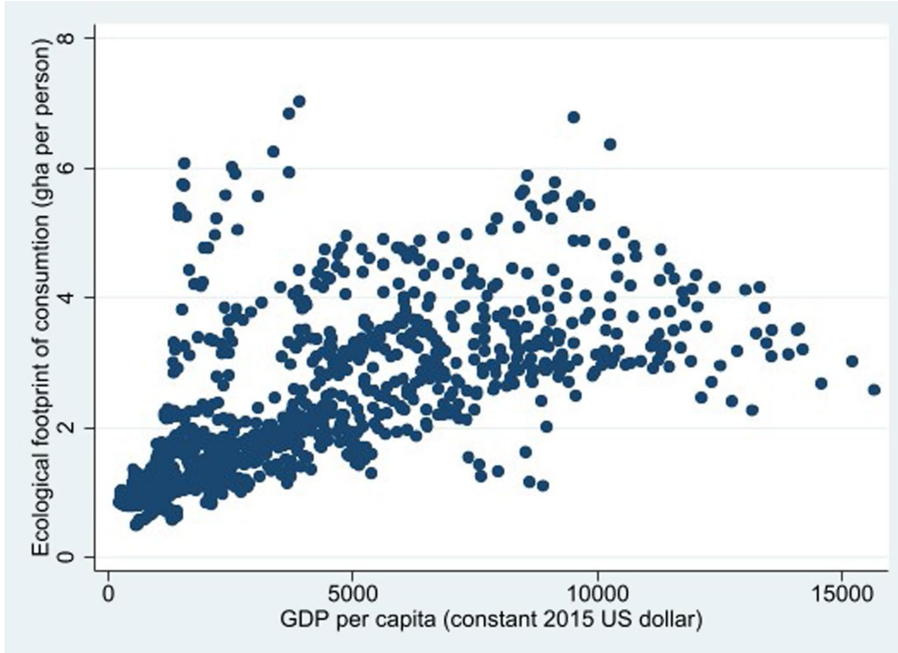

Fig. 4 Relationship between GDP per capita and ecological footprint (developing countries, 1995–2014). Source: Authors

except for FFEC, as the p-values are below 0.01. This suggests a long-term cross-country correlation among the specified variables.

We applied second-generation panel unit-root tests to determine the series' stationarity at the level or first difference. The unit root characteristics of our variables were evaluated using the Pesaran tests, which account for cross-sectional dependence in panel data [56]. The results from the Pesaran test in Table 5 suggest that all series are stationary at the first difference. This result confirms the soundness of using the PMG model, as it does not support variables that may be stationary only at a second difference.

We utilized the Pedroni [53] and Westerlund [87] tests to assess the cointegration among the variables. The results of Westerlund's cointegration test are displayed in Table 6, while Table 7 presents Pedroni's cointegration test findings. The null hypothesis of no cointegration across the panels is rejected, as the p-values are below 0.1, 0.05, and 0.01. As the panels are cointegrated, we can estimate the PMG model to obtain the long-run and short-run coefficients. The sign of the error correction term (ECT) must be negative and significant for estimating the common coefficients in the long run.

We investigate the impact of export diversification on the ecological footprint based on Eq. (3) in the following modifications: (1) LnEFP—dependent variable; DIV—the key explanatory variable; GDPpc, GDPpc2, FFEC, REO—control variables. (2) LnEFP—dependent variable; DIV_IM—the key explanatory variable; GDPpc, GDPpc2, FFEC, REO—control variables. (3) LnEFP—dependent variable; DIV_EM—the key explanatory variable; GDPpc, GDPpc2, FFEC, REO—control variables.

Table 8 provides the outcomes of the PMG estimation for the general sample, which are based on data from 1995 to 2014 for 87 countries.

Table 4 Cross-sectional dependence test. Source: Authors

Variables	CD-test	p-value
EFP	24.00	0.000
DIV	16.16	0.000
DIV_IM	26.21	0.000
DIV_EM	18.91	0.000
GDPpc	203.00	0.000
$GDPpc^2$	200.93	0.000
FFEC	1.42	0.155
REO	14.03	0.000

Table 5 Panel unit root tests. Source: Authors

Variables	CIPS (General sample)		CIPS (Developing countries)		CIPS (Developed countries)	
	I(0)	I(1)	I(0)	I(1)	I(0)	I(1)
EFP	– 2.763***	– 4.942***	– 2.761***	– 4.755***	– 3.328***	– 5.015***
DIV	– 2.362	– 4.028***	– 2.460	– 3.967***	– 2.258	– 4.282***
DIV_IM	– 3.331***	– 4.472***	– 3.424***	– 4.506***	– 3.147***	– 4.689***
DIV_EM	– 2.441	– 4.133***	– 2.549*	– 4.067***	– 2.213	– 4.324***
GDPpc	– 1.657	– 3.078***	– 2.182	– 3.285***	– 2.017	– 2.768**
$GDPpc^2$	– 1.327	– 3.064***	– 1.887	– 3.025***	– 1.692	– 2.833***
FFEC°	0.397	– 5.972***	1.386	– 4.482***	– 1.426	– 6.409***
REO	– 2.784***	– 4.471***	– 2.888***	– 4.389***	– 3.164***	– 4.868***

Critical values: – 2.53 at 10%, – 2.59 at 5%, – 2.72 at 1% (general sample and developing countries).

Critical values: – 2.58 at 10%, – 2.67 at 5%, – 2.83 at 1% (developed countries)

***significance at 1% level

**significance at 5% level

*significance at 10% level

°Pesaran's CADF test for FFEC

Table 6 Results of Westerlund cointegration test. Source: Authors

Models	Statistics	p-value
General sample		
Equation with DIV	– 2.4068	0.0080
Equation with DIV_IM	– 2.4181	0.0078
Equation with DIV_EM	– 2.1857	0.0144
Developing countries		
Equation with DIV	– 1 0.6841	0.0461
Equation with DIV_IM	– 1.7018	0.0444
Equation with DIV_EM	– 1.6068	0.0541
Developed countries		
Equation with DIV	– 1.9709	0.0244
Equation with DIV_IM	– 1.9651	0.0247
Equation with DIV_EM	– 1.5990	0.0549

The Error Correction Term (ECT) reveals that the ecological footprint achieves long-run equilibrium at a rate of – 0.490 in the equation involving the overall Theil index (DIV) and rates of – 0.493 and – 0.462 in the equations with intensive (DIV_IM) and extensive (DIV_EM) margins, respectively. This suggests that, in the presence of disequilibrium, the ecological footprint autonomously restores equilibrium concerning export diversification, GDP per capita, the quadratic term of GDP per capita, renewable electricity generation, and fossil fuel energy consumption.

The long-term interrelationship between the ecological footprint and economic growth supports the Environmental Kuznets Curve (EKC) hypothesis. In the three models examined, there is a significant positive correlation between the logarithm of the ecological footprint (LnEFP) and GDP per capita. In contrast, the relationship between LnEFP and the quadratic form of per capita income is significantly negative. The Environmental Kuznets Curve (EKC) hypothesis suggests that while economic growth initially results in environmental degradation, after reaching a specific level of income, further increases in per capita income lead to improvements in environmental quality. These findings align with the research of [1, 23, 26, 37, 60, 72], which also identified an inverted U-shaped relationship between ecological footprint and economic growth in both developed and developing countries.

The coefficients of the Theil index and its components are positive and statistically significant. As a higher value of the Theil index specifies a lower level of export diversification, the direct relationship between the LnEFP and DIV (or DIV_IM and DIV_EM) means that export diversification diminishes the ecological footprint. This result confirms our first hypothesis. Export diversification helps scale down the ecological footprint as economy shifts towards producing and exporting eco-friendly goods and technology. Export diversification might be associated with better utilization of natural

Table 7 Results of Pedroni cointegration test. Source: Authors

Models	Statistics		p-value
General sample			
Equation with DIV	Modified PP test	3.6580	0.0001
	PP test	− 12.5831	0.0000
	ADF test	− 12.0685	0.0000
Equation with DIV_IM	Modified PP test	4.0571	0.0000
	PP test	− 13.0415	0.0000
	ADF test	− 12.0137	0.0000
Equation with DIV_EM	Modified PP test	4.1421	0.0000
	PP test	− 11.0320	0.0000
	ADF test	− 11.5389	0.0000
Developing countries			
Equation with DIV	Modified PP test	3.7006	0.0001
	PP test	− 8.1654	0.0000
	ADF test	− 7.9246	0.0000
Equation with DIV_IM	Modified PP test	3.6534	0.0001
	PP test	− 8.1266	0.0000
	ADF test	− 8.3627	0.0000
Equation with DIV_EM	Modified PP test	3.2634	0.0006
	PP test	− 9.3754	0.0000
	ADF test	− 9.1596	0.0000
Developed countries			
Equation with DIV	Modified PP test	2.6106	0.0045
	PP test	− 7.2778	0.0000
	ADF test	− 7.1249	0.0000
Equation with DIV_IM	Modified PP test	2.5641	0.0052
	PP test	− 7.3578	0.0000
	ADF test	− 7.2009	0.0000
Equation with DIV_EM	Modified PP test	2.8396	0.0023
	PP test	− 6.0904	0.0000
	ADF test	− 6.6135	0.0000

resources, which allows the use of green technology and energy-efficient industrial processes that reduce environmental deterioration. Ali et al. [6] established the negative influence of export diversification on the ecological footprint in India from 1965 to 2017. A similar result was obtained in [73] in the case of Uzbekistan. Including innovative and sophisticated green products in the export basket benefits the environment.

The positive and significant coefficients of energy consumption produced by fossil fuels seen in the three estimated models further confirm that increased consumption of energy generated from fossil fuels leads to significant environmental deterioration. This result aligns with the findings of Neagu [51], who testified a positive long-run association between the EFP and fossil fuel energy consumption utilizing data from 48 economies from 1995–2014. Finally, the long-run coefficients of renewable electricity output are negative and significant in the models with the overall Theil index and its intensive margin but direct and insignificant in the model with the extensive margin. The increased energy generation from renewables improves the environmental quality. Shayanmehr et al. [69], who studied top renewable energy consumption countries, found that renewable energy has a significant effect on decreasing the EFP; however, this impact is insignificant in nations with lower pollution levels. In a similar line, the inverse impact of renewable energy on the EFP was found in the studies of [9, 23, 25, 41, 62, 67, 77].

In the results for the short-run, only the coefficients of fossil fuel energy consumption are significant and positive in all estimated models. Thus, in the short term, ecological footprint mitigation is associated with reducing the consumption of fossil fuel energy. Furthermore, it is observed that export diversification and renewable electricity generation do not have any significant effect on the ecological footprint in the short run.

Table 8 The long-run and short-run results of PMG estimation (general sample). Source: Authors

Model	Equation with DIV		Equation with DIV_IM		Equation with DIV_EM	
	(1)	(2)	(3)	(4)	(5)	(6)
Variables	Long– run results	Short– run results	Long– run results	Short– run results	Long– run results	Short– run results
ECT		− 0.490***		− 0.493***		− 0.462***
		(0.0345)		(0.0339)		(0.0315)
D. DIV		0.0198				
		(0.0256)				
D. GDPpc (thousand USD)		0.4318 (0.4097)		0.4418 (0.3823)		0.0474 (0.2621)
D. $GDPpc^2$ (million USD)		− 0.0369 (0.2184)		0.0106 (0.1778)		0.1809 (0.1593)
D. FFEC		0.0112*** (0.0025)		0.0108*** (0.0024)		0.0071*** (0.0021)
D. REO		0.0071* (0.0042)		0.0057 (0.0037)		− 0.0029 (0.0043)
DIV	**0.0287*** **					
	(0.0091)					
GDPpc (thousand USD)	0.0303*** (0.0033)		0.0292*** (0.0033)		0.0525*** (0.0037)	
$GDPpc^2$ (million USD)	− 0.00025***		− 0.00024***		− 0.0006***	
	(0.00004)		(0.00004)		(0.00006)	
FFEC	0.0039*** (0.0007)		0.0036*** (0.0007)		0.0090*** (0.0009)	
REO	− 0.0047*** (0.0003)		− 0.0047*** (0.0004)		0.0006 (0.0004)	
DIV_IM			**0.0277*** **			
			(0.0094)			
D. DIV_IM				0.0350		
				(0.0260)		
DIV_EM					**0.0795** **	
					(0.0334)	
D. DIV_EM						0.6410
						(1.3536)
Constant		0.2439***		0.2645***		− 0.0409*
		(0.0337)		(0.0343)		(0.0212)
Number of observations	1.652	1.652	1.652	1.652	1.652	1.652
Number of countries	87	87	87	87	87	87
Number of years	19	19	19	19	19	19

Standard errors in parentheses

***$p < 0.01$

**$p < 0.05$

*$p < 0.1$

The results of PMG estimation for the subsample of developing countries, as presented in Table 9, are very close to those obtained for the general sample. We observed the inverted U-shaped long-run relationship between the EFP and GDP per capita for developing countries, which aligns with the EKC hypothesis. The income threshold for transitioning from environmental degradation to improvement is approximately 10,062 US dollars, aligning with GNI per capita levels in upper-middle-income countries, according to World Bank classifications. Ahmad et al. [1] found a similar result for 22 emerging economies from 1984 to 2016. The overall Theil index and its intensive margin significantly positively affect the EFP in the long term. This outcome supports our second hypothesis. Developing economies can increase environmental quality by implementing export diversification strategies accompanied by effective environmental policies [44].

Export diversification at the intensive margin, which reflects a more balanced distribution of export value among existing product lines, is linked to improvements in product quality or the introduction of high-value-added products within the same sectors, promoting transition from resource, energy, and pollution-intensive activities to environment-friendly production methods. Intensive margin growth stabilizes export earnings in developing countries, facilitating investments towards a green economy [73]. In newly industrialized countries, export diversification at the intensive margin helps to reduce energy demand by optimizing production processes and supply chains [65]. Furthermore, scaling up the production of established exports can encourage investments in cleaner technologies, lowering emissions per unit of production.

The negative and significant coefficients of renewable electricity output in three estimated models confirm that the widespread deployment of renewable energy sources is crucial in diminishing environmental damage in developing countries. Similarly, Sabir and Gorus [60], while studying the South Asian countries for the period 1975–2017, suggested that economies needed to shift toward the path of renewable energy sources to preserve the environment. Likewise, Bulut [15] discovered that the use of renewable energy enhances the quality of the environment in Turkey. The long-run coefficients of fossil fuel energy consumption are direct and significant only in the models with intensive and extensive margins of export diversification, implying that prevailing fossil fuel energy consumption adversely affects the environment in developing nations. The study of Awosusi et al. [11] revealed a similar positive impact of non-renewable energy on EFP for BRICS countries over the period from 1990 to 2017. The extensive use of fossil fuels negatively impacts environmental quality in BRICS countries.

Fossil fuel energy consumption plays a crucial role in escalating the ecological footprint of developing nations in the short and long term. The impacts of other variables are not statistically significant at the 1% or 5% levels. This suggests that for these nations, reducing the ecological footprint is linked to a decrease in fossil fuel energy usage in both time frames, alongside export diversification at an intensive margin, as well as with economic growth and the generation of renewable electricity over the long run.

Table 10 reports the long-run and short-run outcomes of PMG estimation in the sample of developed countries from 1995 to 2014. Similar to the case of developing nations, the long-run relationship of the EFP-GDP per capita is hump-shaped, which aligns with the EKC hypothesis. In advanced economies, the threshold where economic growth transitions from harming the environment to a positive effect is beyond 46,800 US dollars.

Unlike the findings for the general sample and the sub-sample of developing economies, the coefficients of the overall Theil index and its intensive margin are significantly negative in developed economies. This indicates the direct influence of export diversification on the ecological footprint, confirming the third hypothesis of our study. This finding is justified by the inverted U-shaped relationship between GDP per capita and export diversification. Research conducted by Klinger and Lederman [36], Bebczuk and Berrettoni [13], and Cadot et al. [16] indicate that economic growth initially facilitates export diversification; however, beyond a certain threshold, a process of reconcentration emerges as income levels rise. As high-income countries, advanced economies are more inclined to concentrate their export structure on innovative high-value-added goods, which cause less harm to the environment, thus making a relevant contribution to environmental sustainability.

Another explanation for the reverse impact of export concentration on the ecological footprint in advanced economies can be understood through the red-loop versus green-loop model [22]. Developed economies are characterized by red-loop systems that highly rely on non-ecosystem-based local production and the import of natural resources from foreign ecosystems. In contrast, less developed economies fall into the green-loop category, where there is a heavy dependence on local ecosystems, which leads to the overexploitation of resources and environmental degradation [21]. Advanced economies tend to transfer ecologically harmful production processes to developing countries while specializing in high-value, technology-intensive, eco-friendly processes within the global value chains. The relocation of pollution-intensive industries to countries with lax environmental regulations, explained by the Pollution Haven hypothesis, decreases carbon

Table 9 The long-run and short-run results of PMG estimation (developing countries). Source: Authors

Model	Equation with DIV		Equation with DIV_IM		Equation with DIV_EM	
	(1)	(2)	(3)	(4)	(5)	(6)
Variables	Long– run results	Short– run results	Long– run results	Short– run results	Long– run results	Short– run results
ECT		– 0.465***		– 0.469***		– 0.434***
		(0.0444)		(0.0437)		(0.0397)
D. DIV		0.0179				
		(0.0312)				
D. GDPpc (thousand USD)		0.6618 (0.6514)		0.7025 (0.6040)		0.1868 (0.4492)
D. GDPpc^2 (million USD)		– 0.1033 (0.3219)		– 0.0525 (0.2587)		0.0541 (0.2616)
D. FFEC		0.0140*** (0.0035)		0.0133*** (0.0034)		0.0101*** (0.0025)
D. REO		0.0087* (0.0048)		0.0069* (0.0037)		– 0.0012 (0.0047)
DIV	**0.0480***					
	(0.0094)					
GDPpc (thousand USD)	0.0644*** (0.0151)		0.0645*** (0.0152)		0.0964*** (0.0205)	
GDPpc^2 (million USD)	– 0.0032***		– 0.0034***		– 0.0067***	
	(0.0011)		(0.0011)		(0.0017)	
FFEC	0.0025 (0.0009)		0.0026*** (0.0009)		0.0017* (0.0009)	
REO	– 0.0042*** (0.0004)		– 0.0043*** (0.0004)		– 0.0044*** (0.0004)	
DIV_IM			**0.0512***			
			(0.0099)			
D. DIV_IM				0.0357		
				(0.0311)		
DIV_EM					**– 0.0131**	
					(0.0325)	
D. DIV_EM						– 0.3619
						(0.2647)
Constant		0.1155***		0.1198***		0.1791***
		(0.0340)		(0.0330)		(0.0304)
Number of observations	1.120	1.120	1.120	1.120	1.120	1.120
Number of countries	59	59	59	59	59	59
Number of years	19	19	19	19	19	19

Standard errors in parentheses

***$p < 0.01$.

**$p < 0.05$.

*$p < 0.1$

Table 10 The long-run and short-run results of PMG estimation (developed countries). Source: Authors

Model	Equation with DIV		Equation with DIV_IM		Equation with DIV_EM	
	(1)	(2)	(3)	(4)	(5)	(6)
Variables	Long– run results	Short– run results	Long– run results	Short– run results	Long– run results	Short– run results
ECT		− 0.597***		− 0.594***		− 0.545***
		(0.0661)		(0.0661)		(0.0622)
D. DIV		0.0555				
		(0.0440)				
D. GDPpc (thousand USD)		0.0336 (0.0566)		0.0289 (0.0551)		0.0405 (0.0574)
D. $GDPpc^2$ (million USD)		− 0.0009 (0.0010)		− 0.0008 (0.0010)		− 0.0016 (0.0013)
D. FFEC		0.0023 (0.0031)		0.0026 (0.0031)		0.0034 (0.0029)
D. REO		0.0017 (0.0083)		0.0016 (0.0082)		0.000001 (0.0087)
DIV	**− 0.0365****					
	(0.0170)					
GDPpc (thousand USD)	0.0562*** (0.0046)		0.0564*** (0.0046)		0.0694*** (0.0048)	
$GDPpc^2$ (million USD)	− 0.0006***		− 0.0006***		− 0.0008***	
	(0.00007)		(0.00007)		(0.00008)	
FFEC	0.0103*** (0.0016)		0.0102*** (0.0016)		0.0075*** (0.0018)	
REO	− 0.0036*** (0.0007)		− 0.0036*** (0.0007)		− 0.0039*** (0.0008)	
DIV_IM			**− 0.0386****			
			(0.0176)			
D. DIV_IM				0.0580		
				(0.0462)		
DIV_EM					**0.1583**	
					(0.2357)	
D. DIV_EM						3.6719
						(8.8392)
Constant		0.0523		0.0536		0.0126
		(0.0469)		(0.0470)		(0.0386)
Number of observations	532	532	532	532	532	532
Number of countries	28	28	28	28	28	28
Number of years	19	19	19	19	19	19

Standard errors in parentheses

*** $p < 0.01$

** $p < 0.05$

* $p < 0.1$

emissions in developed economies [20]. Thus, the concentration on green production and exporting environmental costs to developing economies contributes to the sustainability in advanced economies.

Wang et al. [79], in research of G-7 countries from 1990 to 2017, found that export diversification increases carbon emissions while ecological innovation reduces them. Likewise, Iqbal et al. [31] revealed the direct effect of export diversification on CO2 emissions for 37 OECD economies from 1970 to 2019. As carbon emissions are the key factors of environmental deterioration, according to these studies, export diversification adversely affects environmental quality in advanced economies. Bake et al. [78], in a study of European Union countries from 1995 to 2018 utilizing the PMG approach, found a substantial negative influence of export concentration on the ecological footprint and recommended promoting export re-concentration to achieve ecological sustainability in developed countries.

The long-run coefficients of all control variables are significant at a 1% significance level in the three estimated models. The results verify the previous findings of the significant direct impact of energy consumption from fossil fuels on the ecological footprint and the indirect influence of renewable electricity output on the outcome variable in the long run. However, in the context of insignificance, none of the coefficients determines the changes in the ecological footprint in the short term.

Our results from the empirical analysis show that export diversification ameliorates environmental quality in a global sample of countries. The adverse effects of diversifying exports on the ecological footprint in developing economies are mainly propelled by changes in export values among existing exports. Increasing the share of environmentally friendly goods and decreasing the share of polluting goods in total exports can go a long way toward environmental sustainability in less developed nations. On the other hand, concentration on intensive margin is revealed to have a negative association with the ecological footprint in developed countries. Concentration on the exports of green products and technologies can reduce environmental degradation in advanced economies. The summary of PMG estimation results for different samples of countries is depicted in Fig. 5.

The heterogeneous effect of export diversification on the environment in developed and developing economies reflects their structural economic differences. Developed economies typically have a comparative advantage in knowledge-based and technology-intensive industries and concentrate their exports on high-tech products and services with a lower environmental impact. Most developing countries depend heavily on commodities and resource-intensive industries. Economic diversification in developing countries helps stabilize export earnings and promote sustainable economic development in the long run. Structural economic changes and export diversification can be associated with transitioning from pollution-intensive industries (raw materials extraction, agriculture) to environment-friendly sectors (manufacturing, services). Therefore, export diversification in developing economies can contribute to environmental sustainability.

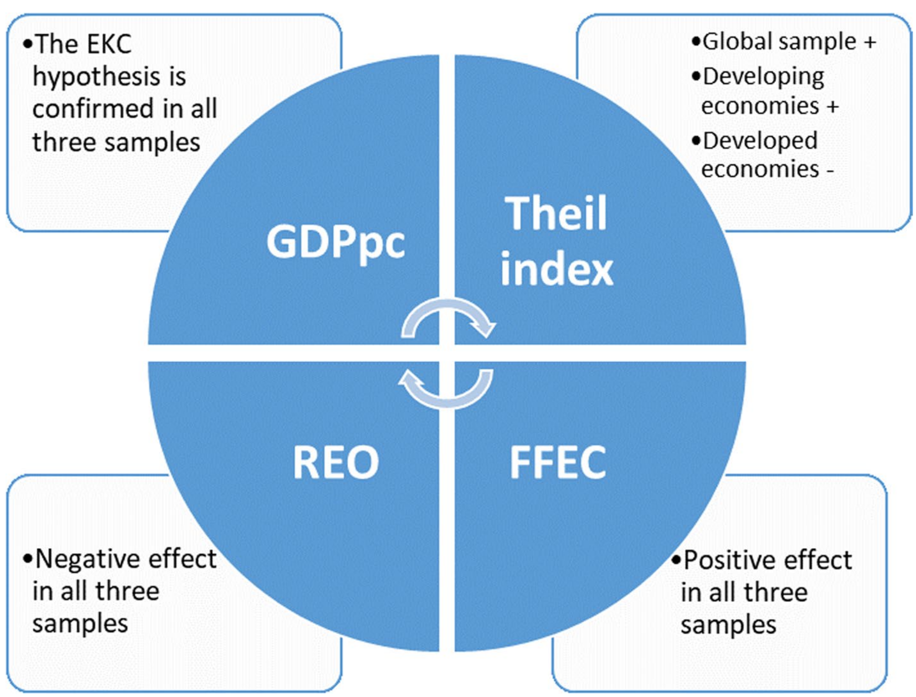

Fig. 5 Empirical findings from PMG estimation. Source: Authors

On the other hand, the observed outcomes of the analysis can be policy-driven. The concentration of developed economies on clean production and exports is enforced by stringent environmental regulations and standards that encourage the adoption of sustainable practices in the production processes. Export diversification in developing economies can be accompanied by importing green technologies and investments, along with stricter environmental policies that facilitate the transition to a green economy. Strict environmental regulations, in turn, can stimulate innovation and improve efficiency, ultimately improving both trade competitiveness and environmental quality [59].

We executed the Granger causality test to define the long-term relationships among the variables [27]. The estimated results are shown in Table 11. Our findings indicate a bidirectional causality between ecological footprint and the overall Theil index, as well as between ecological footprint and both the intensive and extensive margins of export diversification. Additionally, there is also bidirectional causality between EFP and GDP per capita, EFP and fossil fuel energy consumption, and EFP and renewable electricity output. Observed bidirectional causality indicates that environmental quality can enforce policies to promote export diversification, thereby increasing the proportion of eco-friendly products in exports and encouraging the introduction of new sustainable products in the export portfolio of nations. Ecological footprints reflect the resource intensity of production and sustainability of consumption and thus affect GDP per capita. Furthermore, the government can stimulate the transition from fossil fuels to renewable energy sources to tackle environmental problems in case of a high ecological footprint. Therefore, a holistic approach should be implemented to elaborate policy recommendations integrating measures to accelerate export diversification and achieve environmental sustainability.

7 Robustness check

We incorporated the Export Product Concentration Index (EPCI) in UNCTAD's Statistics database into Eq. (3) instead of the overall Theil index to check the results' reliability. The EPCI is a standardized version of the Herfindahl–Hirschman Index, designed to evaluate the concentration of products within a country's merchandise exports. The following formula is used to compute this indicator:

$$H_j = \frac{\sqrt{\sum_{i=1}^{N}\left(\frac{x_{ij}}{X_j}\right)^2} - \sqrt{\frac{1}{N}}}{1 - \sqrt{\frac{1}{N}}};X_j = \sum_{i=1}^{N} x_{ij} \tag{7}$$

Table 11 The Granger causality test results (general sample). Source: Authors

Null hypothesis	W-bar	Z-bar	Z-bar tilde	P-value	Causality	Direction
DIV ≠ LnEFP	2.3864	9.1437***	6.4187***	0.0000	Yes	Bidirectional
LnEFP ≠ DIV	2.1534	7.6073***	5.2163***	0.0000	Yes	
DIV_IM ≠ LnEFP	2.2948	8.5399***	5.9461***	0.0000	Yes	Bidirectional
LnEFP ≠ DIV_IM	1.7594	5.0086***	3.1825***	0.0015	Yes	
DIV_EM ≠ LnEFP	2.3441	9.1285***	6.4068***	0.0000	Yes	Bidirectional
LnEFP ≠ DIV_EM	2.1600	7.6510***	5.2505***	0.0000	Yes	
GDPpc ≠ LnEFP	3.5977	17.1330***	12.6713***	0.0000	Yes	Bidirectional
LnEFP ≠ GDPpc	3.0846	13.7490***	10.0229***	0.0000	Yes	
FFEC ≠ LnEFP	2.2278	8.0981***	5.4416***	0.0000	Yes	Bidirectional
LnEFP ≠ FFEC	2.3046	8.6044***	5.8306***	0.0000	Yes	
REO ≠ LnEFP	1.6050	3.9901***	2.3853**	0.0171	Yes	Bidirectional
LnEFP ≠ REO	2.0682	7.0453***	4.7764***	0.0000	Yes	

*** $p < 0.01$

** $p < 0.05$

* $p < 0.1$

Here, *Hj* is the product concentration index of exports for country *j*, *Xi,j* refers to the value of exports for country *j* and product *i*, *Xj* denotes the total value of exports of country *j*, and *N* is the number of commodities exported at the 3-digit level of the SITC Revision 3. The EPCI varies between zero and one, where a higher value signifies a greater concentration within the structure of merchandise exports. Conversely, an index close to zero shows that a country has achieved a higher degree of export diversification, meaning its exports are evenly distributed across various commodities [76].

The general sample EPCI index varies between 0.04 and 0.98, with a mean of 0.25. The lower the value, the less concentrated the export composition of the economy. The EPCI's mean for developing countries (0.29) is twice higher than for developed economies (0.14), revealing that the former group has a less diversified export portfolio.

Before estimating model (3) with the EPCI as a principal explanatory variable, we assessed cross-sectional dependence in the panel data utilizing the Pesaran [55] CD test. The null hypothesis of cross-section independence was rejected for the EPCI variable, evidenced by a p-value below 0.01. Subsequently, we investigated the unit root characteristics of the EPCI variable applying the Pesaran unit root test. The results from the Pesaran test for the overall sample indicated that the variable is stationary at levels. Separate unit root analyses for the EPCI in both developing and developed nations revealed that the series are stationary at the first difference. Lastly, we applied the Pedroni [53] and Westerlund [87] tests to assess cointegration among the variables. We rejected the null hypothesis of no cointegration across panels in the models for the overall sample, as well as for developing and developed economies, concluding that all panels exhibit cointegration.

We estimated the impact of export concentration on the ecological footprint employing the PMG model in the global sample, developing countries, and developed countries. We used the same control variables as in the benchmark estimates, which include GDP per capita, quadratic terms of GDP per capita, fossil fuel energy consumption, and renewable electricity output. Table 12 demonstrates the results of these estimations.

The long-run association between the ecological footprint and economic growth confirms the EKC hypothesis. The relationship between the LnEFP and per capita income is significantly positive. On the contrary, the association between the LnEFP and squared per capita income is significantly negative in the three estimated models. The coefficients of the EPCI are positive and statistically significant at the 5% level in the estimations for the global sample and developing countries. As a higher value of the EPCI specifies a high level of export concentration, the positive relationship between the LnEFP and EPCI means that diversifying exports reduces the ecological footprint, particularly in less developed economies. The coefficients for the EPCI in advanced economies are negative and statistically insignificant.

With respect to the controlling variables, the decrease in ecological footprint is common among the samples, corresponding with the rise of REO. The FFEC coefficient is positive and statistically significant at the 1% level in models for global samples and developed nations and at the 10% level in estimation for developing economies. These results align with the findings of Shayanmehr et al. [69], who found the direct effect of renewables and the adverse impact of non-renewable energy on EFP, employing data from 27 countries from 1994 to 2018.

In the short term, the coefficients of fossil fuel energy consumption are significantly positive in the models for the global sample and developing nations. This suggests that in less developed economies, reducing fossil fuel energy consumption can lead to ecological footprint mitigation in the short term. Furthermore, the coefficients of renewable electricity output are positive at the 10% significance level in the global sample and the sample of developing nations. Hence, this signifies that higher generation of energy from renewables is associated with a high ecological footprint of developing countries in the short term. The consistency found from the long-term and short-run further justifies the robustness of our research.

We continued the robustness check by employing a fully modified ordinary least squares (FMOLS) method to derive long-run estimations. Table 13 demonstrates the findings from the panel FMOLS estimation.

The estimation results for the overall sample, developing and developed countries, indicate that the coefficients of all variables align with those found in the PMG model, albeit with some variations in their magnitudes. The FMOLS estimation results further corroborate the Environmental Kuznets Curve (EKC) hypothesis across all three samples. Consistent with the PMG model findings, the coefficient for the overall Theil index is positive for both the global sample and developing economies, while it is negative for developed economies. These consistent findings from both the PMG and FMOLS models suggest that, in the long term, export diversification in developing countries enhances environmental quality, whereas export concentration appears to be beneficial for the environment in developed nations.

Table 12 The long-run and short-run results of PMG estimation with export product concentration index (EPCI) as a key independent variable. Source: Authors

Sample	General sample		Developing countries		Developed countries	
	(1)	(2)	(3)	(4)	(5)	(6)
Variables	Long– run results	Short– run results	Long– run results	Short– run results	Long– run results	Short– run results
ECT		– 0.486*** (0.0325)		– 0.469*** (0.0401)		– 0.560*** (0.0653)
D. EPCI		0.0441 (0.1535)		0.1181 (0.1771)		0.0467 (0.2507)
D. GDPpc (thousand USD)		0.3257 (0.3686)		0.4191 (0.5624)		0.0368 (0.0552)
D. $GDPpc^2$ (million USD)		– 0.0009 (0.2000)		– 0.0222 (0.3009)		– 0.0013 (0.0012)
D. FFEC		0.0091*** (0.0024)		0.0106*** (0.0032)		0.0027 (0.0026)
D. REO		0.0092* (0.0052)		0.0117* (0.0065)		0.0021 (0.0078)
EPCI	0.0862** (0.0409)		0.0887** (0.0407)		– 0.0092 (0.1377)	
GDPpc (thousand USD)	0.0356*** (0.0035)		0.0647*** (0.0154)		0.0662*** (0.0047)	
$GDPpc^2$ (million USD)	– 0.0003*** (0.00005)		– 0.0030*** (0.0011)		– 0.0007*** (0.00007)	
FFEC	0.0032*** (0.0008)		0.0017* (0.0009)		0.0096*** (0.0018)	
REO	– 0.0045*** (0.0004)		– 0.0042*** (0.0004)		– 0.0034*** (0.0008)	
Constant		0.2712*** (0.0309)		0.2017*** (0.0324)		– 0.0401 (0.0425)
Number of observations	1.652	1.652	1120	1120	532	532
Number of countries	87	87	59	59	28	28
Number of years	19	19	19	19	19	19

Standard errors in parentheses

***$p < 0.01$.

**$p < 0.05$.

*$p < 0.1$

Table 13 Results of the fully modified ordinary least squares (FMOLS) long-run estimation. Source: Authors

Variables	Global sample		Developing countries		Developed countries	
	Coefficient	t-stat	Coefficient	t-stat	Coefficient	t-stat
DIV	0.01	– 5.46	0.03	7.25	– 0.03	– 20.15
GDPpc (thousand USD)	0.58	33.63	0.83	19.54	0.04	30.92
$GDPpc^2$ (million USD)	– 0.19	– 18.79	– 0.28	– 8.67	– 0.00	– 20.55
FFEC	0.01	69.78	0.01	44.36	0.01	58.61
REO	– 0.13	– 18.70	– 0.19	– 7.82	– 0.01	– 21.61

An additional test to check the robustness of the results was conducted using carbon emissions (CO2) as a dependent variable and the overall Theil index as a key explanatory variable. The data for CO2 emissions per capita measured in metric tons comes from the World Development Indicators database. Before applying the PMG model, we discovered the presence of cross-sectional dependence in the panel data, stationarity of the carbon emissions variable at the first difference, and cointegration among the variables. Lastly, we estimated Eq. (3) for the groups of developing and developed countries utilizing CO2 emissions as a dependent variable. Table 14 shows the results of these estimations. In line with the outcomes of benchmark estimates, the impact of export diversification on the ecological footprint is negative in developing countries but positive in advanced economies in the long run, which supports our findings.

8 Conclusion and recommendations

8.1 Concluding remarks

The present study investigates the impact of export diversification on the ecological footprint of 87 economies during 1995–2014, applying the PMG estimation. Moreover, we explore the long-run relationship between export diversification and the ecological footprint separately in developing and developed economies, examining the effects of intensive and extensive margins of export diversification on environmental quality. Our research reveals that export diversification, in both intensive and extensive margins, reduces the ecological footprint in the global sample of countries. In developing economies, export diversification in the intensive margin also benefits the environment. However, in developed economies, export concentration in the intensive margin is associated with reducing the ecological footprint. Furthermore, the long-run association of the ecological footprint and GDP per capita supports the EKC hypothesis for both developed and developing nations. In this research, more energy consumption from fossil fuels is strongly linked with high magnitudes of environmental degradation, whereas increased energy generation from renewable sources contributes positively to environmental quality. In the short run, fossil fuel energy consumption emerges as an essential determinant of the ecological footprint upsurge in developing economies, highlighting the urgent and immediate need for sustainable energy practices.

The Granger causality test results reveal a bidirectional cause-and-effect relationship between the EFP and all explanatory variables from a long-run perspective. The findings of the robustness checks incorporating the export product concentration index as a proxy for export diversification, applying FMOLS estimation, and using CO2 emissions per capita as a dependent variable coincide with the outcomes of the PMG model.

8.2 Policy implications

Several suggestions can be made based on the findings of our study. First, developing economies should apply effective export diversification strategies to realize sustainable economic development that is environmentally friendly. Some of these strategies include measures aimed at reducing the proportion of primary commodities in total exports while increasing the fraction of high-value-added products (vertical export diversification) that have less adverse impacts on the environment. Regarding the intensive margin of diversification, policymakers can promote shifting to sustainable practices within the existing export sectors to make them less carbon-intensive. Second, policymakers

Table 14 The long-run and short-run results of PMG estimation with CO2 emissions per capita as a dependent variable. Source: Authors

Sample	Developing countries		Developed countries	
	(1)	(2)	(3)	(4)
Variables	Long-run results	Short-run results	Long-run results	Short-run results
ECT		– 0.1619***		– 0.3145***
		(0.0324)		(0.0577)
D. DIV		– 0.0296		0.3082
		(0.0538)		(0.2120)
D. GDPpc (thousand USD)		– 0.3672 (1.2267)		– 0.6471** (0.2734)
D. GDPpc^2 (million USD)		– 0.2877 (0.2515)		0.0136** (0.0065)
D. FFEC		0.0407* (0.0209)		0.1044*** (0.0268)
D. REO		– 0.0067 (0.0208)		0.0365 (0.0615)
DIV	0.1005***		– 0.5449***	
	(0.0242)		(0.1194)	
GDPpc (thousand USD)	0.3463*** (0.0487)		– 0.0533** (0.0250)	
GDPpc^2 (million USD)	– 0.0129*** (0.0029)		– 0.0003 (0.0003)	
FFEC	0.0681*** (0.0067)		0.0686*** (0.0086)	
REO	0.0057*** (0.0014)		– 0.0424*** (0.0057)	
Constant		– 0.4770***		2.6115***
		(0.1535)		(0.5305)
Number of observations	1120	1120	532	532
Number of countries	59	59	28	28
Number of years	19	19	19	19

Standard errors in parentheses

***$p < 0.01$.

**$p < 0.05$.

*$p < 0.1$

should encourage the production and exportation of environmentally friendly goods and services, hence increasing the variety of exports. Focusing on producing and exporting sustainable products, which are internationally traded goods and services produced sustainably and encourage sustainable consumption [75], can significantly enhance the environment in developing countries. The concrete measures for diversification into green products include the identification of sectors with sustainable export potential, the creation of regulatory and institutional frameworks for supporting their development, and implementation measures for realizing export capacity in selected sustainable product sectors. Besides, transition measures towards a green economy should be engaged in the pursuit of improving the energy efficiency of the economy and expanding the consumption of renewable sources. Promoting green industrial policies to accelerate structural transformation towards a resource-efficient economy can incorporate subsidies and tax incentives for firms adopting clean technologies, investments in green energy and R&D, and carbon-pricing mechanisms to internalize environmental costs and encourage greener practices. These will ensure environmental sustainability and make substantial strides towards the achievement of sustainable development goals in developing nations.

Developed countries should continue producing sophisticated and innovative products based on their comparative advantages. In addition, they should significantly expand the export of green technologies and green investments and extend energy efficiency practices to developing countries, thereby contributing to the solution of global environmental problems. Moreover, international cooperation to ensure environmental protection through global trade can be strengthened by easing market access for sustainable products to boost green exports, encouraging green technology transfer to disseminate sustainable practices and aligning trade policies with international environmental standards to accelerate the green transition.

8.3 Future recommendations

The current investigation has several limitations. As the IMF statistics database contains data on the intensive, extensive, and overall Theil indices only until 2014, it was impossible to include post-2014 data in our analysis. However, a more extended study period with recent data in future research could provide more precise conclusions regarding the impact of export diversification on the ecological footprint in both developed and developing economies that are relevant to modern conditions. Future studies should consider sector-specific effects of export diversification on the environment using sectoral data and grouping countries by regions to identify and compare regional trends. Future studies can apply other estimation methods, like CS-ARDL, to check the long-run outcomes of the PMG technique. The potential mechanisms through which export diversification affects the ecological footprint can be thoroughly investigated in future research. Future studies can explore the interaction effects of export diversification and other essential factors of the ecological footprint in different groups of countries.

Author contributions All authors contributed to the study's conception and design. Dr. Gavkhar Sultanova and Dr. Hanan Naser equally contributed to the material preparation, data collection, analysis, and writing the first draft of the manuscript. All authors read and approved the final manuscript.

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Data availability Data is provided within the manuscript or supplementary information files.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

Appendix

See Table 15 here.

Table 15 List of countries in the sample

Developing economies	Developed economies
1. Argentina	1. Australia
2. Bangladesh	2. Austria
3. Brazil	3. Croatia
4. Bulgaria	4. Czechia
5. Belarus	5. Denmark
6. Cameroon	6. Estonia
7. Sri Lanka	7. Finland
8. Chile	8. France
9. China	9. Germany
10. Colombia	10. Greece
11. Congo (the)	11. Ireland
12. El Salvador	12. Israel
13. Ethiopia	13. Italy
14. Gabon	14. Japan
15. Ghana	15. Korea (the Republic of)
16. Guatemala	16. Latvia
17. Haiti	17. Lithuania
18. Honduras	18. Netherlands (the)
19. Hungary	19. New Zealand
20. India	20. Norway
21. Indonesia	21. Portugal
22. Iran (Islamic Republic of)	22. Singapore
23. Iraq	23. Slovakia
24. Côte d'Ivoire	24. Slovenia
25. Jamaica	25. Spain
26. Kazakhstan	26. Sweden
27. Jordan	27. Switzerland
28. Kenya	28. United Kingdom of Great Britain and Northern Ireland (the)
29. Kyrgyzstan	
30. Malaysia	
31. Mauritius	
32. Mexico	
33. Mongolia	
34. Moldova (the Republic of)	
35. Morocco	
36. Mozambique	
37. Nepal	
38. Nicaragua	
39. Nigeria	
40. Pakistan	
41. Panama	
42. Paraguay	
43. Peru	
44. Philippines (the)	
45. Poland	
46. Romania	
47. Russian Federation (the)	
48. Senegal	
49. South Africa	
50. Tajikistan	
51. Thailand	
52. Togo	
53. Tunisia	
54. Türkiye	
55. Ukraine	
56. Egypt	
57. Tanzania, the United Republic of	
58. Uruguay	
59. Uzbekistan	

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