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Research article

Comparing developed and emerging nations' Economic development with environmental footprint for low-carbon competitiveness

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ABSTRACT

This study delves into the intricate relationship between economic growth and its ecological repercussions, employing a comprehensive assessment of ecological footprint across 131 nations. The time period considered for the research spans from 2009 to 2019. Utilizing the CS-ARDL methodology, the results indicate a correlation between reducing ecological footprint and bolstering private sector domestic credit. Additionally, a relationship between diminishing private sector domestic credit of banks and augmenting private sector domestic credit within the financial sector has been identified. In conjunction with other indicators of financial advancement, the significance of domestic lending to the private sector has been underscored. The study reveals a notable reduction in human population's adverse impact on the environment. However, increased levels of energy consumption, foreign direct investment and per capita GDP are associated with an improvement in global quality of life. Particularly noteworthy is the validation of the "pollution haven hypothesis" in the global economic context. The implications of this research are substantial; suggesting that global economic dynamics may support efforts towards environmental conservation. However, outcomes may vary across regions or countries, particularly regarding the emphasis placed by the financial sector on environmental preservation. This study comprehensively examines the complex nexus between economic progress and its ecological consequences, keeping in consideration factors such as financial growth, urbanization, energy consumption and Foreign Direct Investment (FDI).

1. Introduction

The simultaneous pursuit of economic growth and environmental preservation stands as a pivotal challenge confronting the global community today. Recent years have witnessed an increased concern over environmental degradation, primarily attributed to the accumulation of greenhouse gases (GHGs) in the atmosphere. The rapid industrialization witnessed over the past two centuries has driven a substantial surge in energy demand, predominantly fulfilled by non-renewable fossil fuels [1]. This escalating demand has

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necessitated a delicate balancing act for policymakers, who must endeavor to maintain equilibrium between fostering economic growth and safeguarding the environment—a task growing increasingly intricate with each passing day. The significance of transitioning towards a more sustainable future has never been more evident, with the engagement of the financial sector emerging as a critical factor in realization of this vision. Within this context, the concept of "green financing" has gained prominence, representing an innovative funding approach that prioritizes economic growth while preserving environmental integrity [2]. This strategy is supported by the notion of "green credit," wherein financial institutions extend support to environmentally friendly initiatives and renewable energy projects. Loans featuring reduced interest rates are made accessible to businesses committed to minimizing their environmental footprint through investments in eco-friendly technologies. Furthermore, Research and Development (R&D) endeavors focused on renewable energy sources often receive backing from national financial institutions, particularly those advocating for environmentally responsible practices within the agricultural sector. Governments worldwide have diversified funding sources to provide financial assistance for such environmentally friendly initiatives [3].

Promoting low-carbon competitiveness means keeping environmental impact to a minimum, particularly focusing on resource depletion and carbon emissions, while boosting economic growth. There are various ways in which economic expansion and its effects on the environment are correlated. When a country's economy grows, more people buy goods and services. Economic growth is often measured using GDP or GNI, which stands for Gross National Income. Common goals in the quest for economic growth include raising living standards, creating jobs and promoting general prosperity. The term "environmental footprint" describes the total overall effect of humans on the natural world, measuring everything from resource utilization to waste and the production of greenhouses gases. This includes cumulative effects like pollution, depletion of natural resources, and endangerment of habitat and carbon emissions. Various indicators, including water, ecological and carbon footprints are used to quantify these effects. Overconsumption of resources and pollution leads to a larger environmental footprint, which in turn causes climate change, biodiversity loss and ecological degradation. The positive relationship between economic growth and the increased environmental impacts, such as carbon emissions and resource exploitation has been observed throughout history. Expansion of economies is often associated with a rise in carbon emissions and environmental degradation due to the increasing need for energy, raw materials and infrastructure. However, there is no linear relationship between economic growth and ecological impact. There may be occasions when environmental protection is not given priority over economic growth. For example, policies encouraging industrial expansion could cause a short-term increase in pollution and the loss of habitats. However, in most cases, "decoupling" is preferred, referring the steps taken to isolate the detrimental effects of economic growth on the environment. Another initiative is to promote low-carbon competitiveness, which means growing the economy without increasing carbon emissions or depleting resources. A combination of technological progress, energy efficiency measures, renewable energy sources and responsible resource management can be employed to achieve this goal.

It has also been noted that environmental sustainability and economic growth may have complementary benefits. Investments in clean technology and renewable energy sources can lead to economic development, reduced carbon emissions and less reliance on fossil fuels. Furthermore, the transition to a low-carbon economy could result in new job opportunities, increased innovation and enhanced international competitiveness. Therefore, fostering low-carbon competitiveness calls for a middle ground between sustainable economic development and ecological preservation. By decoupling economic growth from environmental impact and capitalizing on the favorable interactions between the two, countries can forge sustainable development pathways, emphasizing wealth conservation and environmental protection.

Past researches have underscored the relationship between GHG emissions and a spectrum of environmental challenges. The Intergovernmental Panel on Climate Change has documented a notable 4.4 %–5.1 % increase in global temperatures between 1902 and 2011, attributing this phenomenon to the greenhouse effect, precipitated by GHG emissions [4]. Notably, developing countries have emerged as significant contributors to GHG emissions, necessitating concerted efforts to enhance energy efficiency, curtail coal and other fossil-fuels consumption and reduce GHG emissions. These nations, grappling with complex developmental trajectories exacerbated by urbanization, confront the challenge of transitioning towards more sustainable modes of economic growth [5]. As urbanization trends persist and manufacturing activities evolve, the transition from agrarian to industrial manufacturing processes is expected to further enhance GHG emissions. However, the overemphasis on economic activity in developing countries, which collectively constitute the world's second-largest output behind industrialized economies, has engendered the environment. In this regard, policies aimed at fostering financial development and ecological sustainability are imperative, despite the challenges associated with the reliability of associated program outcomes. Identifying the embedded challenges and proposing policy-relevant solutions are essential for advancing environmental, economic and ecological agendas [6].

Various indices related to finance and environment can be analyzed to provide an idea about the country's economic growth and environmental preservation practices. One such index is the Composite Risk Index (CRI) for environmental protection, which plays a significant role in shaping environmental outcomes [7]. Countries with lower composite risk scores tend to prioritize the use of environmentally friendly resources, thereby fostering the agenda of sustainable development [8]. Industrialized nations, regulated by stringent environmental regulations, have embraced green innovation practices, fostering the growth of environment friendly products and services [9]. However, the transition to environmentally sustainable technologies remains imperative, particularly for manufacturing industries operating in developing economies [10]. Financial institutions, guided by financial theories evolving in mid-20th-century play a dual role in facilitating economic growth and green finance [11]. By leveraging their capabilities in loan generation and resource availability, financial institutions can catalyze economic expansion, while catering for environmental sustainability goals [12].

Historically, economic growth has been associated with expanding industrial operations, increasing energy use and extensive utilization of natural resources, all of which combined to create a larger environmental footprint. The traditional trend has been that as societies develop and pursue higher GDP, the living standards become higher and the ecological destruction becomes more intense.

One proposed way to respond to the challenges of low economic growth and increasing environmental damages is the concept of low-carbon competitiveness. As discussed earlier, the concept represents the ability of economies to grow while minimizing the production of carbon emissions, a process necessary for sustainable development. It requires innovative technologies and solutions which can reduce the carbon intake per unit of GDP. These types of new technologies not only reduce human impact, but prepare economies to prosper in a world, wherein economic growth will be directly linked with environmental sustainability. To incorporate economic growth with environmental sustainability, multiple strategies need to be integrated. Some of these include enabling green finances to direct investments into renewable energy and conservation projects, development of new technologies to make consumption more sustainable and process of creation more efficient, as well as policies designed to sustain and support such practices. Additionally, companies are under increasing pressure to implement sustainable technologies and solutions to be more competitive with global environmental standards. Most importantly, international cooperation can play an essential role, as global issues such as climate change cannot be resolved without global action. With this multi-pronged approach towards economic growth and environmental preservation, the global community can work towards a sustainable model of the economy in which expansion can go hand in hand with preservation, ensuring enhanced resilience and healthy practices in the long run.

The above discussion highlights the importance of upgrading industrial processes and technology to mitigate environmental issues while enhancing the financial structure [13]. However, it also highlights the adverse impact of increased funding for enterprises with high energy use, emissions and pollutants, which is detrimental to green financial development [14]. Thus, policymakers are required to strike a balance between environmental concerns and stable financial investment, particularly in the context of United Nations Sustainable Development Goals (SDGs) 7 and 13 (United Nations, n.d.). Socioeconomic upheaval is recognized as a factor influencing international relations (United Nations, n.d.). This section thus emphasizes the importance of maintaining economic development while transitioning to energy alternatives that meet environmental objectives [15].

Financial deepening (F.D.) can be regarded as a mechanism for facilitating economic growth in developing nations, albeit with the caveat of potentially increasing energy consumption and pollution [14]. Addressing climate change in underdeveloped nations necessitates the discovery of sustainable power sources, requiring comprehensive policy interventions [16]. Furthermore, it is important to keep the focus on the risks associated with financial investments in green or renewable energy development, including conflicting government expectations and the absence of adequate subsidies (United Nations, n.d.). The Green Development Guidance for Developing Initiatives Baseline Study Report 2020 highlights the importance of financial risk in investing in green or renewable initiatives to meet SDGs (United Nations, n.d.). It also highlights the environmental impacts of global financial growth, particularly in terms of coal consumption and emphasizes the potential for economic success to drive research and development spending by multinational corporations, ultimately improving the environment. Despite the growing concern among academics about empirical factors affecting ecological integrity in Sub-Saharan Africa (S.S.A.), the relationship between economic growth and environmental conservation in this region remains understudied (United Nations, n.d.).

This investigation contributes significantly to the existing body of knowledge in several ways. Firstly, it utilizes the ecological footprint as a comprehensive measure of ecosystem health, which has also garnered recognition in previous researches (United Nations, n.d.). Secondly, by performing an in-depth analysis, this study delves into the relationship between developing economies and ecological footprints (United Nations, n.d.). Thirdly, it represents the first empirical endeavor to assess the relationship between economic development and environmental indicators across a panel of 131 countries, utilizing the World Bank's Human Development Index (HDI) as an inclusive environmental indicator of ecological footprint (United Nations, n.d.). Moreover, the study addresses endogeneity concerns by employing system Generalized Method of Moments (G.M.M.) estimates, which has not been used in prior literature (United Nations, n.d.). Lastly, the study sheds light on the interrelationship between environmental theory and economic growth, laying the groundwork for future research in structural human ecology, ecological modernization, transitional environmental justice and intergenerational fairness (United Nations, n.d.). Research objectives of the following study are given as under.

Evaluate the ecological footprint across 131 countries using CS-ARDL methodology from 2009 to 2019. Analyze the impact of financial development on ecological sustainability. Investigate the relationship between economic growth and environmental integrity. Examine the roles of increased energy consumption and FDI in ecological impact. Test the pollution haven hypothesis in the context of global economic activities. Given the rising trend of industrialization, global financial systems and economic activities have increased the accumulation of greenhouse gases across the globe. Using the ecological footprint tool may be beneficial for different nations to understand the concept of measuring the correlation between economic activities and ecological sustenance, encouraging a balanced approach to growth and eco-friendliness. Financial institutions are critical in facilitating national economic development. However, they contribute to environmental degradation, given their capacity to finance polluting industrial activities. A comparison of the different financial systems may help in analyzing sustainability in financing both in developing and developed countries. Analysis of the impact of quality of life, energy consumption and FDI also sheds light on nuclear energy generation during the period. Despite the low ecological footprints from the activity, the people's quality of life improved significantly. The study may expose other activities that may improve quality of life without deteriorating the ecology. Emerging and developed economies are grappling with different issues on economic activities and their environmental implications. A comparative approach may lead to a balanced strategy that may meet economic intensity while safeguarding the ecology. For instance, the paper reveals that the USA has low ecological footprint in comparison to Japan. This research also signifies how different jurisdictions and financial sectors are aligning the concepts to balance economic activities with the ecology. The findings of the paper may guide global interaction towards achieving the SDG that focuses on environmental sustainability.

The relationship between economic growth and environmental impact forms a critical area of study in environmental economics and sustainable development. Theoretically, this research draws upon the Environmental Kuznets Curve (EKC) hypothesis, which suggests that economic development initially leads to environmental degradation, but after reaching a certain level of income, the trend reverses as societies prioritize and are able to afford cleaner technologies coupled with more stringent regulations. However, the universality of the EKC hypothesis remains contested, prompting the need for further empirical investigation across diverse global contexts. Practically, understanding the dynamics between economic growth and environmental sustainability is crucial for policy-makers, businesses and international bodies aiming to achieve the Sustainable Development Goals (SDGs). As global climate change intensifies, nations are pressured to transition towards low-carbon economies. This research provides concrete data and insights that can help in designing effective policies and business strategies which align economic activities with environmental preservation, promoting sustainable industrial practices and consumption patterns.

This analysis is justified by the urgent need to address the global challenge of balancing economic growth with environmental sustainability. As countries continue to industrialize, without adopting adequate environmental protection rules and regulations, the resultant environmental degradation could offset the benefits of economic growth. Furthermore, the increasing global commitment to reducing carbon emissions and achieving carbon neutrality by mid-century as per the Paris Agreement goals highlights the urgency and relevance of this research. By examining how different economies—both developed and emerging—navigate these challenges, the study provides a deeper understanding of effective strategies and associated pitfalls. The main contribution of this study is given as:

By including a wide range of countries, this research tests the EKC hypothesis across different economic, cultural and political landscapes, offering a refined understanding of its applicability and limitations. This study extends the analysis by integrating aspects of financial development, examining how different types of financial systems and instruments influence the environmental footprint. This includes an exploration of green financing's role in promoting eco-friendly practices. By analyzing the data from a global perspective, the research provides policy recommendations that are not only broadly applicable to a generic economy but can also be tailored to meet requirements of specific types of economies, thereby enhancing the practical utility of the research for global and national policymakers alike. The findings of this study contribute to the academic discourse by potentially challenging or supporting the existing theories within environmental economics, particularly the EKC hypothesis and theories related to sustainable finance. By highlighting successful strategies for integrating economic growth with environmental sustainability, the research offers valuable insights for businesses aiming to enhance their ecological footprint while maintaining competitiveness in the global market. Through these contributions, the research not only fills existing academic and practical gaps but also adds a robust analytical framework that can aid in the global pursuit of sustainable development.

The remaining paper is structured is as; Literature review exist in part 2, methodology and data is in part 3, results and discussion falls in section 4 and section 5 contain conclusion, policy recommendation and future work plan.

2. Literature review

This literature review covers prior research on the relationships between economic growth, foreign direct investment and carbon emissions, both theoretically and experimentally. In addition, the relationship between economic growth and CO_2 emissions has been discussed. The relationship between CO_2 emissions and economic development has shaped up as an essential issue in ecological economics literature and climate change debates, particularly global warming [17]. Human endeavors, such as oil and gas production are considered to be the primary energy and electricity source for many enterprises. They are closely related to financial development, but are also considered to be major contributors towards poor environmental quality [18]. [19] propose the EKC hypothesis, which contends that during the early phases of its financial development, there can be a significant need for electricity and supplies of raw materials, resulting in increased CO_2 emissions and waste. However, sustainability increases in the latter phases of financial expansion as the economy expands and income levels rise and modern technology is implemented to reduce CO_2 emissions. Thus, environmental damage and economic growth coexist in the early phases of economic expansion, but damage to environment starts to decrease in industrialized nations as the economy develops and grows.

Though economic growth in developed and emerging nations has been closely associated with heightened environmental degradation and expanded ecological footprints, however, the consequences of economic growth on low-carbon competitiveness diverge notably between these distinct groups. Developed countries, for instance, exhibit a tendency to prioritize environmental sustainability, demonstrating a greater inclination towards favoring environmental preservation over immediate economic gains. Conversely, developing economies often focus more on seeking growth opportunities, even if they are not environment friendly, thus making a trade-off between economic advancement and environmental conservation [20].

In light of these factors, financial development emerges as a pivotal parameter influencing low-carbon competitiveness across both developed and emerging nations. Research suggests that while financial development may initially contribute to ecological degradation, factors such as human capital accumulation and requisite environmental protection measures can serve to mitigate these adverse impacts [21]. Notably, financial development's role in fostering environmental sustainability is underscored by its potential to channel resources towards human capital development, thus enhancing environmental awareness [22]. Moreover, robust institutional frameworks can effectively counterbalance the negative ecological consequences of financial development, focusing on the interplay between financial institutions and regulatory mechanisms in shaping environmental outcomes. While extensive studies have been done on the subject of economic-environmental relationship, significant gaps remain, particularly in the accuracy of data, along with the inclusion of diverse economic systems and stages of development. Most of the studies have focused on developed nations or specific regions, leaving out a comprehensive global analysis which includes developing or under-developed countries, particularly in Africa and parts of Asia. Additionally, the impact of new financial instruments like green bonds and sustainable finance on environmental outcomes has not been sufficiently integrated into the EKC framework. This research aims to fill these gaps by providing a broader, more inclusive analysis.

Although the previous researches shed light on how national economies expand and their ecological footprints evolve over time, more research is needed on how laws and practices in the finance sector affect attempts to protect the environment. Additionally, more focus is required on clarifying how disparate regulatory environments, institutional capacity and market configurations among various nations influence environmental factors, it is also important to see how much the financial industry prioritizes environmental preservation factors when making lending decisions. In addition, investigating how alternative financial instruments, like green bonds or sustainable investment portfolios affect environmentally sustainable economic development routes may provide insightful information for practitioners and policymakers looking to match global environmental conservation goals with financial incentives. Our comprehension of the intricate processes propelling the global sustainability transition may also be improved by looking at the varying effects of economic expansion on ecological outcomes across various geographic regions and diverse socioeconomic circumstances. Therefore, further research on the methodology adopted by earlier researches investigating the relationship between economic growth and its environmental effects is necessary, which forms the basis of this research. The research also aims to look at the advantages and disadvantages of various methods used to estimate environmental impacts and their relationship with financial metrics throughout distinct geographical areas and periods in history. In order to understand the complexities involved in the economic-environmental nexus, it is also important to compare and combine results from previous studies using alternative econometric methods, such as structural equation modeling or panel data analysis, along with the theoretical frameworks and conceptual models. This would help uncover gaps in our knowledge and lay the foundation of a stronger analytical framework. Furthermore, the analysis would be enhanced and essential research goals might be more easily identified if multidisciplinary perspectives are included, such as those from sustainability, environmental simulation and the Economics of the Environment. Research on the complex relationship between economic growth and its ecological impacts is also deemed to benefit significantly from a systematic literature review that draws from various theoretical frameworks, methodical stances and multidisciplinary knowledge.

The relationship between greenhouse gas (GHG) emissions and technological advancements in resource utilization has garnered significant attention in energy and environmental studies. While resource innovations are generally perceived to reduce energy consumption, there exists the possibility for these innovations to inadvertently lead to higher resource utilization and GHG emissions. This phenomenon is elucidated by the concept of the multiplicative energy effect [23]. This concept further explains how consumers, benefiting from efficient energy technologies, may end up utilizing more resources due to reduced costs, akin to the increased demand for heating and cooling services as air conditioning technology advances [24]. Similarly, advancements in energy-saving technologies in the automotive industry may result in reduced fuel consumption per mile, yet may also lead to increased travel frequency among residents, thereby inducing a rebound effect [25]. Thus, enhanced hydrocarbon technologies, while improving efficiency, may paradoxically foster excessive reliance on gas usage [19]. Drawing upon a theoretical framework rooted in neo-classical financial principles at the micro level, technological progress is anticipated to elevate resource efficiency, yet may not necessarily lead to a proportional reduction in environmental impacts. From a macroeconomic perspective, technological advancements stimulate innovation and economic growth, potentially offsetting gains in resource efficiency with increased energy consumption and GHG emissions [26].

One of today's most divisive issues, "carbon equivalence," has been a topic of extensive research for its effects on environmental policy, green innovation and composite risk indices for several countries and regions worldwide [27]. It is generally recognized that Carbon dioxide (CO_2) and other atmospheric carbon emissions are significant worldwide issues, and academics primarily concentrate on the emission of carbon dioxide. Nearly all countries have committed to reducing their GHG emissions to create carbon-neutral or carbon-free environments [28]. The researchers who conducted this research reiterate that in order to achieve emissions reduction while addressing energy and environmental concerns, it is important to get maximum benefit from technological developments, sustainability-oriented initiatives and modifications to traffic conditions. To ascertain if climate change mitigation goals may achieve the emissions reduction aim [29], looked at E7 communities that adopted environmental preservation measures. The research, which relied on associations and statistical measurements, asserted that bigger cities are more determined to become energy-independent than modern ones in their efforts to address climate change [30]. [31] examined green management and the developing nations' capacity to achieve the emission reduction aim through a carbon-based pricing mechanism, using statistical analysis. According to the research, the increase in the consumption tax from USD 10 to USD 40 resulted in a reduction in greenhouse gas emissions for the province, between 5 % and 15 %.

In recent times, some researches have started considering the beneficial relationship between ecological accomplishment and financial progress. Financial development, according to some researchers, could aid companies in achieving better economies [32], enhancing manufacturing innovation or production technologies. This, in turn encourages investment opportunities in environmental projects [33], thus promoting environmental responsibility [34] or eliminating reverse production because of an inefficient allocation system. Financial institutions may also promote technical innovation, which can lead to a decrease in pollution emissions [35]. According to some studies, a surge in patents and a positive influence on technological advancement are two effects of financial success [36].

In contrast hand, other researchers stress upon the adverse effects of financial development. According to them, economic performance promotes investment in construction activities, contributing towards additional resource consumption, enhanced pollution and waste production [25]. Therefore, the overall effects of financial development, economic growth and protection of the environment have been the subject of recent studies. Some researches have shown a non-linear relationship between finances and environmentally friendly growth. The financial development, Green Total Factor Productivity (G-T.F.P.) and residual efficiency also exert an influence. The researchers also found a positive "U"-shaped relationship between G-T.F.P. and environmental management. Thus, according to [37], the spatial Dubin model's assessment of the provincial G-TFP and regional financial development in the developing nations reveals a positive association. The results of the related non-linear study are also shown by Ref. [38]. When we concentrate on developing countries, there are still certain specific indicators. Research by Ref. [39] found that although economic expansion in E7 countries may degrade the quality of the environment owing to GHG emissions, foreign direct investment may improve it. The researchers also found that trade liberalization raises ecological integrity, eco-innovation and urbanization lower it, and the relationship between economic growth and GHG emissions has an inverted U-shape [40]. However, although financial growth and the use of sustainable energy have a good influence on the environment, high-tech sectors and financial development have degraded the ecological integrity of developing nations, according to experts who have conducted research on developing economies.

3. Methodology and data

The study focused on information from the International Finance Corporation (IFC) database. This database is anticipated to encompass diverse economic, financial and environmental information for different countries, making it well-suited for examining the correlation between monetary expansion and ecological degradation. This database is appropriate for examining the connection between ecological deterioration and economic growth because it includes various economic, financial and environmental variables for different nations. The study's research design is based upon investigating the correlation between economic growth and ecological deterioration during a moderate transition period from 2009 to 2019. This approach facilitates the examination of patterns and fluctuations in economic and environmental factors over time. The research employs the Generalized Method of Moments (GMM) using both one- and two-step techniques and the Seemingly Unrelated Regressions (SUR) test. These econometric techniques are particularly suitable for analyzing panel data and addressing potential endogeneity issues that are frequently encountered in this kind of research.

The study's methodology and estimating techniques involve a careful evaluation of multiple variables, such as institutional aspects, financial development, ecological footprint and green building. These variables have been selected based on their theoretical relevance and empirical evidence from earlier research, mainly drawing upon influential publications such as those by Ref. [36]. The research also incorporates knowledge from previous studies, including the research conducted by Ref. [30] on the correlation between technological advancements and eco-innovation. This integration has assisted in visualizing the results in the larger theoretical and empirical perspective of environmental economics and sustainable development. The study introduces a sophisticated analytical framework that considers the complex relationship between technical progress, economic organization, regulatory environment and financial development in influencing environmental results. This methodology thoroughly examines the complex connection between economic growth and ecological sustainability. The study measures the combined effects of ecological impact, eco-innovation, institutional variable, and financial development on environmental quality. Statistical analysis and modeling approaches have been used to quantify and determine the extent and relevance of these effects. The research technique utilizes a systematic approach to gather, analyze and evaluate data to investigate the correlation between economic expansion and ecological degradation thoroughly.

3.1. Statistical data and methodology

Technical development, as a precursor to eco-innovation, is posited to impact energy efficiency significantly [41]. The ecological footprint serves as a proxy for a country's technological advancement, potentially mitigating the adverse environmental impacts of human activity. However, the intricate relationship between technological advancement and environmental quality underscores a potential double-edged sword, wherein economic growth-driven technological innovation may engender both positive and negative outcomes for environmental sustainability. In addition, the economic structure of most nations is poised to influence eco-innovation, thereby shaping environmental protection efforts. Countries with lower financial development tend to exhibit relatively lower energy resource consumption, thus mitigating adverse environmental impacts. Conversely, the transition from primary to secondary sectors in the developmental trajectory may escalate eco-innovation while aggravating environmental degradation. The convergence of technological advancement and knowledge accumulation is considered pivotal in enhancing energy efficiency and ecosystem resilience.

In addition to other factors, the regulatory landscape significantly impacts environmental outcomes, with stringent regulations imposed to safeguard the environment. However, inadequate enforcement or misidentification of environmental priorities may inadvertently worsen ecosystem degradation, highlighting the complex interplay between regulatory frameworks and environmental protection efforts. Source of data is given as in Table 1.

Financial growth, on the other hand, manifests three distinct yet interconnected environmental implications, namely, the scale effect, composition effect and method effect [42]. While the scale effect posits that increased economic and industrial growth may compromise environmental protection efforts, the composition effect suggests a shift away from resource-intensive sectors for bolstering environmental health. The method effect underscores the importance of advancing technology for sustainable energy

Table 1
Source of data.

Variable	Description	Data Sources
GHG	Greenhouse gas emissions	Global Footprint Network
E.R.T.	Energy consumption	International Energy Agency (IEA) or the Carbon Dioxide Information Analysis Center (CDIAC)
E.F	Environment-related technologies	World Bank, International Finance Corporation (IFC)
E.R.T.	Eco-innovation.	Academic literature, financial market reports
G.L.O	Financial development	United Nations, World Bank
GDP	Gross domestic product	International Energy Agency (IEA), World Bank

sources and waste management practices.

The research proffers a detailed understanding of the cumulative effects of ecological impact, eco-innovation, institutional and financial development on environmental quality. The quantification of these effects underscores the multifaceted nature of the relationship between economic growth and environmental sustainability, emphasizing the need for comprehensive policy interventions to navigate towards a more sustainable future.

They are as described in the following equation (1) and equation (2):

$$ENC = f(ef, ECI, FD - EFnexus, GDP) \tag{1}$$

$$\mathrm{GHG} = f(EFT, ENC, ECI, FD - EFnexus, GDP) \tag{2}$$

FD-EFnexus denotes financial development, *ENC* is energy consumption, *GHG* is greenhouse gas emissions, *E.F.* is ecological footprint, *E.C.I.* is eco-innovation, and *G.D.P.* is the gross domestic product. The socioeconomic equations (1) and (2) may be modified into the following equation (3) and equation (4):

$$ENC_{i,t} = \alpha_0 + \alpha_1 ERT_{i,t} + \alpha_2 ECI_{i,t} + \alpha_3 ECI^2_{i,t} + \alpha_4 INQ_{i,t} + \alpha_5 GLO_{i,t} + \alpha_6 GDP_{i,t} + \alpha_7 GDP^2_{i,t} + \mu_{i,t} \tag{3}$$

$$GHG = \beta_0 + \beta_1 ERT_{i,t} + \beta_2 ENC_{i,t} + \beta_3 ECI_{i,t} + \beta_4 ECI^2_{i,t} + \beta_5 INQ_{i,t} + \beta_6 FD - EFnexus + \beta_7 GDP_{i,t} + \beta_8 GDP^2_{i,t} + \varepsilon_{i,t} \tag{4}$$

Variables *ERTfn* and GDP^2 in Eqs. (3) and (4) represent the squares of the environment and the Gross Domestic Product, respectively. The U-shaped correlation between environmental factor and income level are analyzed by combining these squared variables. Because of their distinct features in terms of economic, social and environmental development, we anticipate significant discrepancies in the signs and magnitudes of the parameters of Equations (3) and (4).

In industrialized and developing nations, significant socioeconomic integration raises the probability of cross-sectional dependency. The initial step is to identify it and ignoring it may result in inaccurate and skewed estimations. We try to verify the cross-sectional dependency according to Pesaran's recommendations. The research then runs several tests to see whether the dataset is stationary [43].

The next step is to examine the cointegration of the various variables. We achieve this by using Pedroni's [44] methodology. The Westerlund [45] test is based on whether there has been a general mistake correction for the panel and each panelist. The test reveals cointegration in all or some of the panels, where it rejects the false hypothesis depicts that there is no cointegration. The approaches like FMOLS, DOLS and afterward C.C.R., are suitable for assessing the long-run connection if all the tests above indicate that our panel data are constituted by cross-sectional dependency, semi and cointegration. These methods use various strategies, but they all aid in solving the endogeneity and multi-collinearity issues. To obtain the long-run coefficient, the FMOLS and C.C.R. specifically integrate a moderate adjustment to the Estimation method (Pedroni, 2000). The estimation technique is given as in equations (5)–(8).

$$\hat{\alpha}^*_{FMOLS} = \frac{1}{N}\sum_{i=1}^{N}\left[\left(\sum_{t=1}^{T} n\left(X_{i,t} - \bar{X}_i\right)^2\right)^{-1}\left(\sum_{t=1}^{T}\left(X_{i,t} - \bar{X}_i\right)Y^*_{i,t} - T\hat{\gamma}_i\right)\right] \tag{5}$$

$$Y^*_{i,t} = Y_{i,t} - Y_i - \left(\Omega_{2,1,i} / \Omega_{2,2,i}\right)\Delta X_{i,t} \tag{6}$$

$$\Omega_{i,t} = limT\rightarrow\infty E(1/T)\left(\sum_{i=1}^{T} n\xi_{i,t}\right)\left(\sum_{i=1}^{T} n\xi_{i,t}\right)' \tag{7}$$

$$\gamma_i = \hat{\Gamma}_{2,1,i} + \hat{\Omega}^0_{2.1,i} - \left(\hat{\Omega}_{2,1,i} \Big/ \hat{\Omega}_{2,2,i}\right)\left(\hat{\Gamma}_{2,1,i} \Big/ \hat{\Omega}^0_{2.2,i}\right) \tag{8}$$

These methods have been used in several studies which have looked at the factors that influence eco-innovation with environment protection [46]. This research continues with the investigation of a directed causal connection among components after obtaining a long-run relationship. Additionally, this research employs Chudik & Pesaran's Pool Mean Group with cross-sectionally augmented Autoregressive Distributed Lag (PMG-ARDL) to ensure the stability of the estimated findings in the face of cross-sectional dependency, given as under in equations (9) and (10).

$$\alpha^*_{DOLS} = \frac{1}{N}\sum_{i=1}^{N}\left[\left(\sum_{t=1}^{T} nZ_{i,t}Z'_{i,t}\right)^{-1}\left(\sum_{t=1}^{T} nZ_{i,t}\widetilde{Y}_{i,t}\right)\right] \tag{9}$$

$$Z_{i,t} = \left[X_{i,t} - \overleftarrow{X}_i, \Delta X_{i,t-K_i,\ldots,\Delta X_{i,t+K_i}}\right] \tag{10}$$

This research also investigates a directed causal link across variables after obtaining a deep connection. The Dumitrescu-Hurlin test is used because it considers the cross-sectional dependency, if such a phenomenon occurs. The option of at least a causal link is compared to the assumptions with no effect. For two nation groups, developed and developing, it is important to investigate the effects of ecological footprint, eco-innovation and financial development on greenhouse gas emissions. The first important factor, footprint, is calculated using environmental-related data sets. The variable has been utilized in many researches to investigate how environmental impact affects ecological integrity [47]. use the notion that a more developed economy can manufacture and export a wider variety of goods than a less developed one, in order to gauge the effect on that particular nation. Therefore, these writers use the information on global commerce that links nations to the goods in which they have comparable advantages. The Observation of Environmental database is where the information for eco-innovation is found. Several publications have been written to examine the link between eco-innovation and environment since the Eco-innovation observatory published data on eco-innovation. Investigators' dataset of Political Risk Guide serves as the source for the data. The variable is developed mainly by averaging multiple indices per year, which include bureaucratic effectiveness, democracy accountability, government effectiveness and corruption. The K.O.F. financial development index, which measures the financial, socioeconomic and ideological elements of financial progression is used to represent financial development [48]. The above index provides a much more complete picture of financial development than some other single measures like trade or government deficit openness given as in Table 2.

Table 3 demonstrates that the average energy consumption and greenhouse gas emissions of developed nations are higher than those of developing nations. However, developing country emissions of greenhouse gases and eco-innovation differ considerably from developed nation levels. Advanced economies are more intricate and globally linked than those of underdeveloped nations. In terms of income per person, there is a substantial difference between developed and developing countries. Developed economies get multiple more patents per year than emerging nations regarding environmental advancements.

4. Results and discussions

4.1. Pesaran cross-sectional dependence test

The results presented in Table 4 indicate the outcomes of the Pesaran cross-sectional dependence test, which assesses the presence of interdependence among different countries' data. Notably, at a significance level of 1 %, the null hypothesis of cross-sectional independence is rejected for all parameters, both in developed and developing nations. This rejection suggests that there exists significant cross-sectional dependence among the variables examined, indicating that the data from different countries are not entirely independent of each other. To address this issue of cross-sectional dependence, the research employs a second-panel unit root test, which caters for such interdependence in the data. This methodological approach is considered crucial for ensuring the robustness and reliability of the empirical findings, as it acknowledges and then adjusts the potential influence of cross-sectional dependence on the results.

Furthermore, the specific parameter estimates provided in Table 4 shed light on the magnitude and significance of the relationship between the variables under investigation in both developed and developing countries. For instance, the coefficients for Greenhouse Gases (GHG), Environmental Regulation and Taxation (ERT), Ecological Footprint (EF) and Financial Development-Economic Nexus (FD-EFNEXUS) are all statistically significant across both groups of countries, albeit with varying magnitudes.

These findings strengthen the linkage between theory, empirical analysis and the broader context of environmental sustainability and economic development. The significant coefficients underscore the importance of factors such as environmental regulation, financial development and ecological footprint in shaping the environmental and economic outcomes of both developed and developing nations. Moreover, the acknowledgment and adjustment for cross-sectional dependence enhances the validity of the empirical results, providing more accurate results.

The study's findings highlight various critical areas of the relationship between economic development and environmental degradation.

4.2. Unit root test

Table 5 provides the results of the Unit Root Test conducted for both developed and developing nations. The study utilizes different test methodologies, including the Levin-Lin-Chu and Pesaran tests, to examine the stationarity of the variables. While Pesaran's findings are preferred due to their resistance to cross-sectional dependency, sensitivity analysis is conducted using other tests such as Levine-Lin-Chu's an Im-Peasaran Shin's tests [49]. In Panel (1) of Table 5, the unit root test results for the level and delta (first difference) of each variable are presented separately for developed and developing nations. The unit root test assesses whether a time series variable is stationary or non-stationary. Generally, stationary variables exhibit stable mean and variance over time, while non-stationary variables show trends or random fluctuations. For developed nations, the Pesaran test indicates that financial

Table 2
Description of variables.

Variables	Symbol	Measurement
Greenhouse gas emissions	*G.H.G*	Million tons of Carbon dioxide
Energy consumption	*E.R.T.*	Exajoules
Environment-related technologies	*E.F.*	Number
Eco-innovation	*E.R.T.*	Index
Financial development	*G.L.O.*	Index
GDP	*G.D.P*	Constant 2010 US$

Table 3
Variables statistics.

Variable	Developed countries					Developing countries				
	O.b.s	Mean	Std. Dev.	Min	Max	O.b.s	Mean	Std. Dev.	Min	Max
GHG	222	6.689	0.877	5.708	8.680	222	6.556	1.103	4.939	9.138
ERT	222	2.749	0.791	1.830	4.575	222	2.450	1.019	0.718	4.874
EF	222	7.534	1.265	5.018	9.750	222	4.580	2.289	−1.109	9.045
ERT	222	1.676	0.511	0.411	2.625	222	0.346	0.383	−0.506	1.164
FD-EFNEXUS	222	4.374	0.088	4.042	4.495	222	4.062	0.160	3.494	4.282
GDP	222	10.594	0.136	10.250	10.888	222	8.448	0.901	6.355	9.614

Table 4
Cross-sectional dependence test.

	Developed countries	Developing countries
GHG	7.659***	12.729***
ERT	23.106***	15.521***
EF	9.905***	15.596***
ERT	14.840***	4.377***
FD-EFNEXUS	23.017***	22.265***
G.D.P	10.250***	11.411*

Note: *,**,*** show the significance level of 1 %,5 % and 10 % respectively.

Table 5
Results of the unit root test.

Panel (1) Unit Root								
	Developed Nations				Developing Nations			
	LEVIN-LIN-CHU		PESARAN		LEVIN-LIN-CHU		PESARAN	
	level	Delta	level	Delta	level	Delta	level	Delta
GHG	0.483	−11.859***	1.392	−10.813***	−1.109	−3.161***	0.073	−3.951***
ERT	−0.276	−12.305***	0.875	−11.400***	−1.259	−3.172***	0.648	−3.477***
EF	−1.235	−12.345***	−1.112	−12.135***	−1.040	−11.641***	1.072	−13.030***
E.R.T.	−1.547*	−12.473***	0.661	−11.718***	−0.940	−10.144***	−0.739	−9.428***
FD-EFNEXUS	−0.952	−11.040***	−1.953**	−10.477***	−9.057***	−5.468***	−6.426***	−5.773***
GDP	0.003	1.418**	0.427	−1.371***	0.261	−1.876***	0.021	−2.874***
Panel (2)								
	Developed Nations				Developing Nations			
	Lags(1)		Lags(2)		Lags(1)		Lags(2)	
Z(test)	level		Level		level		level	
GHG	−1.020	−7.458***	−1.329	−5.178***	1.421	−6.139***	0.958	−0.744
ERT	−0.524	−10.266***	0.551	−6.536***	−1.147	−6.035***	−2.337	−1.502*
EF	−0.583	−7.674***	−0.088	−4.539***	−0.084	−8.040***	1.150	−4.456***
ERT	−0.373	−8.054***	−0.430	−2.904***	1.171	−10.236***	1.260	−3.573***
FD-EFNEXUS	−1.300*	−9.052***	−1.455*	−3.209***	−0.964	−8.974***	−0.748	−5.609***
GDP	2.438	−3.312***	0.582	−1.796**	−0.850	−4.256***	0.423	−1.828**

Note: *,** and *** show the significance level of 1 %,5 %, and 10 % respectively.

development (FD-EFNEXUS) is stationary at the level, while the other variables such as greenhouse gas emissions (GHG), Environmental Regulation and Taxation (ERT), Ecological Footprint (EF) and GDP are non-stationary. Similarly, in developing nations, financial development is stationary at the level according to the Pesaran test, while the other variables exhibit a non-stationary behaviour. In Panel (2), the results of the Z-test for stationarity are presented for both developed and developing nations, considering different lag structures. The Z-test assesses whether the estimated coefficient on the first difference term is statistically significant, indicating stationarity. Again, the findings reveal a mix of stationary and non-stationary variables across different lag structures and country groups.

These results have important implications for understanding the dynamics of economic growth, environmental sustainability and financial development in both developed and developing nations. Stationarity or non-stationarity of variables can influence the modeling and forecasting of economic and environmental outcomes, highlighting the need for robust analytical techniques and policy interventions tailored to specific contexts. Moreover, the sensitivity analysis using different test methodologies adds credibility to the findings and enhances the robustness of the conclusions drawn from the study.

The findings presented in Table 6 shed light on the relationship between relevant variables by examining cointegration using both the Pedroni and Westerlund tests. Cointegration analysis helps determine whether variables move together in the long run, indicating a stable relationship between them. In Panel 1, the results of the Pedroni test for cointegration are reported for both developed and developing nations. The test statistics indicate the presence of cointegration for some variables. Specifically, in developed nations, the null hypothesis of no cointegration is rejected for the variables *Vv* and *RHO*, as evidenced by statistically significant t-statistics. Similarly, in developing nations, the null hypothesis is rejected for the variables *RHO* and *T-Stat*. These findings suggest a long-term relationship between the examined variables in both developed and developing contexts.

In Panel 2, the results of the Westerlund test for cointegration are presented. The test statistics (Z test) indicate whether the null hypothesis of no cointegration is rejected. In developed nations, the null hypothesis is rejected for variables *Gt, Ga,* and *Pa*, suggesting the presence of cointegration. Similarly, in developing nations, the null hypothesis is rejected for variables *Ga* and *Pa*. These results further support the notion of a long-term relationship between the variables under investigation. Overall, the cointegration tests provide empirical evidence of significant linkages between the selected characteristics in both developed and developing countries. This supports the theoretical framework which suggests that various factors, such as financial development, environmental regulation and economic growth interact and influence each other over time. Understanding these linkages is crucial for policymakers and stakeholders in formulating effective strategies to promote sustainable development and mitigate environmental degradation. Moreover, the utilization of both the Pedroni and Westerlund tests enhances the robustness of the analysis and strengthens the validity of the findings, contributing to the broader literature on economic and environmental dynamics.

The results presented in Tables 7 and 8 provide estimates for energy consumption and greenhouse gas emissions, respectively using the FMOLS, DOLS and C.C.R. techniques. These estimations help evaluate the long-term relationship between greenhouse gas emissions, eco-innovation, and their potential determinants.

In Table 7, focusing on energy consumption, several pertinent findings emerge. Firstly, the coefficients for eco-friendly variables (EF) are negative and statistically significant across all estimation techniques and country categories (Developed and Developing Nations). This indicates that higher eco-friendly practices are associated with lower energy consumption, aligning with expectations of sustainability efforts leading to reduced environmental impact. Additionally, the coefficients for energy-related technologies (ERT) and its squared term (ERT_squared) vary in sign across techniques and country categories, suggesting a non-linear relationship between these variables and energy consumption. Moreover, financial development (FD-EFNEXUS) exhibits a mixed effect on energy consumption, with coefficients showing both negative and positive signs, highlighting the complexity of the relationship between financial development and environmental outcomes. Overall, the adjusted R-squared values indicate that the models explain a substantial portion of the variation in energy consumption, emphasizing upon the validity of the estimations.

Turning to Table 8, which examines greenhouse gas emissions, similar patterns are observed. The coefficients for eco-friendly variables (EF) are negative and statistically significant, indicating that higher eco-friendly practices are associated with lower greenhouse gas emissions. However, the relationship with energy-related technologies (ERT) is less consistent, with coefficients showing both positive and negative signs across techniques and country categories. Financial development (FD-EFNEXUS) exhibits a more consistent negative relationship with greenhouse gas emissions across all estimation techniques and country categories, suggesting that greater financial development may contribute to lower emissions. Moreover, the adjusted R-squared values indicate the strength of the models in capturing variation in greenhouse gas emissions.

Overall, these findings provide valuable insights into the dynamics between eco-innovation, energy consumption and greenhouse gas emissions in both developed and developing nations. They underscore the importance of sustainable practices and financial development in mitigating environmental degradation and advancing global efforts towards a more sustainable future. The nuanced relationships revealed by the estimations contribute to a deeper understanding of the complex interplay between economic development, technological innovation and environmental outcomes.

The FMOLS, DOLS, and C.C.R. methods have been employed to assess parameters and associated confidence intervals for both developed and developing countries. A notable positive correlation between eco-innovation and greenhouse gas emissions emerges,

Table 6
Cointegration Tests results.

Panel 1 Results of Pedroni test				
	Developed Nations		Developing Nations	
Stat.	Panels	A	Panel	B
Vv	−0.082	.	−1.325	.
RHO	2.233**	3.062***	1.702*	2.504**
T-Stat	−1.846*	−1.908*	−1.932*	−2.060**
ADF	−1.085	−1.462	−0.443	−0.559
Panel 2 Westerlund test results				
	Developed Nations		Developing Nations	
Stat.	Z test	Z test	Z test	Z test
G_t	−2.134***	−2.3249	−1.718**	−3.347
G_a	−10.603***	−2.5389	−11.470*	−2.354
P_t	−4.049	−0.646	−3.886	−1.334
P_a	−8.560**	−1.687	−7.529*	−2.203

Note: *,**,*** shows the significance level of 1 %,5 % and 10 % respectively.

Table 7
Estimation results for energy consumption.

	(6)	(5)	(4)	(3)	(2)	(1)
	Developed Nations			Developing Nations		
	FMOLS	DOLS	CCR	FMOLS	DOLS	CCR
EF	−1.084*** (0.003)	−1.126*** (0.012)	−0.074*** (0.002)	0.026*** (0.003)	0.108*** (0.016)	0.020*** (0.004)
ERT	0.045 (0.026)	0.236*** (0.230)	0.147** (0.056)	−2.022*** (0.246)	−2.065*** (0.644)	−2.865*** (0.487)
ERT_squared	−1.005 (1.011)	−0.207*** (0.031)	−0.024* (0.010)	0.768*** (0.056)	0.752*** (0.232)	1.097*** (0.195)
FD-EFNEXUS	−1.322*** (1.033)	−0.577*** (0.126)	−0.279*** (0.043)	0.413*** (0.032)	0.894*** (0.288)	−0.033 (0.108)
GDP	48.191*** (0.645)	36.100*** (4.154)	52.473*** (0.784)	4.590*** (1.095)	14.960*** (3.928)	12.381*** (2.171)
dERT/dERT		1.270	2.174	0.321	0.373	0.306
dirt/GDP	10.745	9.387	9.215	9.432	2.215	6.421
adjusted R-squared	0.934	0.845	0.764	0.991	0.998	0.995

Note: ***, ** and * indicate significance at the 1 %, 5 %, and 10 % levels, respectively.

Table 8
Estimation results of Greenhouse gas emissions.

	(6)	(5)	(4)	(3)	(2)	(1)
	Developed Nations			Developing Nations		
	F.M.O.L.S	D.O.L.S	C.C.R	F.M.O.L.S	D.O.L.S	C.C.R
E.F.	−0.028*** (0.002)	−0.035* (0.021)	−0.028*** (0.003)	0.010*** (0.002)	0.042*** (0.005)	0.009* (0.005)
ERT	1.159*** (0.024)	1.041*** (0.171)	1.203*** (0.044)	0.139 (0.200)	−0.784*** (0.217)	0.579*** (0.311)
ERT_squared	−0.366*** (0.007)	−0.327*** (0.054)	−0.379*** (0.013)	−0.026 (0.079)	0.339*** (0.083)	−0.194 (0.124)
FD-EFNEXUS	−1.283*** (0.023)	−0.673*** (0.191)	−1.269*** (0.032)	0.213*** (0.046)	0.235*** (0.089)	0.042 (0.066)
GDP	43.738*** (0.914)	26.288*** (0.123)	45.890*** (0.019)	−4.212*** (0.659)	−7.077*** (1.199)	−9.112*** (1.065)
GDP_squared	−2.033*** (0.042)	−1.224*** (0.006)	−2.134*** (0.001)	0.222*** (0.035)	0.384*** (0.063)	0.477*** (0.057)
GHG/dERT	1.583	1.592	1.587		0.156	
GHG/GDP	10.757	10.739	10.752	9.486	9.215	9.551
adjusted R-squared	0.981	0.970	0.977	0.992	0.997	0.993

Note: *,** and *** shows significance level of 1 %,5 %, and 10 % respectively.

aligning with prior research findings [50]. One plausible explanation is the historical dominance of carbon emissions as the primary source of greenhouse gas emissions. Additionally, an examination of economic variables influencing energy consumption can shed light on factors impacting greenhouse gas emissions. The estimated results enable a comparison of socioeconomic variables influencing the ecological environment between developing and developed countries, situated in contrasting socioeconomic contexts.

The estimated findings for eco-innovation in both developed and developing countries are discussed initially, followed by those for greenhouse gas emissions across the two selected countries. Table 7 presents estimated findings regarding factors influencing energy utilization. It suggests that reducing one's ecological footprint could contribute to lower energy consumption. This finding underscores the effectiveness of renewable energy sources in simultaneously optimizing output and economic development while minimizing environmental costs. Emission technologies, categorized as environmental technology, hold promise in reducing pollution by enhancing the efficiency of energy sources used in manufacturing or treating commodities.

According to calculations using DOLS and C.C.R. methods, the eco-innovation nexus exhibits an exaggerated U-shaped pattern with a critical point estimated between 1.176 and 1.570. Structural dynamics may further elaborate this relationship. During early economic growth, countries with minimal environmental concerns may exhibit limited product activities and eco-innovation. As the economy transitions from agriculture to industrialization, accompanied by a more diverse and environmentally hazardous product mix, eco-innovation could escalate energy consumption, stimulating output growth. Environmental innovations may be neglected until reaching industrial scale due to substantial initial investment. Consequently, technologies that balance environmental efficiency and growth could mitigate sustainable technology in the future, characterizing eco-innovation as a pollution reduction technique.

Conversely, developed countries with lower corruption levels are more likely to implement well-designed and enforced pollution control policies (Sheng et al., 2020). The pollutant attribution theory posits that ecosystems in developed countries may benefit from greener technologies and superior management practices adopted elsewhere, potentially explaining the negative relationship between financial expansion and eco-innovation. Effective engagement in global value chains enables wealthier countries to transfer sectors with higher eco-innovation to less developed and developing nations, possibly accounting for the modest relationship between financial development and eco-innovation. We find evidence of the elements that impact eco-innovation in emerging nations, typically in numerous directions. Columns (4)–(6) of Table 7 show FMOLS, DOLS and C.C.R. coefficients and standard deviation for developing countries. The positive environment-related technical coefficient has statistical significance which illustrates that environmental effect in emerging countries has changed production and consumption patterns toward more efficient approaches. Green innovation has the capacity to explain this phenomenon. Systems theory's rebound effect method evaluates technology's environmental performance through its interactions with the socioeconomic system. After adopting sustainable technologies, the energy market, consumer behavior and infrastructure system improvements may quantify the ecological footprint's negative impacts on eco-innovation and the environment. Green innovation reduces energy costs and boosts household productivity and income. Though family eco-innovation shows increases, however, the macroeconomic revival is much stronger.

Economic competitiveness is considered to be a factor that raises energy consumption, if the measure is between 0.321 and 0.373,. The threshold above which more economic growth begins raising energy consumption varies from 11,361 to 38,989 (constant 2010 US $), and developing nations also experience a U-shaped connection. It should be emphasized that during the beginning of the 1990s, the developing world continued to rely on an economy based on renewable resources.

The empirical data show that eco-innovation in developing nations is associated with higher institutions and global integration. On the one hand, the fast industrial development and the provision of public and civic services in such nations may be fueled by the development of their institutions, which ultimately leads to higher energy consumption. This suggests the negative effect of financial developers' impact on economic growth. Specifically, developing economies may import capital-intensive items and more polluting projects from wealthy nations. As a result, financial and trade openness encourages consumption and investment, boosting eco-innovation. The projected findings for Developed nations for greenhouse gas emissions utilizing FMOLS, DOLS, and C.C.R. are shown in Columns (1) to (3) of Table 8. Environmental technology coefficients are negative significant values, which indicate that a larger ecological footprint helps to reduce greenhouse gas emissions. Our results are in line with the empirical data for European Nations. This research has already shown the negative impacts of green technology on energy use.

Additionally, technologies that are concerned with the environment promote the manufacturing. Consequently, green technologies might directly help reduce environmental damage in the manufacturing phase in the industry where they are developed and used. Additionally, the spread of environmental technology, transfer of technology and environmental assets may increase overall sustainability impact across the production process.

It can be seen that the eco-innovation coefficients and squared are "±" considered both positive and negative. This research suggests that economic complexity and greenhouse gas emissions in developed nations have an asymmetric U-shaped interaction. Approximately 1.583–1.592 is the eco-innovation threshold, above which the environmental impact of the production structure transforms from detrimental to advantageous. The asymmetric U-shaped relationship between green consumption and carbon emissions, given the detrimental effects of the environment on the ecological state indicates that the advent of eco-innovation correlates with the growth of production activities and the introduction of industrialization, which produce more emissions in the early stages of economic development. Consequently, there is a poor correlation between eco-innovation and environmental quality [51]. When eco-innovation reaches critical value, an economy with a sufficiently large scale of production begins to see changes in the input mix and new technology developments that might improve energy efficiency. The mix is changing simultaneously, moving away from heavy industries with extensive resource development towards the lighter services and manufacturing sectors. Additionally, as the economy grows more complicated, money increases public demand for environmental knowledge and well-being [52]. [53] determined the environmental impact is the last stage of eco-innovation progression. Given that its calculated parameter is positive and statistically significant, Environmental quality in developed nations is significantly influenced by financial development.

Additionally, the formulation and implementation of laws governing natural resource utilization are primarily within the purview of governments, with institutions integrated into the governance structure playing a significant role in shaping environmental quality through the efficacy of these laws. As previously noted, nations with lower levels of government mismanagement are more likely to draft and successfully implement laws and regulations aimed at regulating pollution. Moreover, modern democracies with substantial political freedom empower citizens to voice concerns about environmental issues, potentially leading to higher environmental quality.

The statistically significant negative coefficient of financial development suggests that financial development may have a more positive ecological impact in developed nations. This finding aligns with the theoretical concept of the trade-environment nexus, as concluded by Ref. [54]. Developed countries, being high-income nations, often have substantial financial resources. They tend to export capital-intensive goods (with significant environmental implications) and import labor-intensive goods during economic and financial growth, resulting in cleaner products. Additionally, developed nations may benefit from the spillover effects of research and development (R&D) in trade, particularly in the realm of eco-products, which can accelerate the adoption of green technology, reducing energy consumption and improving the environment.

The rise of the financial system in developed nations can be considered conducive to environmental sustainability. This finding aligns with the pollution halo effect theory, suggesting that inbound foreign direct investment (FDI) may bring greener technology and improved management practices related to future investments in environmental sectors. Consequently, the host nation is incentivized to adopt ecologically sustainable practices. Moreover, developed nations have demonstrated a strong commitment to international environmental norms through active involvement in international treaties and working groups addressing climate change. Therefore, their political and financial development initiatives may contribute to better environmental quality.

These results for developed nations are consistent with those presented by Ref. [55], who provide empirical evidence that financial growth facilitates the transfer of pollution from developed to developing countries, during both production and consumption. The findings from panel data analysis across 25 developed nations in Asia, North America, Western Europe and Oceania corroborate the theory of financial development's impact on carbon emissions.

Regarding the coefficient of GDP per capita and its square, they exhibit both positive and negative relationships with environmental quality. This research confirms the existence of the Environmental Kuznets Curve (EKC) in developed nations, with the turning point estimated to be between 46,119 and 46,957 (constant 2010 U S. $). This discovery supports the inverted U-shaped association between financial development and environmental degradation across nations, adding to the body of evidence supporting the EKC theory.

Panels (4) & (6) of Table 8 depict the estimated results for developing nations. As the predicted coefficient of the environment-related innovation variable is favorably substantial at a 1 % level throughout the three techniques, it is significant to observe that ecological footprint negatively influences environmental quality. It demonstrates once again the positive feedback loops created by environmental technology. According to this study's findings, in particular, the creation and acceptance of green innovations result in more eco-innovation and consequently, more serious environmental deterioration. High population density and economic expansion are the driving forces behind emerging economies, including developing ones. In comparison, the number of people in developing nations in 2019 is more than four times as in developed nations, making up around 48 % of the people worldwide. Because environmental degradation depends on population density and technology, developing nations are likely to be more negatively affected by increased consumption. Manufacturing green components or products in developing nations would need a greater amount of environmentally damaging industrial production, due to their generally weaker productive capacities. Rebound effects are thus more likely to happen. Additionally, it takes more energy to build the infrastructure needed to use new green technology.

Similarly, the research investigates the cyclical influence of environmental technology on carbon dioxide emissions from 1991 to 2019. The findings, which are supported by empirical methods, describe how positive shocks to green technologies have a negative influence on emissions. The estimate of the ecological footprint's economic growth in developing nations is consistent with empirical data showing the damaging effects of green technologies on the environment. However, earlier research confirms that the maximum impact exists in developed economies. All three assessment methods disagree on the impact of eco-innovation on greenhouse gas emissions in developing nations. The C.C.R. technique supports the positive correlation between eco-innovation and greenhouse gas emissions. However, the multiple regression analysis estimators show that there are no substantial environmental effects of eco-innovation. However, according to the DOLS parameters, there is a correlation between eco-innovation and the emission of greenhouse gases. In particular, column (5) of Table 8 demonstrates that, at a 1 % degree of significance, the coefficient of the environment and its square are both positive and negative. The reduction in greenhouse gas emissions to the eco-innovation progress significantly reduces the level of environmental quality. The estimated findings of the association between income level and ecological sustainability also point to a U-shaped relationship. Higher-income levels help to better regulate environmental quality throughout the early stages of the economy. However, economic growth based on boosting output and consumption might turn a positive trend into a negative one, this curve will be predicted to turn to 10,047 and 14,059 (constant 2010 U S. $). These results diverge from those of

Table 9
Results of Dumitrescu and Hurlin's causality test.

Null hypothesis	Developed Nations		Developed Nations	
	Z statistics	Causality flow	Z statistics	Causality flow
ERT ≠> *GHG*	3.628***	ERT ↔ GHG	4.426***	ERT ↔ GHG
GHG ≠> *ERT*	2.897***		6.043***	
EF ≠> *GHG*	3.686***	EF ↔ GHG	4.943***	EF ↔ GHG
GHG ≠> *EF*	31.322***		11.499***	
ERT ≠> *GHG*	5.891***	ERT ↔ GHG	−1.661*	ERT ↔ GHG
GHG ≠> *ERT*	9.524***		6.147***	
FD-EFNEXUS ≠> *GHG*	2.867***	FD-EFNEXUS → GHG	2.695***	FD-EFNEXUS ↔ GHG
GHG ≠> *FD-EFNEXUS*	−0.941		3.476***	
GDP ≠> *GHG*	4.317***	GDP ↔ GHG	2.583***	GDP ↔ GHG
GHG ≠> *GDP*	1.984**		1.733*	
EF ≠> *ERT*	4.643***	EF ↔ ERT	3.859***	EF ↔ ERT
ERT ≠> *EF*	16.620***		10.280***	
ERT ≠> *ERT*	5.345***	ERT ↔ ERT	4.487***	ERT ↔ ERT
ERT ≠> *ERT*	7.505***		4.118***	
FD-EFNEXUS ≠> *ERT*	2.974***	FD-EFNEXUS → ERT	3.281***	FD-EFNEXUS ↔ ERT
ERT ≠> *FD-EFNEXUS*	−0.751		2.934***	
GDP ≠> *ERT*	1.521	GDP ← ERT	3.477***	GDP ↔ ERT
ERT ≠> *GDP*	2.155**		45.404***	
ERT ≠> *EF*	11.071***	ERT ↔ EF	0.645	ERT ← EF
ETR ≠> *ERT*	8.999***		1.845*	
EF ≠> *FD-EFNEXUS*	0.376		2.500**	
GDP ≠> *EF*	8.410***	GDP ↔ EF	12.830***	GDP ↔ EF
EF ≠> *GDP*	3.657***		5.107***	
INS ≠> *ERT*	−1.248	INS ← ERT	3.423***	INS → ERT
ERT ≠> *INS*	2.444**		−0.157	
FD-EFNEXUS ≠> *ERT*	2.696***	FD-EFNEXUS ↔ ERT	1.011	FD-EFNEXUS ← ERT
ERT ≠> *FD-EFNEXUS*	3.240***		2.960***	
GDP ≠> *ERT*	20.863***	GDP ↔ ERT	3.751***	GDP ↔ ERT
ERT ≠> *GDP*	−1.861*		70.757***	
FD-EFNEXUS ≠> *INS*	5.659**	FD-EFNEXUS → INS	1.688*	FD-EFNEXUS ↔ INS
INS ≠> *FD-EFNEXUS*	1.199		1.689*	
GDP ≠> *INS*	9.673***	GDP ↔ INS	1.177	GDP ← INS
INS ≠> *GDP*	2.613***		2.010**	
FD-EFNEXUS ≠> *GDP*	1.538	FD-EFNEXUS ≠ GDP	21.619***	FD-EFNEXUS → GDP
GDP ≠> *FD-EFNEXUS*	−0.754		1.4886	

Note: *,** and *** shows significance level of 1 %,5 %, and 10 % respectively.

Table 10
Robustness test (estimation results using PMG-ARDL).

	(8)	(7)	(6)	(5)	(4)	(3)	(2)	(1)
	Greenhouse gas emissions				Energy consumption			
	Developed countries		Developing countries		Developed countries		Developing countries	
	Long-run	Short-run	Long-run	Short-run	Long-run	Short-run	Long-run	Short-run
E.F.	−0.067* (0.035)	−0.003 (0.018)	0.007*** (0.002)	−0.003 (0.005)	−0.027*** (0.007)	−0.005 (0.011)	0.024*** (0.005)	0.008 (0.005)
ERT	1.579*** (0.322)	0.965*** (0.087)	1.038*** (0.018)	0.420*** (0.082)				
ERT	0.541* (0.328)	−0.050 (0.042)	−0.250*** (0.040)	0.009 (0.206)	0.542*** (0.091)	−0.249 (0.289)	−1.329*** (0.188)	0.203 (0.146)
ERT_squared	−0.191* (0.104)	0.014 (0.014)	0.063*** (0.018)	−0.014 (0.106)	−0.148*** (0.030)	0.074 (0.080)	0.468*** (0.067)	−0.069 (0.056)
INQ	−0.046 (0.047)	0.001 (0.006)	0.018*** (0.003)	−0.001 (0.009)	−0.021*** (0.003)	0.001 (0.008)	0.030*** (0.006)	0.003 (0.004)
FD-EFNEXUS	−1.267* (0.687)	0.085 (0.133)	0.281*** (0.054)	−0.156 (0.179)	−0.607*** (0.094)	0.307 (0.228)	0.094 (0.103)	−0.144 (0.152)
GDP	31.580* (18.819)	0.145 (7.178)	−0.650** (0.312)	−5.612 (7.551)	22.483*** (0.534)	−17.348 (19.656)	1.593* (0.910)	−7.464 (10.440)
GDP_squared	−1.509* (0.891)	−0.002 (0.339)	0.034* (0.019)	0.287 (0.425)	−1.048*** (0.027)	0.823 (0.931)	−0.059 (0.050)	0.479 (0.646)
E.C.T.	−0.112*** (0.037)		−0.571*** (0.134)		−0.648*** (0.186)		−0.488*** (0.174)	

Note: ***, ** and * indicate significance at the 1 %, 5 %, and 10 % levels, respectively.

developed countries and point towards the financial development and economic growth theory [56]. The reduction in Carbon dioxide emissions during the first stages of economic growth and eco-innovation evolution suggests the presence of a "technology impact" that contributes to the enhancement of environmental protection. According to this study's findings, the structural transformation among developing countries began with economics founded on natural resources and low levels of technology. When eco-innovation reaches a sufficiently high level, developing nations demonstrate a discernible beneficial influence. Additionally, the economy based on natural resources is linked to high pollution levels and intense resource exploitation. By switching to more modern manufacturing techniques instead of older ones and shifting the economy away from industries reliant on natural resources, it is possible to improve economic output while simultaneously lowering environmental externalities. But as the economy grows, the scale effect, which is supported by steadily increasing output and the industrialization process, takes over and stresses the environment. However, developing nations do experience the innovation rebound effect. Due to the rebound effect, expanding eco-innovation may not be discouraged due to the positive effects of technology developments on the environment. This research strongly suggests that eco-innovation & carbon dioxide emission in developing nations have a non-linear relationship. As a result, environmental advantages from increased environmental consciousness changes in input mix (from brown to green) or the transition to a lighter industrial sector as well as service industry may not be seen in developing nations, due to a lack of economic knowledge and income levels. Our results support the assertion that eco-innovation negatively affects ecosystems that are mostly irreversible over time and have little potential for recovery. We conclude that developing nations have not yet advanced to a point where positive environmental effects can be demonstrated, according to the information set from 1991 to 2019. In developing nations, the association is evident with greenhouse gas emissions according to all three techniques, including CCR, and D.OL.S. However, statistically significant findings support the correlation shown by the two earlier methodologies. Instead of environmental concerns, authorities in developing nations often give higher priority to urgent national challenges like economic growth, unemployment, and poverty. As a result, such nations' developing institutions support fast industrial development and the quick delivery of public and civic services, both of which increase pollution. The results align with those reported by Ref. [57] for 87 developing countries and the findings for 26 underdeveloped countries.

A significantly substantial and positive correlation between financial development and greenhouse gas emissions has been found by FMOLS and DOLS. It may be demonstrated by the growth in energy consumption from both production and consumption. The research, therefore, lends credence to the theoretical framework [58] put forward on the link between commerce and the environment and the pollution haven theory of FDI. Our research supports the thesis that developing nation's trade off environmental aspects for financial advantages.

The findings of Dumitrescu and Hurlin's causality test are shown in Table 9. In both industrialized and developing nations, there are feedback effects between greenhouse gas emissions, energy usage and environmental technology. According to this, there must be two-way causal linkages between energy usage, eco-innovation and the emission of greenhouse gases. Furthermore, there are also several multi-directional, incidental correlations between eco-innovation and greenhouse gas emissions, as well as between factors which influence it. Institutions do not correlate with greenhouse gas emissions in underdeveloped nations, although the feedback result between institutions and emissions of greenhouse gases is discovered in developed countries. The results also demonstrate the causal relationship between financial development and greenhouse gas emissions in developing nations, but only a one-way relationship between financial development and emissions in developed nations.

4.3. Robustness test

Utilizing the PMG-ARDL approach for sensitivity analysis, we validated the core empirical findings while considering cross-sectional dependence. Table 10 illustrates the outcomes of these estimations concerning greenhouse gas emissions and energy consumption across both developed and developing nations. The coefficients derived from the PMG-ARDL estimations offer deeper insights into the relationships among various factors, encompassing Ecological Footprint (EF), Eco-innovation (ERT), Institutional Quality (INQ), Financial Development (FD-EFNEXUS) and economic indicators (GDP and GDP_squared), vis-à-vis Greenhouse gas emissions and energy usage. Regarding greenhouse gas emissions, the coefficients associated with ecological footprint (EF) exhibit negativity in the long run for both developed and developing countries, indicating that higher adherence to eco-friendly practices correlate with a gradual reduction in greenhouse gas emissions over time. The coefficients for eco-innovation (ERT) and its quadratic term (ERT_squared) manifest mixed effects, implying a non-linear association between eco-innovation and emissions. Additionally, financial development (FD-EFNEXUS) showcases diverse impacts on emissions, with some coefficients reflecting negativity and others positivity, highlighting the intricate relationship between financial progress and environmental outcomes.

Similarly, in the realm of energy consumption, the coefficients linked to ecological footprint (EF) predominantly show negativity, signaling that elevated levels of eco-friendly practices are tied to diminished energy usage over both the long and short terms. Meanwhile, the coefficients for eco-innovation (ERT) and its squared term (ERT_squared) present varied effects, while those for institutional quality (INQ) and financial development (FD-EFNEXUS) exhibit disparities across different estimation methods and country classifications.

Overall, the PMG-ARDL estimations bolster the primary findings, affirming the intricate interplay among ecological footprint, eco-innovation, institutional quality, financial development, carbon emissions and energy consumption in both developed and developing nations. These results emphasize the critical role of sustainable practices and institutional frameworks in mitigating environmental degradation and fostering long-term sustainability amid economic development endeavors.

4.4. Discussion

The study's findings, which provide support for and new evidence against previous researches, illuminate various critical areas of the relationship between economic development and environmental degradation. This study lends also support the previous ideas that developing nations follow the Environmental Kuznets Curve (EKC), which states that environmental degradation improves at a certain point in economic development. A literature review in this area corroborates these results [59]. In addition, by taking potential temporal lags and cross-sectional variations into account, the enhanced distributed lag autoregressive model provides a more thorough analysis and strengthens the conclusions [23].

On the other hand, the study dispels myths by showing that GHG emissions are inversely related to economic growth, a widely held belief. Although there was a positive correlation between economic growth and higher greenhouse gas emissions, the study notes that this may only sometimes be the case. Impacts on the link between economic growth and environmental quality can be attributed to secondary factors such as technical advancements, changes in production and consumption patterns and increases in energy efficiency. In light of these results, it is clear that more comprehensive governmental strategies are required to resolve environmental issues [25].

The emerging pattern of urbanization that drives the economic growth of developing countries also places great emphasis on protecting the environment, making it imperative to strive for a reduction in the nation's environmental impact. The outcomes of this examination provide convincing proof that the Environmental Kuznets Curve (EKC) phenomenon is also evident in developing countries, despite having been previously observed in other regions. Nevertheless, for these nations to attain their carbon neutrality objectives, they must prioritize enhancing their G.D.P., implementing environmental levies, encouraging eco-friendly technologies and investing in research and development for renewable energy. In addition, the utilization of the cross-sectionally augmented distributed lag autoregressive model exemplifies the comprehensiveness with which our research has considered the delicate relationship between GDP and GHG emissions. By incorporating the potential time lags associated with the response and cross-sectional variations, the model allows for a more robust consideration of the data involved. Similarly, the results of the paired panel and Granger causality analysis also confirm the validity of the findings presented within this research. This confirmation is possible due to the unique methodological approaches utilized in analyzing causality and relationships. Overall, as these analytical techniques are fundamentally distinct, the confirmation of the initial findings only strengthens the results as reported. The assumption that there is no significant relationship between GDP and GHG emissions challenges common perceptions. As stated earlier, such findings presume a more multi-faceted relationship between economic growth and greenhouse emissions. Indeed, as the economic growth was primarily positively correlated with an increase in GHG emissions, this unidirectional relationship cannot be the case. As indicated earlier, secondary factors such as technological innovations, changed patterns of production and consumption and improvement in energy efficiency are among the most likely sources of this disconnect. The latter underscores the necessity of more holistic policy approaches. Additionally, this study confirms prior research that consistently found a significant one-sided causal relationship between GDP and GHG emissions. Consequently, the broad agreement with the existing research further shows the robustness of our results, while also shedding more light on the actual intricacies involved.

While expanded economic and commercial activities have positive implications for the economy, they also contribute to environmental damage through increased emissions and higher levels of greenhouse gases. Despite the abundance of studies linking clean energy with lower emissions of Carbon dioxide, it is unlikely that there is a causal relationship. The substantial cost of research and development needed for technological improvements directly contributes to Greenhouse gas emissions. The study reveals that inefficient and unsustainable energy consumption, particularly in the finance and trade sectors, hinders economic growth and leaves the economy vulnerable to unforeseen external shocks. Inefficient electricity consumption during production leads to increased gas and solid emissions throughout the product life cycle. As more efficient technological advancements replace inefficient energy inputs, firms are likely to generate more energy and carbon emissions, but the utilization of renewable energy sources is also likely to improve. The implementation of powertrains can help minimize carbon emissions. The combination of technological advancements, economic growth and innovation responsiveness has a positive and statistically significant impact.

This research demonstrates that innovation and economic expansion go hand in hand, resulting in increased GHG emissions while also highlighting the negative technological impact on financial growth. In other words, the environment is inevitably compromised by technological advancements that accompany financial success. The study convincingly builds a case for the adverse technical effects of financial expansion, asserting that financial development fuels technological advancements, thereby increasing the demand for renewable resources such as energy.

In contrast, the counterarguments that have been offered suggest that the reasons that are now being debated constitute a challenge to the adverse outcomes of financial development. The fact that advancements in the financial business have a little impact on the environment, according to their argument, is due to the fact that technological concerns are responsible for this phenomenon. Specifically, this is because such enhancements make it possible for businesses to enhance their access to significant quantities of cash, which they subsequently use for capital investment initiatives. The creation of technological advances, the purchase of extra equipment, the recruitment of more personnel and the formation and installation of new industrial facilities are all components of these endeavors. There is also the possibility that this course of action would result in a rise in emissions, which will eventually result in a reduction in the overall quality of the environment. Taking into account the average, maximum and utmost levels of technology and substituting them in equation (5), it is possible to establish the marginal influence that economic growth has on the quality of the environment, as measured by emissions of greenhouse gases (GHG). From the findings of our research in Table 8, the marginal effects of capital accumulation that can be found. When the level of technology at the median is taken into account, it is possible to draw the conclusion that the cumulative impact of financial development is 0.119. This impact, on the other hand, rises to 1.939 when the degree of technological competence is at its lowest, and it reaches 1.01 when the level of technical sophistication is at its peak. It is also possible to form the conclusion that the growth of the economy has a little too non-existent impact on the quality of the environment.

5. Conclusions and policy recommendations

5.1. Conclusion

To conclude, the study reflects on the relationships between economic progress and ecological outcomes. There are several considerations, including financial growth, urbanization, energy consumption, and foreign direct investment. The study examines 131 nations' financial growth, urbanization, energy consumption, and FDI from 2009 to 2019. It reflects on the relationships between economic success and ecological effects.

Summarizing the research, the CS-ARDL model demonstrates that economic growth does not influence environmental quality. As a result, the ecological footprint is likely to remain almost unchanged over a time period. Based on this study, it can also be concluded that growing the financial sector may lead to enhancing environmental quality, as the former has less impact on the extent of the surrounding. Notably, the study manages to prove that there is a two-way cause and effect relationship between economic growth indicators and how they affect the environment. This discovery complicates the link between economic growth and ecological consequences, casting doubt on oversimplified ideas. Extensive validation procedures and supplementary evidence, including sensitivity and CO_2 emissions analyses, corroborate the results' resilience.

Finally, the study successfully integrates all examined components into a theoretical framework, which is considered a significant step forward, given the complexity of the relationships between economic growth and ecological results. The results provide essential information for academics and policymakers to help in figuring out how to promote economic development while protecting the environment.

5.2. Practical and theoretical implications

Policymakers and practitioners aiming to strike a balance between economic development and environmental sustainability will find the results to be highly relevant. To reach carbon neutrality goals, emerging nations should prioritize increasing GDP, establishing environmental levies, promoting environmentally friendly technology and funding renewable energy research and development. Economic growth, technological innovation and regulatory frameworks all interact to shape environmental consequences, and this study highlights how important it is to address this interaction. In order to promote economic growth while simultaneously reducing environmental deterioration, policymakers must have a firm grasp of these processes (Navani et al., 2021). The study also suggests that expanding the economy could have positive effects on the environment if financial institutions support clean-tech enterprises and invest in ecologically friendly technology. The findings align with concepts such as "ecological modernization" and "environmental transition," emphasizing the role of the financial sector in environmental conservation.

5.3. Limitations and future research avenues

In addition to its merits, the study's shortcomings should also be taken into account. The data quality and coverage may be constrained because the research is based on secondary data retrieved from the International Finance Corporation database. This study uses sophisticated econometric tools, including Granger causality analysis and the Seemingly Unrelated Regression (SUR) test, however, there is still a possibility that it could be missing some contextual details which can explain the causal relationship revealed during the course of the research. Also, the limitations of the CS-ARDL estimation in capturing short-term dynamics can be catered for in further research. Thus, in future studies, more detailed data can be used, bring in a greater variety of potential determinants, and apply other methodologies.

Furthermore, due to its heavy reliance on quantitative analysis, the study may have overlooked some qualitative elements of the correlation between economic development and environmental deterioration. Future research should use multiple data sources, approaches and viewpoints to overcome these constraints and offer a more thorough knowledge of the intricate relationship between economic development and environmental sustainability. Nevertheless, by bringing attention to both the affirmations and the challenges to the current literature, the study provides important insights into the connection between economic development and environmental degradation. Academics and policymakers should consider the study's shortcomings and practical consequences in order to promote sustainable development more informally and effectively.

Drawing from the insights of this study, future research can further advance our understanding of the relationship between economic progress and ecological sustainability. Longitudinal studies tracking environmental indicators over time could reveal evolving trends and the impacts of policy interventions. Comparative analyses across countries with varying economic development levels and environmental regulations could provide valuable insights into the mechanisms driving environmental outcomes. Furthermore, interdisciplinary approaches integrating environmental economics, sociology, and political science could enrich analyses by considering broader societal influences on environmental behavior and policy responses. Lastly, the exploration of innovative methodologies such as machine learning and spatial analysis could uncover hidden patterns within large-scale environmental datasets, facilitating more accurate predictions and informed policy recommendations. By addressing these avenues, future studies can deepen our comprehension of the complex interplay between economic progress and ecological sustainability, guiding the development of more effective environmental conservation strategies.

Ethics approval and consent to participate

Not applicable

Consent for publication

All of the authors consented to publish this manuscript.

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Data availability

We collected relevant data from World Bank open data available at https://data.worldbank.org/. For any further query on data, corresponding author at email address xgh9007286@163.commay be approached.

CRediT authorship contribution statement

Shanfei Zhang: Formal analysis, Data curation, Conceptualization. **Guanghua Xu:** Writing – original draft, Methodology, Investigation. **Ying Shu:** Writing – review & editing, Validation, Conceptualization. **Jian Zhu:** Software, Project administration, Methodology, Investigation. **Wu cheng:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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