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Integrating Economic Development, Innovation, and Environmental Performance for Sustainable Futures: Insights from a Global Study

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Abstract

This study aims to investigate the complex interplay between GDP per capita, innovation index, and environmental performance across a comprehensive dataset comprising 102 countries spanning from 2008 to 2022. Utilizing descriptive statistics, cointegration tests, and Granger causality analysis, the research delves into the intricate relationships among these pivotal variables. The findings unveil significant long-term equilibrium relationships among environmental performance, innovation, and economic development. Furthermore, bidirectional causal links are discerned, indicating that enhancements in environmental performance stimulate innovation, and conversely, innovation influences environmental performance. Likewise, economic development exerts influence on both innovation and environmental performance. These insightful revelations underscore the multifaceted dynamics among economic growth, innovation, and sustainability, thereby underscoring the imperative for integrated approaches to foster sustainable development. The comprehension and harnessing of these interrelationships are paramount for crafting efficacious policies and strategic business initiatives geared towards steering humanity toward a more sustainable and prosperous future.

Keywords: panel data, causal relationship, sustainability, competitiveness, economic growth, environmental performance, innovation, economic development

1. Introduction

The continuous process of economic development, along with transformations in lifestyles, modes of production, and consumption patterns, has generated substantial environmental impacts (Bengtsson et al., 2018). In this context, the search for innovative solutions that can effectively improve environmental quality takes on a sense of urgency.

Innovation emerges as a fundamental piece in this equation, with the potential to shape the trajectory towards a truly sustainable society. By optimizing production processes, reducing resource consumption, and introducing products and services aligned with environmental demands, innovation has the capacity to mitigate environmental impact (Stachowiak et al., 2020).

However, the interrelationships between economic development, innovation, and environmental performance are intricate. These relationships exhibit a multidimensional nature, in which environmental performance can both influence innovation practices and be influenced by them, creating an interdependent cycle that is inexorably linked to economic development.

The complexity of this interconnection is underscored by the UN guidelines (2023), which highlight the joint promotion of these factors to achieve sustainable balance. Causal analysis emerges as a tool to unravel this complexity, revealing how each nation's innovative capacity can shape its environmental performance and vice versa. These insights provide input for the formulation of business strategies and public policies, promoting not only innovation but also sustainable economic growth.

With this scenario in mind, the present study seeks an in-depth understanding of the causal relationships between environmental performance, innovation, and economic development in diverse contexts. The objective is to elucidate how these relationships can be orchestrated synergistically to drive sustainable development across a

broader spectrum of nations, aligning with the vision outlined by the UN (2023). Through meticulous analysis, it is hoped to contribute to the design of coherent strategies that can guide innovation and economic growth towards a more balanced and sustainable future.

2. Theoretical Framework

2.1 Sustainable Development and Environmental Performance

Sustainable development (SD) has become a widely disseminated slogan in contemporary development discourse (Mensah, 2019). However, despite its dissemination and the enormous popularity it has gained over the years, the concept still seems to lack clarity. Nevertheless, the issue of sustainable development revolves around the pursuit of equity, both among and within generations, essentially anchored in three distinct yet interconnected pillars: environment, economy, and society.

Sustainable development – or, as it is often called, the challenge of the 21st century – has been the subject of much study and discussion worldwide (Sachs et al., 2019; Rasoolimanesh et al., 2020; Khosla et al., 2021; Biermann et al., 2022; Leal Filho, Salvia, & Eustachio, 2022; Gyimah, Appiah, & Appiagyei, 2023; Khan, Ahmad, & Majava, 2023; Sahoo & Goswami, 2024; Romera & Le Bigot, 2024; Dietschy, 2024).

According to contributions from Sterling (2013), Folke et al. (2016), and UNDP (2020), sustainable development seeks efficient management of natural resources through the use of clean technologies to promote poverty reduction and social inequality. Furthermore, this concept encompasses the promotion of environmental justice and respect for human rights, establishing itself as a continuous process of transformation towards a more equitable, prosperous, and healthy future for both people and the ecosystems of our planet.

As pointed out by Wiek, Withycombe, and Redman (2011), sustainable development has undergone significant evolution, transforming from a relatively simple concept into a more comprehensive and complex one. This concept involves substantial changes in how humans produce, consume, and relate to the environment. It is in this context that the model of the sustainable development tripod arises, also known as the Triple Bottom Line (3BL): profits (profit), people (people), and planet (planet). This model unifies, in a single concept, the principles of economic prosperity, environmental quality, and social justice (Vizeu et al., 2012; Juma et al., 2022; Di Pasquale et al., 2023; Yuen et al., 2023).

However, it is important to highlight that the implementation of sustainable development requires collective commitment, guided by clear goals and appropriate indicators. Practices and behaviors need to be transformed in pursuit of a more sustainable future (UNDP, 2020). Thus, sustainable development goes beyond a theoretical concept, demanding concrete action and engagement from various societal actors to promote real and lasting change.

Recognizing this need and the lack of quantitative measures for sustainable development, a team of researchers and policy experts from the Yale Center for Environmental Law and Policy (Yale University) and the Columbia University's Center for International Earth Science Information Network (CIESIN), in collaboration with the World Economic Forum, developed in 2006 a pilot indicator called the Environmental Performance Index (EPI). Currently, this indicator is used by several countries to promote and measure sustainable development (Srebotnjak, 2014).

This initiative aims to fill an existing gap by providing a tool, the Environmental Performance Index (EPI), used by several countries to assess environmental performance and guide more sustainable policies. Additionally, the EPI has been widely used by researchers as a benchmark indicator for each country's environmental performance (Srebotnjak, 2014; Gorham, Lehman, & Kelly, 2019; Shittu et al., 2021; Adeel-Farooq, Raji, & Qamri, 2022; Pujiati & Feronica, 2023; Ushakov & Shatila, 2023).

2.2 Economic Development and Environmental Performance

Economic development plays a crucial role in human and social progress. However, it is essential to recognize that this development can also lead to significant and complex negative impacts on the environment (Naqvi et al., 2023; Kirikkaleli, 2020; Yang, Shao, & Fan, 2021). With the increasing demand for natural resources and the unrestrained exploitation of these resources, environmental impacts are becoming increasingly evident.

According to Söderbaum (2017) and other researchers such as Rockström et al. (2017) and Balsalobre-Lorente et al. (2019), economic activities have negative impacts on the environment, ranging from air and water pollution to climate change and biodiversity loss. Environmental degradation can have negative consequences for economic development, such as decreased air and water quality, affecting public health and leading to increases in public health costs. These negative impacts not only affect quality of life but can also have long-term economic

consequences, such as inflation or reduced per capita GDP.

However, environmental performance should not be seen as a barrier to economic development but as an opportunity to promote innovation and increase business competitiveness. Investments in clean and sustainable technologies, known as green innovation, can have a positive impact on the environment, as argued by Sachs (2015) and Kirikkaleli (2020). Furthermore, promoting environmental performance can have positive impacts on the financial performance of companies, reducing operational costs and creating business opportunities through the pursuit of more sustainable solutions.

Thus, the protection and preservation of the environment can be seen as a strategic investment to ensure the sustainability of economic growth. A more integrated approach between the economy and the environment is essential to address current and future challenges (Dasgupta et al., 2021).

2.3 Innovation and Economic Development

The Oslo Manual defines innovation as “the implementation of a new or significantly improved product (good or service)/process/method” (OECD, 2019). WIPO (2022) complements this, stating that innovation plays a significant role in creating new jobs, generating income, and reducing poverty.

Innovation is not limited to research and development (R&D) or the introduction of new technologies. It encompasses incremental improvements in existing products or processes, as well as radical and disruptive changes that bring about significant transformations (OECD, 2019). OECD (2019) emphasize that without innovation, capital accumulation would be less dynamic and expanded, as innovation is the engine of economic development and has been considered a long-term driving force for economic growth and capitalism (Schumpeter, 1939).

Studies by Cook and Smith (2012), Castellacci and Natera (2013) and Kirikkaleli (2020) emphasize that innovation is fundamental for economic and social development, being the main mechanism through which capitalism evolves. Some authors specifically argue that innovation is a key element for the competitiveness of companies and countries, being essential to drive long-term economic growth (Fagerberg, Mowery, & Nelson, 2015; Lima-Rua, Musiello-Neto, & Arias-Oliva, 2023).

According to OECD (2019), innovation generates positive impacts on the economy by creating job opportunities, increasing productivity and competitiveness, and contributing to solving social and environmental problems. Furthermore, innovation can also contribute to sustainable development by enabling the creation of more efficient and less harmful products and processes for the environment (Kirikkaleli, 2020).

However, as highlighted by Han et al. (2022), the relationship between innovation and economic development is not linear and can be influenced by various factors. This includes countries' ability to invest in R&D, availability of financing for innovation, quality of education and training of human resources, as well as the existence of public policies that incentivize innovation, among others. In this regard, Rogers, Singhal, and Quinlan (2019) corroborate, stating that innovation can be an important tool to drive economic development, but a conducive environment is necessary to allow its emergence and diffusion.

2.4 Economic Development, Innovation, and Environmental Performance

Economic development, environmental performance, and innovation are interconnected and essential elements for promoting a prosperous and balanced society in the long term (United Nations, 2020). In this sense, the introduction of new technologies and products allows companies to increase efficiency, reduce costs, and increase profits. Moreover, innovation opens up new markets and enhances competitiveness, driving economic growth.

Innovation also plays a significant role in the pursuit of sustainable development, generating solutions for economic, social, and environmental challenges (Kirikkaleli, 2020). However, the relationship between economic development, innovation, and environmental performance is complex and multifaceted (United Nations, 2020). Innovations can have positive or negative effects on environmental performance, depending on their nature, scope, socio-economic context, and public policies (Boons et al., 2013). Economic development can lead to environmental and social problems, but it can also drive investments in research and development to improve environmental performance (Kirikkaleli, 2020).

Innovation is a key factor for sustainability and the improvement of countries' environmental performance. However, it is important to note that economic development often neglects social and environmental dimensions, resulting in inequality and irreversible environmental damage.

The relationship between economic development, environmental performance, and innovation capacity is

bidirectional and nonlinear (Dangelico & Pujari, 2010). Table 1 presents the main theoretical and empirical evidence of causal relationships between innovation, economic development, and environmental performance of countries, highlighting the complexity of these interactions. It is necessary to seek a balance between the three elements to promote sustainable development and a balanced society.

Table 1. Main studies on the causal relationship between economic development, innovation, and sustainable development

Authors and Year	Variables Examined	Observed Results
Balsalobre-Lorente*et al.* (2019)	GDP, renewable energy, natural resources, CO_2 emissions	Increase in GDP and consumption of natural resources contribute to the increase in CO_2 emissions.
Cheng *et al.* (2021)	Technological innovation, environmental pollution	Technological innovation has the potential to aid in reducing environmental pollution.
Gao *et al.* (2023)	Green innovation, GDP, and environmental performance	Green innovation has a positive effect on environmental performance, but the effect is limited by lack of government support and pressure to maximize profits.
Guan *et al.* (2018)	Chinese GDP growth, energy intensity, economic structure, and population	Economic growth in China has driven an increase in CO_2 emissions, but changes in the economy, technology, and emissions reduction policies have mitigated negative impacts.
Guerrero-Lemus*et al.* (2019)	Green innovation and economic growth	Green innovation helps in the economic growth of countries.
Fishman *et al.* (2021)	Innovation technologies	Innovation is bidirectional, it is important to consider both the positive and negative impacts of innovation when assessing its relationship with the environment.
Jin, Guo, & Deng (2020)	Technological innovation, energy conservation, carbon reduction, and environmental pollution	Technological innovation in energy conservation and carbon reduction can help reduce environmental pollution.
Liao *et al.* (2022)	Innovation, GDP, and CO_2 emissions	Innovation has a positive (reducing) effect on CO_2 emissions in the short term, but a negative (increasing) effect in the long term. In addition, innovation drives economic growth, which stimulates more innovation.
Nasir, Huyin, & Tram (2019)	Innovation, GDP, and environmental quality	Innovation has a positive effect on environmental quality, but this is limited by lack of financial and technological resources in developing countries.
Lin & Zhun (2018)	Innovation, GDP, greenhouse gas emissions	Innovation has a reducing effect on CO_2 emissions.
Sarkar *et al.* (2019)	Innovation, GDP, and carbon emissions	Innovation has a negative effect on carbon emissions, but this effect is mitigated by GDP growth and lack of effective environmental policies.
Wu, Wang, & Zhang (2020)	Technological innovation, environmental performance	Technological innovation can improve the environmental performance of countries.

Source: Own elaboration (2024).

According to Table 1, several studies have analyzed the complex relationship between innovation, economic development, and environmental performance, revealing significant findings. For instance, Wu, Wang, and Zhang (2020) demonstrated that technological innovation can enhance countries' environmental performance. Conversely, Guan et al. (2018) observed that economic growth in China has driven CO2 emissions, but policies and changes in the economy and technology have helped mitigate these negative impacts. Lin and Zhun (2018) found that innovation reduces CO2 emissions. Additionally, Liao et al. (2022) identified that innovation may have a negative long-term effect, increasing CO_2 emissions, although it boosts economic growth. Nasir and Huyine Tram (2019) highlighted that innovation has a positive effect on environmental quality but is constrained by the lack of financial and technological resources in developing countries.

These findings suggest that the relationship between innovation, economic development, and environmental performance exhibits bidirectional causal flows. This implies that environmental performance can affect innovation practices, while innovation driven by economic development can influence environmental

performance. Furthermore, it is evident that environmental performance is intrinsically linked to economic development.

Given this scenario, it is crucial to understand these relationships to underpin the formulation of policies and practices that stimulate innovation and economic development simultaneously. It is essential to adopt an integrated approach that takes into account the environmental impacts of economic activities, aiming to achieve positive long-term outcomes. Understanding these interactions provides support for promoting an adequate balance between economic growth, innovation, and environmental sustainability (Smith & Mayer, 2018).

3. Methodology

3.1 Data

This research aims to identify the cause-and-effect relationships between environmental performance, innovation, and economic development in a sample of 102 countries during the period from 2008 to 2022. Environmental performance was measured using the Environmental Performance Index (EPI), which was developed in 2002 and evaluates 40 performance indicators distributed across 11 categories related to environmental management. These categories include climate change, environmental health, and ecosystem vitality (EPI, 2022). The EPI provides a comprehensive summary of sustainability status in 180 countries, ranking them according to their performance. EPI data are available every two years.

The level of innovation in each country was measured using the Global Innovation Index (GII), which is one of the primary indicators for assessing the innovation environment in each country. The GII employs various criteria such as investments in R&D, collaboration between companies and universities, and intellectual property (WIPO, 2022). Innovation data were obtained from WIPO (2022). Economic development, on the other hand, was measured using Gross Domestic Product (GDP) per capita, with data obtained from the World Data Bank (2023). To ensure data stationarity, the percentage variation of GDP per capita was calculated every two years.

3.2 Sampling Period and Sample Selection

After establishing the data sources, the analysis period was defined. The choice of this period took into account the availability of information related to the study, as the main reports used began their publications in 2002 and 2007. Additionally, it is noteworthy that one of the reports is biennial, which justified the selection of the range from 2008 to 2022 for analysis.

The sample of observed countries was selected from the integration of data from the main reports, resulting in a sample of 102 countries with common information for the construction of the statistical analysis. The selection of countries considered criteria such as geographical representativeness and availability of necessary data for analysis.

3.3 Unit Root Test - Augmented Dickey-Fuller (ADF)

One of the most relevant statistical tests for this research is the panel unit root test proposed by Im, Pesaran, and Shin (2003). This test is used to determine whether a panel time series is stationary or non-stationary, being crucial to enable proper statistical analysis.

The stationarity of a time series is important because it affects the behavior of variables over time. A non-stationary time series may exhibit significant trend or seasonality, which compromises statistical analyses and the correct interpretation of results (Brockwell & Davis, 2002).

In the present study, the Augmented Dickey-Fuller (ADF) test was used, which is widely applied to test the null hypothesis that a time series is non-stationary. The ADF test in panels involves combining data from multiple countries into a single time series. The test statistic is calculated using the formula below:

$$Y_{i,t} = \rho_i Y_{i,t-1} + X_{i,t}\delta_i + \epsilon_{i,t} \quad (1)$$

In which, X it represents the exogenous variables in the model, including any fixed effects or individual trends, ρ_i are the autoregressive coefficients, and the errors ϵ are assumed to be mutually independent peculiar disturbances. If $\rho_i<1$, Y_i is considered weakly stationary (trend). On the other hand, if $\rho_i=1$, then Yi contains a unit root.

The panel ADF test was applied to evaluate whether the time series of environmental performance, innovation, and economic development are stationary or non-stationary. If the null hypothesis of non-stationarity is not rejected, it will be necessary to perform transformations on the data to make them stationary. A common approach is differencing, which involves calculating the differences between consecutive observations of the time series.

Differencing involves subtracting the value of one data point from the value of the previous data point. For example, the first difference of a time series $Y(t)$ can be calculated as: $Y'_{(t)}=Y_{(t)}-Y_{(t-1)}$. This difference results in a

new time series Y', which contains the variations between consecutive observations. The transformation of data through differencing aimed to remove trends and non-stationary patterns, enabling the application of the Pedroni Cointegration and Granger Causality tests.

3.4 Pedroni Cointegration

Engle and Granger (1987) state that a stationary linear combination is called a cointegration equation and can be interpreted as a long-term equilibrium relationship between variables (Eviews, 2022). Cointegration tests, such as unit root tests, are used to verify whether the residuals generated by the regression of the series are stationary or not. They are used as a preliminary test to check the relationship between economic variables (Gujarati & Porter, 2011).

According to Cohen (2013) and Enders (2014), the most suitable cointegration test for panel data analysis is the Pedroni test because it allows the inclusion of different types of trends and regressions in its analysis. In this work, the Pedroni cointegration test is used, which tests three deterministic models: without trend and without intercept (None), with intercept (Const.), and with intercept and trend (Trend), as presented in Table 2 and equations 2, 3, and 4.

Table 2. Deterministic models

Models	Formula	
None	$Y_{i,t} = \delta Y_{i,t-1} + u_{i,t}$	(2)
Const.	$Y_{i,t} = \beta_1 + \delta Y_{i,t-1} + u_{i,t}$	(3)
Trend.	$Y_{i,t} = \beta_1 + \beta_2 T_{i,t} + \delta Y_{i,t-1} + u_{i,t}$	(4)

Source: Eviews (2022).

These formulas represent the deterministic models tested in the Pedroni cointegration test, where $Y_{i,t}$ is the dependent variable $T_{i,t}$ represents time u_t is the error term.

According to Pedroni (1999), in the first step, a test is applied to verify if each time series is stationary. If a series is not stationary, a first-order differencing is performed on the series to make it stationary. In the second step, the existence of cointegration among the resulting stationary series from the first step is tested. These two steps are repeated for each deterministic model. Equation 5 is used for this analysis.

$$Y_{i,t} = \sigma_i + \delta_i t + \beta_{1i} x_{1i,t} + \beta_{2i} x_{2i,t+} \dots \beta_{Mi} x_{Mi,t+} e_{i,t} \tag{5}$$

In this equation, σ and β are individual and trend parameters, and "t" represents the lag that compares the residuals of the regression of each series on the other series. The statistical significance of the t-statistic is used to determine whether there is cointegration between the series (Enders, 2014). Thus, after verifying the reliability of the regression, it is possible to perform the Granger causality test.

3.5 Granger Causality Test

Granger (1969) defines causality as the ability of the present to be explained by past values. In practice, Granger causality is tested by analyzing the precedence and information content contained in time series. If time series X contains information that helps predict time series Y, beyond the information contained in time series Y itself, then it is said that time series X "causes" time series Y. In other words, time series X provides additional information that improves the forecast of time series Y.

Gujarati and Porter (2011) further explain that the dependence of one variable on another does not necessarily imply the existence of influence between them. That is, causality is not necessarily linked solely to the fact that they have any type of relationship. To facilitate understanding of how the Granger causality test works, EViews (2022) was used, which implies that the information relevant for forecasting variables x and y is exclusively contained in their time series. This is conducted through the estimation of the regression pair as follows.

$$y_t = \sigma_0 + \sigma_1 y_{t-1} + \cdots \sigma_l y_{t-1} + \beta_1 x_{t-1} + \cdots + \beta_l x_{-l} + \in_t \tag{6}$$

$$x_t = \sigma_0 + \sigma_1 x_{t-1} + \cdots \sigma_l x_{t-1} + \beta_1 y_{t-1} + \cdots + \beta_l y_{-l} + u_t \tag{7}$$

The F statistics are the Wald statistics for the joint hypothesis. Thus, if $\beta_1 = \beta_2 = \cdots = \beta_l = 0$, the null hypothesis is that x does not Granger-cause y in the first regression and that y does not Granger-cause x in the second regression. Furthermore, according to Cavalcanti (2010), four distinct cases can be observed as a result of this test: (i) unidirectional causality from y to x; (ii) unidirectional causality from x to y; (iii) bidirectional causality; (iv) absence of causality in any direction. Thus, Cavalcanti (2010) and Gujarati and Porter (2011) converge on the idea that changes in x precede changes in y over time if variable x Granger-causes variable y.

4. Results and Discussions

This study aimed to analyze the cause-and-effect relationship between GDP per capita, innovation index, and environmental performance of 102 countries from 2008 to 2022. Figure 2 represents the countries analyzed.

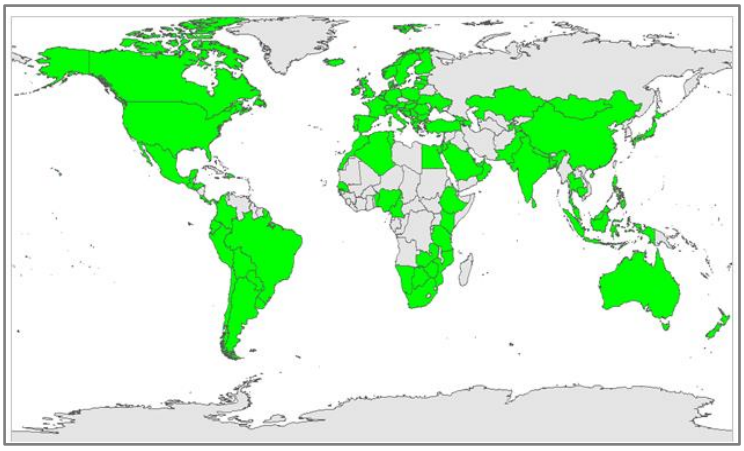

Figure 1. Countries analyzed

Source: Author's own elaboration (2024).

It is important to note that the selection of the 102 countries for this research was carried out after integrating the available data from the mentioned reports. The choice was made with the aim of including countries that provided common information for the construction of the statistical analysis.

Some geographical and economic patterns can be identified among the analyzed countries, with 39 countries located in Europe, 18 countries in South and Central America, 2 countries in North America, 24 in Asia, 2 in Oceania, and 17 countries in Africa. It is observed that the sample includes countries from different continents, providing a global perspective in the analysis. Additionally, the populations residing in these countries represent approximately 4.8 billion people (approximately 61% of the world's population).

Furthermore, it is relevant to present a descriptive statistical analysis of the collected data for each variable. Table 3 presents the descriptive statistics of the variables used in this study.

Table 3. Descriptive statistics

Variable	Mena	Standard Deviation	Minimum	Maximum	N
Environmental Performance Index	57.24	14.54	18.90	90.68	102
GDP per Capita (US$)	19,707.74	23,438.71	320.86	103,590.15	102
Global Innovation Index	39.99	12.57	14.60	75.40	102

Fonte: Author's own elaboration (2024).

Analyzing Table 3, several important pieces of information can be observed. Regarding the Environmental Performance Index (EPI): the mean of 57.24 indicates a moderate value for environmental performance in the analyzed countries. However, the variation is notable, with the highest-performing country reaching 90.68 and the lowest-performing country registering 18.90. This wide variation highlights the diversity of environmental management and sustainability practices among countries.

Looking at GDP per capita, the mean of $19,707.74 reflects the average Gross Domestic Product per capita in the analyzed countries. However, there is a significant dispersion in the values, with the minimum being $320.86 and the maximum reaching $103,590.15. This substantial difference between the lowest and highest values emphasizes the economic inequalities existing among the selected countries.

Finally, considering the Global Innovation Index, the mean of 39.99 indicates a moderate level of innovation in the analyzed countries. Similar to environmental performance, there is significant variation, with the highest-index country reaching 75.40 and the lowest-index country registering 14.60. This discrepancy highlights differences in the innovation environment and research and development activities among countries.

It is interesting to note that the countries with the best positions in both the Environmental Performance Index and the Global Innovation Index are predominantly Nordic European countries, considered developed and known for their sustainable practices and innovation capacity. On the other hand, countries with the worst results are mainly located in Africa and South Asia, where there are significant challenges in terms of economic development and environmental sustainability.

The difference between the minimum and maximum values in each variable highlights the heterogeneity of the analyzed countries. This considerable variation reinforces the importance of understanding and investigating the relationships between the variables addressed in the research, such as environmental performance, innovation, and economic development.

These preliminary observations from the descriptive analysis emphasize the diversity and disparities existing among countries in terms of environmental performance, innovation, and economic development. This understanding reinforces the need to investigate the cause-and-effect relationships between these variables in search of insights and guidance to promote global sustainability and development. However, before proceeding with the Granger causality test, it is necessary to analyze the stationarity of the data.

According to Teräsvirta, Tjostheim, and Granger (2011), stationarity is a crucial aspect that must be taken into account when testing Granger causality. They argue that ignoring it can lead to misleading results and wrong conclusions about the existence of causality between time series. To verify the stationarity of the data, this study conducted the unit root test, as shown in the following table.

Table 4. Unit Root Test for Variables: Environmental Performance, Innovation Index, and Percentage Change (Δ%) of GDP per Capita from 2008 to 2022 (biennial basis)

Variable	Lag	Trend	Const	None
Environmental Performance Index	0	79.669	105.105	232.594 **
	1	202.847 *	232.847 *	558.402 ***
Global Innovation Index	0	944.184 ***	182.669	163.442 ***
	1	1,077.090 ***	1,602.250 ***	1,475.760 ***
Δ% of GDP per Capita	0	787.320 ***	1,175.110 ***	1,413.230 **
	1	648.009 ***	1,002.310 ***	1,759.270 ***

Legend: * significance at 10%; ** significance at 5%; *** significance at 1%; Δ%: percentage change. None: deterministic model without trend and without intercept; Const: deterministic model with intercept; Trend: deterministic model with intercept and trend.

Source: Author's own elaboration (2024).

According to Table 4, it is evident that for all three deterministic models tested, namely: without trend and without intercept (None), with intercept (Const.), and with intercept and trend (Trend), the null hypothesis of unit root was rejected for both the first difference (lag 1) of the environmental performance variable and the first difference of the Innovation Index. On the other hand, the null hypothesis of unit root for the level variable (lag 0) of the percentage change in GDP per capita was rejected. In other words, there is sufficient evidence to conclude that the series is stationary, possessing stable and consistent statistical properties over time (Enders, 2014; Brockwell & Davis, 2002).

Subsequently, the cointegration test was conducted using panel data. In this regard, Stock and Watson (1993) emphasize that this test allows researchers to assess the presence of long-term relationships between variables, which is essential for modeling the dynamics of complex economic systems.

Table 5 displays the results of the Pedroni Cointegration test applied to the variables: the first difference of environmental performance, the first difference of the Innovation Index, and the percentage change in GDP per capita for the period from 2008 to 2022 (on a biennial basis).

The results of the Pedroni cointegration test applied to the variables of the first difference of environmental performance, initial difference of the Innovation Index, and percentage change in GDP per capita on a biennial basis during the period from 2010 to 2022 are observed in Table 5. The table presents the test statistics for different deterministic models (Trend, Const, and None) and different restrictions ($r \leq 2$, $r \leq 1$, $r \leq 0$) related to the number of cointegration relationships. The values shown represent the test statistics for each combination of model and restriction. Furthermore, the analysis of the results indicates that the test statistics values for cointegration were significant for all model and restriction combinations.

Table 5. Pedroni Cointegration Test applied to the variables: First Difference (Δ) of Environmental Performance, First Difference (Δ) of Innovation Index, and Percentage Change (Δ%) of GDP per Capita on a biennial basis, for the period from 2010 to 2022 (biennial basis)

	Δ Environmental Performance cointegrated with Δ Innovation Index			Δ Environmental Performance cointegrated with Δ% GDP per Capita on biennial basis			Δ Innovation Index cointegrated with Δ% GDP per Capita on biennial basis		
H0	Trend	Const	None	Trend	Const	None	Trend	Const	None
r≤2	NA	-5.345 ***	-17.076 ***	NA ***	-27.355 ***	-16.078 ***	NA	-1,463.800 ***	-11.875 ***
r≤1	-12.739 ***	-4.176 ***	-6.390 ***	-18.652 ***	-10.848 ***	-12.016 ***	17.170 ***	-17.858 ***	21.125 ***
r≤0	-14.306 ***	-7.779 ***	-13.481 ***	-9.453 ***	-7.339 ***	-11.838 ***	32.976 ***	-31.228 ***	21.241 ***

* significance at 10%; ** significance at 5%; *** significance at 1%; Δ indicates the first difference; Δ%: Percentage Change; None: deterministic model without trend and without intercept; Const: deterministic model with intercept; Trend: deterministic model with intercept and trend; NA: not available.

Source: Author's own elaboration (2024).

Based on the significant results, it can be concluded that the null hypothesis of no cointegration between the variables was rejected. This means that the time series were cointegrated, suggesting the presence of a long-term equilibrium relationship among the analyzed variables. This finding is aligned with previous studies by Sarkar et al. (2019), Guerrero-Lemus et al. (2019), Gao et al. (2023), and others, which also identified causal relationships between variables related to the environment, innovation, and economic development.

However, it is important to note that these results indicate the presence of cointegration but do not establish the direction or specific type of causal relationship between the variables. Therefore, to support the relationships mentioned in this study, it is recommended to conduct the Granger causality test, as mentioned in the analysis.

In summary, the results of the cointegration test indicate the presence of a long-term equilibrium relationship among the analyzed variables. This finding strengthens the hypothesis that there is a possible causal relationship between environmental performance, innovation, and economic development. To further understand these relationships, it is necessary to conduct the Granger causality test to identify the causal directions between the variables.

Table 6. Granger Causality Test applied to the variables: First Difference (Δ) of Environmental Performance, First Difference (Δ) of Innovation Index, and Percentage Variation (Δ%) of GDP per capita on a biannual basis, for the period from 2010 to 2022 (biannual basis)

Lag	Δ of Environmental Performance ~ Δ of Innovation Index	Δ of Innovation Index ~ Δ of Environmental Performance	Δ% of GDP per capita on a biannual basis ~ Δ of Environmental Performance	Δ of Environmental Performance ~ Δ% of GDP per capita on a biannual basis	Δ% of GDP per capita on a biannual basis ~ Δ of Innovation Index	Δ of Innovation Index ~ Δ% of GDP per capita on a biannual basis
1	15.791 ***	0.360	9.732 ***	7.751 ***	4.313 **	0.010
2	26.132 ***	108.760 ***	11.832 ***	13.874 ***	3.405 **	41.317 ***
3	12.832 ***	95.529 ***	15.470 ***	10.981 ***	2.317 *	21.911 ***
4	10.737 ***	3.411 ***	4.756 ***	6.389 ***	4.148 ***	9.810 ***
5	3.393 ***	2.833 **	5.094 ***	5.572 ***	2.127 *	4.008 ***
6	1.569	3.952 ***	2.059 *	1.180	2.165 *	1.571

Legend: * 10% significance level; ** 5% significance level; *** 1% significance level; Δ indicates the first difference; Δ% indicates the percentage variation; ~ indicates the Granger non-causality hypothesis.

Source: Own elaboration (2024).

According to Table 6, it is observed that the null hypothesis of non-causality between the variables was rejected, meaning that the first difference of environmental performance causes Granger causality in the first difference of lag1 to lag5 of the Innovation Index (15.791 sig. 0.01; 26.132 sig. 0.01; 12.832 sig. 0.01; 10.737 sig. 0.01; 3.393 sig. 0.01). It was also observed that the null hypothesis that the First Difference of the Innovation Index does not

cause Granger causality in the first difference of environmental performance was rejected, in lag 2 to lag 6 (108.760 sig. 0.01; 95.529 sig. 0.01; 3.411 sig. 0.01; 2.833 sig. 0.01; 3.952 sig. 0.01). Thus, a bidirectional relationship is established, as an increase in environmental performance practices encourages innovation, and innovation, in turn, can improve environmental performance (Gao et al., 2021).

It is concluded, therefore, that a variation in the environmental performance of the analyzed countries implies a variation in the Innovation Index from t=1 to 5 subsequent biennia (t=5). In practice, it is noted that besides a short-term relationship, where environmental performance is impacted by innovation, as explained in the studies by Cheng et al. (2021) and Gao et al. (2021), there is also a long-term relationship pointed out by Balsalobre-Lorente et al. (2019), Liao et al. (2022). This is because the pace of innovation for environmental performance is slow (Silvestre, 2015), and the results of an Innovation Index variation are only demonstrated from t=2. The environmental benefits of innovation can occur at different times throughout the product or innovative process life cycle, resulting in immediate or medium to long-term environmental benefits (Machol & Rizk, 2013).

On one hand, studies such as those by Wu, Wang, and Zhang (2020), Nasir, Huyin, and Tram (2019), Cheng et al. (2021), and Gao et al. (2021) demonstrate that innovation has a positive effect on environmental performance. On the other hand, Nasir, Huyin, and Tram (2019) assert that the effect of innovation is linked to financial resources. To clarify this scenario, the relationship between GDP per capita and the first difference of environmental performance was analyzed. It was observed, in the same table, the null hypothesis that the variation of GDP per capita causes Granger causality in the first difference of environmental performance (9.732 sig. 0.01; 11.832 sig. 0.01; 15.470 sig. 0.01; 4.756 sig. 0.01; 5.094 sig. 0.01; 2.059 sig. 0.01), as well as the first difference of environmental performance causes Granger causality in the percentage variation of GDP per capita (7.751 sig. 0.01; 13.874 sig. 0.01; 10.981 sig. 0.01; 6.389 sig. 0.01; 5.572 sig. 0.01; 1.180 sig. 0.01) of the analyzed periods. Thus, a bidirectional relationship between the variables is evidenced.

According to the study by Balsalobre-Lorente et al. (2019) and Fishman et al. (2021) it is observed that the increase in GDP and the level of economic development of countries can contribute to an increase in environmental performance. Just as environmental performance contributes to economic development as complemented by Liao et al. (2022) and Guan et al. (2018). As an example, these authors cite the case of China, where only in the long term, after undergoing changes in the economic structure and adopting cleaner technologies and emission reduction policies, the country was able to help mitigate negative impacts on the environment, thereby increasing environmental performance.

This is because the relationship between economic development and environmental performance variables is complex and can be influenced by various factors, such as: economic structure, market dynamics, level of development, and innovation. Therefore, in order to clarify this relationship, it was also important to consider the null hypothesis that the variation of GDP per capita causes Granger causality in the first difference of the Innovation Index.

Similarly, a bidirectional relationship between the variables is highlighted. However, it is relevant to note that the first difference of the Innovation Index does not cause Granger causality in lag 1. This can be explained by Guan et al. (2018) and Liao et al. (2022), who point out that innovation drives economic growth, which in turn can stimulate more innovation, but this only occurs during a period of enterprise maturation or application of developed innovation.

The results of this research show that the relationship between economic development, innovation, and environmental performance is complex and interconnected. Studies indicate that innovation plays a crucial role in pursuing sustainable development, generating solutions for economic, social, and environmental challenges. The introduction of new technologies and products allows companies to increase efficiency, reduce costs, and increase profits, while opening new markets and enhancing competitiveness.

However, the relationship between these elements is multifaceted. Innovations can have both positive and negative effects on environmental performance, depending on their nature, scope, socio-economic context, and public policies (Boons et al., 2013). Economic development can lead to environmental and social problems, but it can also drive investments in research and development to improve environmental performance.

Studies such as those by Wu, Wang, and Zhang (2020), Guan et al. (2018), Nasir, Huyin, and Tram (2019), Liao et al. (2022), Cheng et al. (2021), and Gao et al. (2021) highlight the complexity of these interactions. Some show that technological innovation can improve the environmental performance of countries, while others reveal that economic growth can drive CO_2 emissions, but policies and changes in the economy and technology can mitigate these negative impacts. Furthermore, there is evidence that innovation reduces CO_2 emissions (Lin & Zhun, 2018; Nasir; Huyin & Tram, 2019; Liao et al., 2022). However, it can also have negative effects in the long term. The

lack of financial and technological resources in developing countries can limit the positive impact of innovation on environmental quality.

To promote more sustainable and integrated development, it is necessary to seek a balance between economic development, innovation, and environmental performance. This implies considering the positive and negative impacts of innovation, implementing policies that encourage sustainable innovation, and ensuring that economic growth is accompanied by environmental protection measures. Furthermore, it is essential to adopt holistic approaches that consider social and environmental dimensions, in order to avoid inequalities and irreversible damage to the environment.

5. Final Considerations

The pursuit of more sustainable development is essential in the face of environmental impacts caused by economic growth and changes in lifestyles and consumption patterns. In this context, innovation plays a fundamental role in enabling improvements in production processes, reducing resource consumption, and creating sustainable products and services.

This study analyzed the causal relationships between environmental performance, the Innovation Index, and economic development in 102 countries during the period from 2008 to 2022. The results corroborate with previous research, such as those by Wu, Wang, and Zhang (2020), Nasir, Huyin, and Tram (2019), Cheng et al. (2021), Sarkar et al. (2019), Guerrero-Lemus et al. (2019), Gao et al. (2021), Balsalobre-Lorente et al. (2019). These studies highlighted the importance of innovation for economic development and environmental performance, as well as the positive influence of economic development on innovation and environmental performance. Additionally, they demonstrated how the adoption of innovative practices and greater economic development can positively impact environmental sustainability.

The economic analysis conducted in this study demonstrated that the relationships between the variables are significant both in the short and long term. These results have important implications for business and governmental decision-making, as well as for future research on innovation and its impacts on economic and environmental performance.

It is important to note the limitations of this study, which relied on panel data and may not have considered other factors such as geography, climate, public policies, and religion, which could also influence the results.

Promoting more sustainable development requires the integration of economic development, innovation, and environmental performance. These relationships should be understood and explored in an integrated manner, seeking a balance between economic growth and environmental protection.

The findings of this study, along with previous research, provide evidence that this integrated approach is not only viable but also necessary to ensure a more sustainable future for present and future generations. This evidence may have important implications for the formulation of public policies and business practices aimed at sustainable development.

In conclusion, understanding and promoting the relationships between economic development, innovation, and environmental performance are essential to achieve more sustainable development. Effective integration of these variables should be pursued through strategies and policies aimed at balancing economic growth with environmental protection. This approach will contribute to a more sustainable future and the well-being of current and future generations.

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