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Causality Between Carbon Emissions, Temperature Changes, and Health Expenditures: A Comparative Panel Approach with Environmental and Economic Indicators

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Abstract: This study investigates the causal relationships between carbon emissions, temperature increases, and health expenditures within the framework of environmental and economic indicators. With the accelerating global impacts of climate change and rising carbon emissions, understanding their effects on public health systems has become critical. This research evaluates these interdependencies using panel causality models, dividing 115 countries into two groups—developing and developed—based on Gross National Income (GNI) per capita (PPP) and health expenditures as a percentage of GDP. Dumitrescu–Hurlin panel causality analysis was applied to examine bidirectional relationships among key indicators, including population density, temperature changes, carbon emissions, GNI, and health expenditures. The findings reveal that population density has significant causal effects on both temperature changes and carbon emissions, while carbon emissions also influence health expenditures. Moreover, the causality from population density to temperature changes is stronger in developed countries, whereas the impact of temperature changes on health expenditures is more pronounced in developing countries. These results highlight the need to strengthen climate adaptation capacities in the health systems of developing countries and implement stricter carbon emission reduction policies in developed nations as essential strategies to address these interconnected challenges.

Keywords: carbon emissions; health expenditures; climate change

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1. Introduction

Today, it is increasingly emphasized that climate change causes irreversible losses and damages to the physical and biological environment and human life, with the scale of these damages growing as the global impact intensifies [1]. While it ranks among the most critical environmental challenges of the 21st century, it has also become a factor profoundly affecting economic structures and public health systems [2,3]. Although international agreements and policies aimed at mitigating these impacts are intensifying, understanding the causal relationships between environmental and economic indicators is crucial in developing effective strategies.

Factors such as population density, energy consumption, industrial activities, and transportation contribute to environmental changes [4]. In densely populated regions, increased energy demand can lead to higher carbon emissions and, consequently, rising temperatures [5,6]. A study conducted in developing countries reported that a 1% increase in economic growth results in a rise in carbon emissions ranging from 0.23% to 2.32% [7]. However, while advanced technological infrastructure in developed countries can mitigate these effects, inadequate infrastructure and low environmental awareness in developing countries can amplify their impact [8]. Additionally, an increasing population density directly raises energy consumption and fossil fuel use, thereby increasing carbon emissions [1]. In developed countries, energy efficiency and the use of renewable energy sources help reduce this impact, whereas rapid urbanization and industrialization in developing countries may exacerbate it [6,7].

Temperature increases can affect economic factors such as agricultural productivity and energy production costs, thereby influencing Gross National Income per capita (GNI PPP) [9]. Agriculture, in particular, is the sector most sensitive to climate change. In this regard, GNI PPP is a stronger indicator than Gross Domestic Product (GDP) per capita in determining vulnerability to climate change, as it partially reflects the pace of economic development, dominant sectoral impacts, and economic capacity in the comparison of developed and developing countries [10,11]. Since the agricultural sector accounts for a larger share of economic performance in developing countries, this relationship tends to be stronger in these regions. Globally, agriculture significantly affects livelihoods, occupying approximately 40% of the Earth's land and consuming 70% of water resources [12]. In contrast, developed countries, with their lower dependency on agriculture, are likely to have higher adaptation capacities.

Higher income levels often lead to increased energy consumption and intensified industrial activities, which can contribute to higher carbon emissions. However, in developed countries, environmental regulations and the use of clean energy can limit this effect [13–15]. For instance, a study conducted in 30 provinces of China from 1995 to 2019 examined the effects of green investment, renewable energy consumption, and technological innovation on CO_2 emissions and observed a significant reduction in carbon emissions [13]. Similarly, a study involving 14 Asian countries from 1990 to 2011 revealed an inverted U-shaped relationship [16]. Studies conducted using the Chinese example on the impact of environmental policies on green innovation in developing countries suggest that environmental protection policies can increase firm-level innovation activities [13,16–18].

Carbon emissions are the primary driver of global warming and rising temperatures [19]. Although this relationship affects all countries similarly, developed countries are better equipped to manage the long-term consequences of this impact due to advanced technologies and policies [20]. CO_2 emissions from developing countries surpassed those from developed countries in 2005 and now account for 63.4% of global emissions [21]. While absolute emissions in developed countries are declining, CO_2 emissions from developing countries increased by 6753.2 Mt between 2006 and 2016, and this trend is expected to continue in the foreseeable future [20,21].

The degradation of air quality and climate change-induced natural disasters impose significant burdens on healthcare systems [22]. Outdoor pollution has been linked to mortality rates, as evidenced by reports of 4000 deaths in London in 1952 and 400 deaths in New York in 1963 due to pollution [23,24]. While robust healthcare infrastructure in developed countries may mitigate these effects, weaker healthcare systems in developing countries exacerbate them [22]. Rising temperatures also increase healthcare expenditures through heat-related illnesses, vector-borne infections, and declines in agricultural production [25]. Moreover, although diseases like malaria, cholera, and dengue fever, which can be linked to climate change, have shown a declining trend over the years, the prevalence of non-communicable diseases attributed to climate change is rising [26,27]. Success in combating infectious diseases, driven by advancements in the pharmaceutical industry, may limit the tendency of climate change to increase infectious disease rates [28]. However, even a reduced prevalence of vector-borne diseases does not prevent a rise in healthcare expenditures [29].

Most studies in the literature examining the relationships between carbon emissions, temperature increases, and healthcare expenditures indicate that these variables are often addressed within a one-dimensional or limited framework [30–32]. However, the indirect effects of environmental and economic factors on these relationships, particularly differences between developed and developing countries, remain underexplored. Specifically, comparative research on the impacts of environmental changes on healthcare systems using indicators reflecting economic capacity, such as GNI PPP, is scarce in the literature [31]. This gap makes it challenging to understand the effects of environmental changes on healthcare systems across different economic and social contexts [31,33].

The primary objective of this study is to analyze the potential causal relationships between carbon emissions, temperature increases, and health expenditures within the context of environmental and economic indicators. The globally rising levels of carbon emissions and temperature changes have not only environmental impacts but also causal effects on public health systems. In this context, this study aimed to examine and clarify the relationships between these changes and the economic structures and environmental factors in countries grouped by health expenditures and income levels.

By addressing the causal effects of carbon emissions and temperature changes associated with climate change on health expenditures, alongside environmental and economic factors, this study aimed to expand the discussion on this topic. To evaluate the presence of causal relationships, indicators such as gross national income per capita adjusted for purchasing power parity and the share of health expenditures in gross domestic product were considered and countries were classified as developed or developing. Based on this classification, this study examined the potential indirect effects of environmental changes on health systems and analyzed the differences between the two country groups using a comparative approach informed by the findings.

2. Materials and Methods

The study was designed as a secondary data analysis and utilized panel causality models to examine potential causal relationships between carbon emissions, temperature increases, and health expenditures. Econometric methods were applied to evaluate the effects of environmental and economic indicators in the context of causality. Data were obtained from the platforms of Our World in Data, the World Bank, and the FAO, and the relevant variables were analyzed annually for each country (Table 1).

Table 1. Definitions of the variables.

Abbreviation	Indicator	Provider	Source
GNI	GNI PPP (currently USD)	World Bank	World Bank. (2021). GNI PPP, 2021. https://databank.worldbank.org/source/world-development-indicators/Series/NY.GNP.PCAP.PP.KD (accessed on 1 January 2025). [34]
HE	Health expenditure, total (% of GDP)	World Bank	World Bank (2024). Health expenditure, total (% of GDP). https://data.worldbank.org/indicator/SH.XPD.CHEX.GD.ZS (accessed on 1 January 2025). [35]
CO_2	Per capita CO_2 emissions	Our World in Data	Global Carbon Budget (2024). Population based on various sources, (2024). https://ourworldindata.org/grapher/co-emissions-per-capita (accessed on 1 January 2025). [36]

Table 1. *Cont.*

Abbreviation	Indicator	Provider	Source
PD	Population density	Our World in Data	Our World in Data (2024). Population Density, 2024. https://ourworldindata.org/grapher/population-density (accessed on 1 January 2025). [37]
TC	Temperature change on land	FAO	Food and Agriculture Organization of the United Nations. Temperature change statistics 1961–2023—Global, regional and country trends. https://www.fao.org/faostat/en/#data/ET (accessed on 1 January 2025). [38]

Carbon emissions were measured using per capita carbon dioxide (CO_2) emissions. This indicator represents the amount of CO_2 emitted per person as a result of fossil fuel use and industrial processes. Temperature increases are expressed as the annual average temperature change (°C) and are considered a key indicator for evaluating the impacts of global climate change [39]. Temperature change data are provided by the Food and Agriculture Organization [40] for each country. Health expenditures were measured as the ratio of total health expenditures to gross domestic product (GDP). This indicator, provided by the World Bank, reflects the total annual expenditures on health goods and services within a country, excluding capital expenditures such as infrastructure and equipment [41]. Additionally, economic indicators such as population density and GNI (Gross National Income per capita, adjusted for Purchasing Power Parity) were included in the model to assess their role in the causality relationships examined between environmental and economic factors. Population density represents the number of people per square kilometer, while the GNI indicator is used to measure the size of an economy and individuals' income levels [34].

The primary aim of the models and variable selections used in the study's design was to clarify the complex relationships between environmental and economic indicators and, specifically, to evaluate the indirect and direct effects of these relationships—particularly those of carbon emissions and temperature increases linked to climate change—on health expenditures. Initially, the causal examination of population density on temperature changes and carbon emissions was constructed based on the notion that factors such as increased energy consumption, transportation, and industrial activities may elevate CO_2 emissions, thereby leading to temperature changes. This was considered a critical starting point for analyzing the environmental consequences of human activities.

Subsequently, the causal relationship between temperature changes and gross national income per capita (adjusted for purchasing power parity, GNI PPP) and the potential causality of GNI PPP on carbon emissions were explored. Temperature changes can directly impact climate-sensitive sectors, including agriculture and energy production, and thereby influence countries' economic performance. Similarly, economic indicators, like per capita income, may trigger CO_2 emissions through the increased energy demand and industrialization associated with economic growth. This approach aimed to highlight both the effects of environmental changes on economic structures and the potential environmental burden of economic growth.

Furthermore, this study evaluated whether temperature changes have a causal relationship with GNI PPP and whether GNI PPP influences CO_2 emissions. Temperature changes, by affecting agricultural productivity and increasing energy-related costs like cooling and heating, are expected to have a causal link with economic performance. Additionally, CO_2 emissions have a direct influence on temperature changes, contributing to the greenhouse effect, methane emissions, and glaciers melting. Both CO_2 emissions and temperature changes impose financial burdens on health expenditures by deteriorating air quality, leading to respiratory diseases, fostering conditions for infectious diseases, and causing health problems linked to climate disasters and drought-induced nutritional challenges.

The causal relationships between carbon emissions, temperature changes, and health expenditures differ between developed and developing countries due to variations in economic structures, environmental policies, health system capacities, and adaptation abilities. In developed countries, environmental risks are often mitigated through effective policies, renewable energy use, and robust health infrastructures. In contrast, developing countries experience more pronounced effects due to reliance on fossil fuels, the environmental costs of industrialization, and limited resources. In these countries, the direct burden of temperature increases on health systems is more acutely felt due to weaker infrastructure and lower adaptation capacities. Meanwhile, in developed countries, the capacity of individuals and governments to adapt and respond to environmental changes is higher, which can make the impact on health expenditures more indirect or limited.

Therefore, analyzing the two country groups separately to compare the causal effects of environmental changes on health systems offers a critical opportunity to evaluate current policies and develop sustainable health systems. This study's model, presented in Figure 1, reflects this approach.

Figure 1. Distribution of clustered countries based on health expenditure as a share of GDP and GNI PPP.

In this study, the GNI PPP (Gross National Income per capita adjusted for Purchasing Power Parity) indicator was chosen over GDP per capita because GNI PPP provides a more accurate representation of countries' economic capacities for international comparisons. GNI PPP reflects the income levels of a country's citizens while accounting for price differences between countries, making it particularly suitable for analyzing economic disparities between developing and developed nations. This approach was chosen to enable a more precise evaluation of the impact of health expenditures and environmental indicators across countries.

Additionally, "Health Expenditure, Total (% GDP)" was selected as the indicator for health expenditures due to its capacity to reflect the share of health expenditures within the total economic output, which is critical in assessing economic sustainability.

The percentage-based expression facilitates comparisons among countries with diverse economic structures and allows the analysis of imbalances in spending ratios between developed and developing countries. For this reason, it was deemed to be more beneficial in this research model. This approach not only moves beyond absolute health expenditure figures but also enables an evaluation of a country's economic commitment to its health system, providing a basis for a deeper examination of its relationships with environmental variables. The alternative hypotheses for the study are presented in Table 2.

Table 2. Research hypotheses.

Country Type	H_A	Hypotheses
Developing countries	H_{1a}	In developing countries, population density has a causal relationship with temperature changes.
	H_{2a}	In developing countries, population density has a causal relationship with CO_2 emissions.
	H_{3a}	In developing countries, temperature changes have a causal relationship with gross national income per capita (GNI PPP).
	H_{4a}	In developing countries, gross national income per capita (GNI PPP) has a causal relationship with CO_2 emissions.
	H_{5a}	In developing countries, CO_2 emissions have a causal relationship with temperature changes.
	H_{6a}	In developing countries, CO_2 emissions have a causal relationship with health expenditures.
	H_{7a}	In developing countries, temperature changes have a causal relationship with health expenditures.
Developed countries	H_{1b}	In developed countries, population density has a causal relationship with temperature changes.
	H_{2b}	In developed countries, population density has a causal relationship with CO_2 emissions.
	H_{3b}	In developed countries, temperature changes have a causal relationship with gross national income per capita (GNI PPP).
	H_{4b}	In developed countries, gross national income per capita (GNI PPP) has a causal relationship with CO_2 emissions.
	H_{5b}	In developed countries, CO_2 emissions have a causal relationship with temperature changes.
	H_{6b}	In developed countries, CO_2 emissions have a causal relationship with health expenditures.
	H_{7b}	In developed countries, temperature changes have a causal relationship with health expenditures.
(Both Developing and Developed)	H_{1c}	In both developing and developed countries, population density has a causal relationship with temperature changes.
	H_{2c}	In both developing and developed countries, population density has a causal relationship with CO_2 emissions.
	H_{3c}	In both developing and developed countries, temperature changes have a causal relationship with gross national income per capita (GNI PPP).
	H_{4c}	In both developing and developed countries, gross national income per capita (GNI PPP) has a causal relationship with CO_2 emissions.
	H_{5c}	In both developing and developed countries, CO_2 emissions have a causal relationship with temperature changes.
	H_{6c}	In both developing and developed countries, CO_2 emissions have a causal relationship with health expenditures.
	H_{7c}	In both developing and developed countries, temperature changes have a causal relationship with health expenditures.
Differences	H_{1d}	There is a difference in the causal relationship of population density with temperature changes between developing and developed countries.
	H_{2d}	There is a difference in the causal relationship of population density with CO_2 emissions between developing and developed countries.
	H_{3d}	There is a difference in the causal relationship of temperature changes with gross national income per capita between developing and developed countries.
	H_{4d}	There is a difference in the causal relationship of gross national income per capita with CO_2 emissions between developing and developed countries.
	H_{5d}	There is a difference in the causal relationship of CO_2 emissions with temperature changes between developing and developed countries.
	H_{6d}	There is a difference in the causal relationship of CO_2 emissions with health expenditures between developing and developed countries.
	H_{7d}	There is a difference in the causal relationship of temperature changes with health expenditures between developing and developed countries.

To perform clustering analysis by country, cross-sectional data for 115 countries covering the years 2000–2021 were generated with higher weights assigned to more recent years.

This was achieved by weighting the values from recent years to incorporate the effect of time in the clustering process, utilizing the following formula:

$$X_{cross-sectional} = \frac{\sum X_t \times \left[\frac{Year_t - Year_{2000}}{Year_{max} - Year_{min}}\right]}{\sum\left[\frac{(Year_t - Year_{2000})+1}{(Year_{max} - Year_{min})+1}\right]}$$

To ensure the comparability of data across variables, z-score standardization was applied as a preprocessing step before conducting the k-means clustering analysis. Following this scaling process, the k-means clustering algorithm was utilized to divide the countries into two clusters based on GNI PPP (current USD) and the share of health expenditure in GDP. The k-means algorithm optimized the cluster centers and assigned each observation to the nearest cluster center [42]:

$$WCSS = \sum_{k=1}^{2} \sum_{i \in C_k} \|x_i - \mu_k\|^2$$

As a result of the clustering analysis, the means of Cluster 1 and Cluster 2 were evaluated, with Cluster 1 identified as developing countries and Cluster 2 categorized as developed countries due to its relatively higher values. Before proceeding to causality tests, the stationarity of variables in the panel data were assessed using the Levin–Lin–Chu unit root test, developed in 2002 [43]. For non-stationary variables, first-order differences (l) were taken, and their stationarity was re-evaluated. Subsequently, causal relationships between the variables were examined using the relatively recent Dumitrescu–Hurlin panel causality test.

The Dumitrescu–Hurlin test [44] analyzes whether the past values of a variable X improve the ability to predict the current values of another variable Y within a panel dataset. According to Granger's theory, if the past values of X enhance the explanatory power of Y, then X is considered to cause Y [45]. A key advantage of the Dumitrescu–Hurlin test is its ability to account for heterogeneity across panel units, such as countries, thereby eliminating the requirement for the same causal relationship to exist in every unit. Furthermore, the method is suitable for heterogeneous panel data analyses that include both fixed and dynamic effects. The test employs asymptotic and semi-asymptotic distributions developed by Dumitrescu and Hurlin to calculate a global Z-statistic based on averages. This Z-statistic is used for hypothesis testing, where the null hypothesis states that X has no causal effect on Y, while the alternative hypothesis asserts that X causes Y in at least one panel unit. Another significant advantage of this method is its flexibility in handling panel units with varying levels of stationarity, allowing it to work with different lag lengths or degrees of independence for all series in the analysis [44].

The optimal lag length in panel data analysis and time series models determines how past values of the dependent variable should be incorporated into the model [46]. If the lag length is not selected correctly, then autocorrelation issues may arise, leading to inaccurate predictions. Optimal lag selection is typically determined based on information criteria such as the Akaike Information Criterion (AIC), Hannan–Quinn Criterion (HQ), and Schwarz Criterion (SC) or by evaluating forecasting performance. Identifying an appropriate lag structure enhances the statistical validity of the model, improves prediction accuracy, and allows for a more reliable analysis of relationships between variables [47]. The Akaike Information Criterion, Hannan–Quinn Criterion, and other information criteria are used to determine the optimal model complexity in time series and panel data models. AIC balances model explanatory power while preventing overfitting, where a lower AIC value indicates a preferred model. HQ, on the other hand, is often used in large datasets as it provides less biased estimates. These criteria play a crucial role in avoiding unnecessary complexity in models with excessive parameters and ensuring more accurate predictions. The Levin–Lin–Chu (LLC) unit root test is a statistical test used to determine whether series in panel datasets are stationary [43]. In panel data analysis, ensuring that variables are stationary is crucial in avoiding the presence of misleading relationships in the estimates. The LLC test examines whether all cross-sectional units share a common autocorrelation coefficient to assess stationarity. The test's null hypothesis (H_0) assumes that the variable contains a unit root, meaning that it is non-stationary, whereas the alternative hypothesis (H_1) assumes that the variable is stationary. Since non-stationary variables can compromise the reliability of the model, the LLC test is one of the most frequently used methods in panel data analysis.

In the process of defining the models, criteria such as the Akaike Information Criterion, Schwarz Criterion, Hannan–Quinn Criterion, and Final Prediction Error (FPE) were considered to determine the optimal lag length. These criteria aim to balance model complexity with data fit, facilitating the selection of the most appropriate model [48]. During the application of the LLC test, differencing was performed as necessary to achieve stationarity based on the hypothesis test results [43]. When conducting the Dumitrescu–Hurlin panel causality test with differenced series, it is a standard practice to add an additional lag to the determined lag length (i.e., lag length + 1). This adjustment is used to better capture the dynamic structure of the model and minimize autocorrelation issues, making it a widely accepted approach in panel data analysis [44]. Accordingly, the research hypotheses were constructed based on the following regression model.

To compare the $\widetilde{Z}$ values of developed and developing countries, the Wald test was employed [49]:

$$W = \frac{\widetilde{Z}_{developed} - \widetilde{Z}_{developing}}{\sigma^2_{developed} - \sigma^2_{developing}}$$

All analyses in the study were conducted using R 4.4.2 software. The results were interpreted at a 95% confidence level, and hypothesis tests were evaluated accordingly.

3. Results

A k-means clustering analysis was performed based on GNI PPP (current USD) and the share of health expenditures in GDP. Prior to clustering, the values of these two variables were scaled after being cross-sectionalized with time-weighted adjustments for each country. This clustering analysis was conducted to classify countries into developed and developing groups based on GNI PPP (current USD) and the share of health expenditures in GDP.

The clustering analysis identified two distinct groups: Cluster 1, representing developing countries, and Cluster 2, representing developed countries. The results showed that developing countries (Cluster 1) had an average health expenditure share of 4.99% (±1.46) of GDP and an average GNI PPP of 8933 USD (±7260 USD), while developed countries (Cluster 2) exhibited higher values, with an average health expenditure share of 8.52% (±2.63) of GDP and an average GNI PPP of 31,306 USD (±22,711 USD). According to this classification, 77 countries were categorized as developing, while 38 were classified as developed. The findings indicate that developed countries generally have higher shares of health expenditures, per capita income, CO_2 emissions, and population density, whereas developing countries are characterized by lower levels in these aspects along with more irregular temperature change patterns (Figure 1).

Figure 2 provides an example of trends for five variables from three randomly selected countries in each cluster, using a fixed random seed (set.seed (123)). A fixed random seed ensures that the random selection process remains reproducible, meaning that if the analysis is repeated, the same set of countries will be selected each time. This approach enhances the consistency and comparability of the results. The concept of setting a seed is widely used in statistical and computational analyses to control randomness, ensuring that findings are replicable [50].

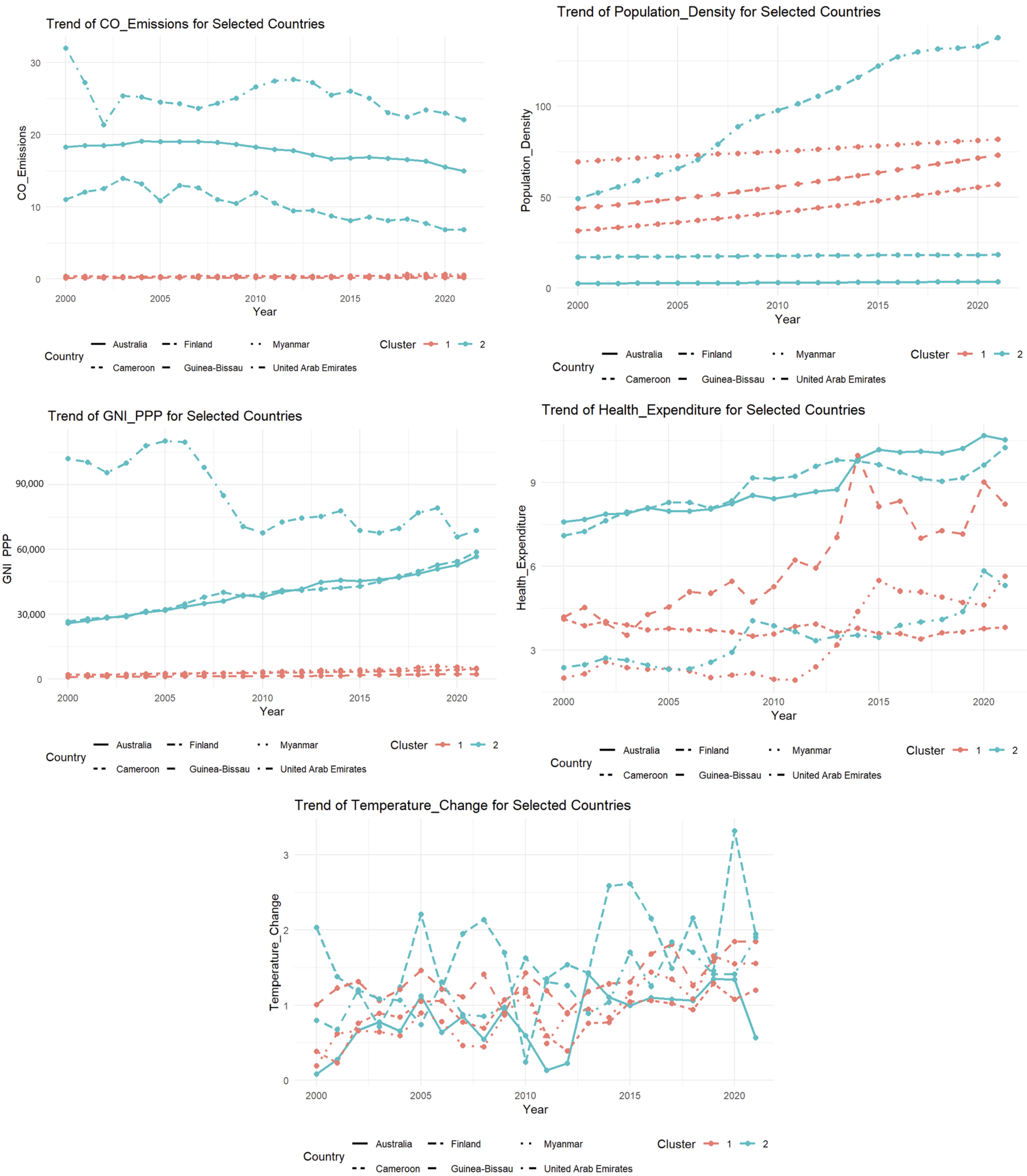

Figure 2. Trend examples for 5 variables for 6 randomly selected countries from clusters.

Figure 2 presents the trends for the CO_2 Emissions, Population Density, GNI PPP, Health Expenditure, and Temperature Change variables for six randomly selected countries (three from Cluster 1 and three from Cluster 2) during the period 2000–2021.

The results determining the optimal lag length for causality analyses are presented in Table 3.

Table 3. Lag selection of models.

	Models	AIC	HQ	SC	FPE
Developing countries	Population Density→Temperature Change	4	3	3	4
	Population Density→CO_2 Emissions	3	1	1	3
	Temperature Change→GNI PPP	4	3	3	4
	GNI PPP→CO_2 Emissions	3	1	1	3
	CO_2 Emissions→Temperature Change	4	4	3	4
	CO_2 Emissions→Health Expenditure	4	3	1	4
	Temperature Change→Health Expenditure	4	3	3	4
Developed countries	Population Density→Temperature Change	3	3	2	3
	Population Density→CO_2 Emissions	1	1	1	1
	Temperature Change→GNI PPP	4	3	2	4
	GNI PPP→CO_2 Emissions	3	1	1	3
	CO_2 Emissions→Temperature Change	3	2	2	3
	CO_2 Emissions→Health Expenditure	1	1	1	1
	Temperature Change→Health Expenditure	3	3	2	3
All	Population Density→Temperature Change	3	3	3	3
	Population Density→CO_2 Emissions	1	1	1	1
	Temperature Change→GNI PPP	4	4	3	4
	GNI PPP→CO_2 Emissions	3	3	1	3
	CO_2 Emissions→Temperature Change	3	3	3	3
	CO_2 Emissions→Health Expenditure	3	1	1	3
	Temperature Change→Health Expenditure	4	3	3	4

AIC, Akaike Information Criterion; HQ, Hannan–Quinn Criterion; SC, Schwarz Criterion; FPE, Final Prediction Error.

The optimal lag structure for each model was determined using criteria such as the AIC, HQ, SC, and FPE. Consistency among these criteria was observed in most models. For example, in the model including all countries, all criteria suggested a lag of 3 for the relationship between Population Density and Temperature Change, while a lag of 1 was recommended for the relationship between Population Density and CO_2 Emissions. However, in cases where differences between the criteria were observed, the dominant criteria were selected. When equal values were proposed, AIC was prioritized (Table 3).

The Levin–Lin–Chu unit root test was applied to assess the stationarity of variables in the panel dataset. This test determines whether a variable maintains a constant mean and variance over time or exhibits a systematic trend. According to the hypotheses used in the test, the null hypothesis (H_0) assumes that the variable contains a unit root, meaning that it follows a stochastic trend and is non-stationary. In contrast, the alternative hypothesis (H_A) assumes that the variable is stationary, implying that its statistical properties remain stable over time.

According to the results of the Levin–Lin–Chu test, the stationarity of variables was evaluated to determine the necessity of differencing. Variables such as Temperature Change and Population Density were found to be stationary at level (0th difference), and the unit root assumption was rejected due to the significance of the *p*-value. In contrast, the variables GNI PPP and CO_2 Emissions required first differencing to achieve stationarity. For developed countries, in addition to GNI PPP and CO_2 Emissions, the variable Health Expenditure as a percentage of GDP also required first differencing. After these processes, the test statistics indicated significance, confirming that these variables were now stationary. For causal analysis based on level values, the first differenced variables were incorporated into the causality models as lag lengths (Table 4).

Table 4. Levin–Lin–Chu unit root tests.

	Variables	Δ	z	*p*	Result
Developing countries	Temperature Change	0	−12.312	<0.001 ***	H_0 rejected
	Health Expenditure in GDP	0	−2.054	0.020 *	H_0 rejected
	GNI PPP, currently USD	1	−14.048	<0.001 ***	H_0 rejected with differencing
	Population Density	0	−4.243	<0.001 ***	H_0 rejected
	CO_2 Emissions Per Capita	1	−26.582	<0.001 ***	H_0 rejected with differencing
Developed countries	Temperature Change	0	−7.569	<0.001 ***	H_0 rejected
	Health Expenditure in GDP	1	−16.532	<0.001 ***	H_0 rejected with differencing
	GNI PPP, currently USD	1	−13.150	<0.001 ***	H_0 rejected with differencing
	Population Density	0	−2.752	0.003 **	H_0 rejected
	CO_2 Emissions Per Capita	1	−6.332	<0.001 ***	H_0 rejected with differencing
All	Temperature Change	0	−14.44	<0.001 ***	H_0 rejected
	Health Expenditure in GDP	0	−1.858	0.032 *	H_0 rejected
	GNI PPP, currently USD	1	−18.967	<0.001 ***	H_0 rejected with differencing
	Population Density	0	−4.963	<0.001 ***	H_0 rejected
	CO_2 Emissions Per Capita	1	−23.485	<0.001 ***	H_0 rejected with differencing

*, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$.

The findings of hypothesis tests related to causality analyses are presented in Table 5.

The Dumitrescu–Hurlin panel causality test evaluated the existence of causal relationships between variable pairs. For all countries, the causality test for Population Density on Temperature Change yielded a $\widetilde{Z}$ statistic of 15.682 and a *p*-value < 2.2×10^{-16}, leading to the rejection of the null hypothesis and demonstrating a significant effect of Population Density on Temperature Change. The causality test for Population Density on CO_2 Emissions resulted in a $\widetilde{Z}$ value of 24.144 and a *p*-value < 2.2×10^{-16}, also indicating a significant relationship. However, the causality test for Temperature Change on GNI PPP showed a $\widetilde{Z}$ statistic of −0.24137 and a *p*-value of 0.8093, failing to reject the null hypothesis, and no causality was found. The test for GNI PPP on CO_2 Emissions produced a $\widetilde{Z}$ value of 7.967 and a *p*-value of 1.625×10^{-15}, indicating a significant causal effect of GNI PPP on CO_2 emissions. For CO_2 Emissions on Temperature Change, the $\widetilde{Z}$ statistic was 2.7709 with a *p*-value of 0.00559, revealing a significant relationship, suggesting that CO_2 emissions may influence temperature change. The test for CO_2 Emissions on Health Expenditures yielded a $\widetilde{Z}$ value of 2.527 and a *p*-value of 0.0115, while the test for Temperature Change on Health Expenditures showed a $\widetilde{Z}$ value of 2.4382 and a *p*-value of 0.01476. Both tests disproved the null hypothesis, demonstrating significant causal relationships in each case (Table 5).

For developing countries, the causality test for Population Density on Temperature Change yielded a $\widetilde{Z}$ statistic of 6.8432 and a *p*-value of 7.744×10^{-12}, leading to the rejection of the null hypothesis and demonstrating a significant causal relationship between Population Density and Temperature Change. Similarly, the test for Population Density on CO_2 Emissions resulted in a $\widetilde{Z}$ statistic of 9.9045 and a *p*-value < 2.2×10^{-16}, indicating a significant relationship. However, the causality test for Temperature Change on GNI PPP showed a $\widetilde{Z}$ statistic of −0.51403 and a *p*-value of 0.6072, failing to reject the null hypothesis, and no causal relationship was found between these variables. The causality test for GNI PPP on CO_2 Emissions yielded a $\widetilde{Z}$ statistic of 5.6091 and a *p*-value of 2.034×10^{-8}, confirming a significant causal relationship. In contrast, the test for CO_2 Emissions on Temperature Change showed a $\widetilde{Z}$ statistic of 0.38377 and a *p*-value of 0.7011, and the null hypothesis could not be rejected. The test for CO_2 Emissions on Health Expenditures yielded a $\widetilde{Z}$ statistic of 3.398 and a *p*-value of 0.0006787, indicating a significant causal relationship. Lastly, the causality test for Temperature Change on Health Expenditures resulted in a $\widetilde{Z}$ statistic of 1.9221 and a *p*-value of 0.05459, showing borderline significance, with the null hypothesis being rejected at the margin (Table 5).

Table 5. Test results for models.

	Hypothesis	$\widetilde{Z}$	df	*p*-Value	Result
Developing countries	Population Density $\nRightarrow$ Temperature Change H_0: no causality	6.8432	4	7.744×10^{-12} ***	H_0: rejected
	Population Density $\nRightarrow$ CO_2 Emissions H_0: no causality	9.9045	4	$<2.2 \times 10^{-16}$ ***	H_0: rejected
	Temperature Change $\nRightarrow$ GNI PPP H_0: no causality	−0.51403	5	0.6072	H_0: cannot be rejected
	GNI PPP $\nRightarrow$ CO_2 Emissions H_0: no causality	5.6091	4	2.034×10^{-8} ***	H_0: rejected
	CO_2 Emissions $\nRightarrow$ Temperature Change H_0: no causality	0.38377	5	0.7011	H_0: cannot be rejected
	CO_2 Emissions $\nRightarrow$ Health Expenditure H_0: no causality	3.398	5	0.0006787 ***	H_0: rejected
	Temperature Change $\nRightarrow$ Health Expenditure H_0: no causality	1.9221	4	0.05459	H_0 is at the borderline of being rejected *(indicating weak evidence against the null hypothesis)*
Developed countries	Population Density $\nRightarrow$ Temperature Change H_0: no causality	11.006	3	$<2.2 \times 10^{-16}$ ***	H_0: rejected
	Population Density $\nRightarrow$ CO_2 Emissions H_0: no causality	23.952	2	$<2.2 \times 10^{-16}$ ***	H_0: rejected
	Temperature Change $\nRightarrow$ GNI PPP H_0: no causality	0.31183	5	0.7552	H_0: cannot be rejected
	GNI PPP $\nRightarrow$ CO_2 Emissions H_0: no causality	5.8753	4	4.221×10^{-9} ***	H_0: rejected
	CO_2 Emissions $\nRightarrow$ Temperature Change H_0: no causality	2.8731	4	0.004065 **	H_0: rejected
	CO_2 Emissions $\nRightarrow$ Health Expenditure H_0: no causality	5.8611	2	4.599×10^{-9} ***	H_0: rejected
	Temperature Change $\nRightarrow$ Health Expenditure H_0: no causality	1.5054	4	0.1322	H_0: cannot be rejected
All	Population Density $\nRightarrow$ Temperature Change H_0: no causality	15.682	3	$<2.2 \times 10^{-16}$ ***	H_0: rejected
	Population Density $\nRightarrow$ CO_2 Emissions H_0: no causality	24.144	2	$<2.2 \times 10^{-16}$ ***	H_0: rejected
	Temperature Change $\nRightarrow$ GNI PPP H_0: no causality	−0.24137	5	0.8093	H_0: cannot be rejected
	GNI PPP $\nRightarrow$ CO_2 Emissions H_0: no causality	7.967	4	1.625×10^{-15} ***	H_0: rejected
	CO_2 Emissions $\nRightarrow$ Temperature Change H_0: no causality	2.7709	4	0.00559 **	H_0: rejected
	CO_2 Emissions $\nRightarrow$ Health Expenditure H_0: no causality	2.527	4	0.0115 *	H_0: rejected
	Temperature Change $\nRightarrow$ Health Expenditure H_0: no causality	2.4382	4	0.01476 *	H_0: rejected

The Dumitrescu–Hurlin panel causality test; *p*-value was calculated according to the degree of freedom; *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$.

For developed countries, the results of the Dumitrescu–Hurlin panel causality test indicate that the causality from Population Density to Temperature Change is significant, with a $\tilde{Z}$ statistic of 11.006 and a p-value < 2.2×10^{-16}. Similarly, the causality from Population Density to CO_2 Emissions is also significant, with a $\tilde{Z}$ statistic of 23.952 and a p-value < 2.2×10^{-16}. However, the test for Temperature Change on GNI PPP showed a $\tilde{Z}$ statistic of 0.31183 and a p-value of 0.7552, failing to reject the null hypothesis, indicating no causal relationship. The causality test for GNI PPP on CO_2 Emissions yielded a $\tilde{Z}$ statistic of 5.8753 and a p-value of 4.221×10^{-9}, demonstrating a significant causal relationship. The causality from CO_2 Emissions to Temperature Change showed a $\tilde{Z}$ statistic of 2.8731 and a p-value of 0.004065, indicating a significant relationship. Furthermore, the causality from CO_2 Emissions to Health Expenditures yielded a $\tilde{Z}$ statistic of 5.8611 and a p-value of 4.599×10^{-9}, confirming a significant relationship. However, the test for Temperature Change on Health Expenditures resulted in a $\tilde{Z}$ statistic of 1.5054 and a p-value of 0.1322, failing to reject the null hypothesis (Table 5).

Differences in causality relationships between developing and developed countries were analyzed using the Wald test, as presented in Table 6.

Table 6. Comparison of causality relationships between developing and developed countries.

Models	Developing (n = 77)	Developed (n = 38)	Wald-Stat	p-Value
	$\tilde{Z}$	$\tilde{Z}$		
Population Density→Temperature Change	6.8432	11.006	440.907588	6.87×10^{-98} **
Population Density→CO_2 Emissions	9.9045	23.952	5020.818972	0.00×10 **
Temperature Change→GNI PPP	−0.51403	0.31183	17.353591	3.10×10^{-5} **
GNI PPP→CO_2 Emissions	5.6091	5.8753	1.802987	0.179
CO_2 Emissions→Temperature Change	0.38377	2.8731	157.667226	3.66×10^{-36} **
CO_2 Emissions→Health Expenditure	3.398	5.8611	154.362061	1.93×10^{-35} **
Temperature Change→Health Expenditure	1.9221	1.5054	4.417977	0.035 *

*, $p < 0.05$; **, $p < 0.001$.

The causality from Population Density to Temperature Change was found to differ significantly between developing and developed countries (W = 440.91, $p < 0.001$), with stronger causality observed in developed countries. Similarly, the impact of Population Density on CO_2 Emissions also showed a significant difference between the groups (W = 5020.82, $p < 0.001$), with this causality being more pronounced in developed countries. For the relationship between Temperature Change and GNI PPP, a significant difference was identified between the groups (W = 17.35, $p < 0.001$), with the causality being stronger in developing countries. Conversely, the effect of GNI PPP on CO_2 Emissions did not show a significant difference between the groups (W = 1.80, $p = 0.179$). The causality from CO_2 Emissions to Temperature Change demonstrated a significant difference (W = 157.67, $p < 0.001$), with stronger causality in developed countries. Similarly, the causality from CO_2 Emissions to Health Expenditures also showed a significant difference between the groups (W = 154.36, $p < 0.001$), being more prominent in developed countries. Finally, the causality from Temperature Change to Health Expenditures revealed a significant difference (W = 4.42, $p = 0.035$), with stronger causality observed in developing countries (Table 6).

Figure 3 explains the results of the Dumitrescu–Hurlin panel causality test. Accordingly, for Developing and Developed countries, population density has a significant causal effect on temperature change and CO_2 emissions, while CO_2 emissions are found to influence both temperature change and health expenditures. The causal relationship between GNI PPP and CO_2 emissions is also significant across both country groups. In developing countries, population density has a strong causal effect on temperature change and CO_2 emissions; however, the causal relationship between CO_2 emissions and temperature change is not significant. In developed countries, CO_2 emissions influence both temperature change and health expenditures, while the causal relationship between temperature change and health expenditures is not significant.

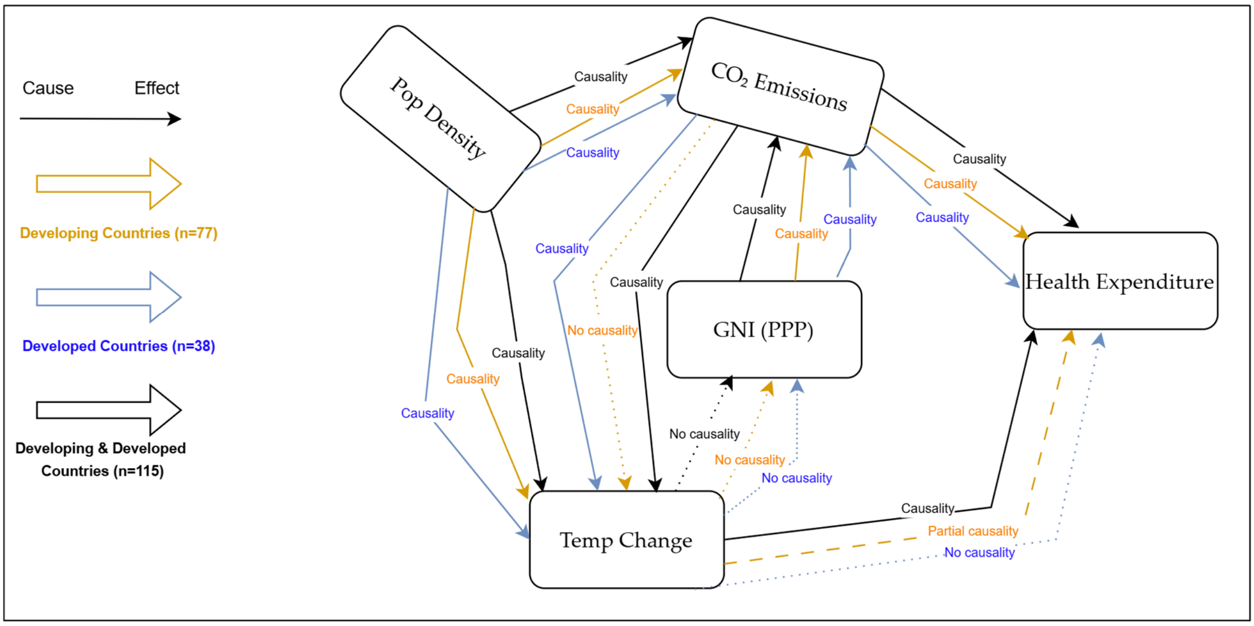

Figure 3. Causal relationships according to research findings.

4. Discussion

This study comparatively examines the impact of environmental indicators such as population density, temperature changes, and CO_2 emissions on economic structures and health expenditures in both developed and developing countries. The findings reveal that environmental changes create a complex web of interactions that shape not only the physical environment but also economic and health systems. In developing countries, the direct effects of climate change on economic growth and health expenditures are more pronounced, whereas in developed countries, these effects are typically mitigated through regulatory policies, robust health infrastructure, and environmental adaptation measures.

A study conducted in G7 countries found that long-term increases in GDP per capita were associated with reductions in greenhouse gas emissions [51]. In another study covering BRICST and G7 countries, the effects of fintech applications and natural resource abundance on energy consumption were examined, and differences among countries were revealed using a special climate change index [52]. Similarly, another study involving 919 European cities observed higher levels of air pollution in densely populated urban areas but also noted that these cities were more energy-efficient. Moreover, areas with abundant green spaces exhibited lower levels of air pollution, which were linked to positive health outcomes [53]. These findings emphasize the importance of interdisciplinary approaches in understanding the impact of environmental indicators on economic and health systems. They also underscore the need for policymakers to prioritize sustainability and public health in urban planning.

Research indicates that population density generally reduces CO_2 emissions, although this effect diminishes as density increases [54]. Among the 115 countries analyzed in this study, population density was found to have a significant causal effect on temperature changes. In developing countries, population density significantly affects not only temperature changes but also CO_2 emissions. Similarly, in developed countries, population density has a strong influence on both variables. In developing countries, issues such as inadequate urban infrastructure and uncontrolled urban migration may be key contributors to variations in carbon emissions [55,56]. On the other hand, in developed countries, well-planned urban infrastructure, the effective use of public transportation systems, and the adoption of energy-efficient technologies act as mitigating factors, reducing the environmental impacts of population density. This study also highlighted the fact that population density, particularly as an indicator of energy consumption and industrial activities, has a significant causal effect on CO_2 emissions across all countries. While this relationship is marked by a steeper upward trend in developing countries, a causal effect is also observed in developed nations. Similar findings were reported in a study using the STIRPAT model, which demonstrated that urbanization and real economic development have only a small impact on CO_2 emissions in low-income countries, whereas real economic development in upper–middle-income countries leads to a reduction in CO_2 emissions [57]. These findings suggest that in developing countries, economic growth is often prioritized over addressing global environmental challenges.

Countries with energy-intensive economic growth and high fossil fuel consumption for energy production, particularly those dominated by tertiary industries, tend to have larger carbon footprints [58]. In Sweden, renewable energy sources were found to be negatively associated with carbon emissions, whereas energy efficiency measures involving coal and gas were also negatively correlated [59]. In analyzing the effects of temperature changes on economic structures, this study found no significant causal effect of these changes on per capita Gross National Income (GNI PPP). However, the findings show that GNI PPP, an indicator of economic growth, increases CO_2 emissions consistently across all country groups. While the effect of GNI PPP on CO_2 emissions is significant in developing countries, a similar relationship was observed in developed countries. Importantly, no significant difference in the magnitude of this effect was found between the two groups, indicating that economic growth in both contexts leads to similar environmental outcomes through energy consumption and industrialization. Research investigating historical climate impacts across 77 countries and over 1500 regions found no significant effect on sustained economic growth but highlighted the substantial influence of temperature on productivity levels. By the end of the century, a global average surface temperature increase of approximately 3.5 °C is projected to reduce global output by 7–14%, with even higher damages expected in tropical and impoverished regions [60]. These findings underscore the critical importance of energy efficiency, renewable energy promotion, and transitioning to low-carbon technologies in mitigating the environmental impacts of economic growth. Furthermore, the consistent results across both developed and developing countries suggest that the more pronounced effects of temperature changes on GNI PPP in developing nations may stem from the indirect impacts of climate-sensitive sectors such as agriculture and energy on economic growth. For instance, a study controlling for income inequality found that temperature increases and rainfall anomalies significantly exacerbate intranational inequality, particularly in rural areas with larger populations and a higher prevalence of agricultural workers [33]. The impact of CO_2 emissions on temperature changes is significant across all countries, yet this effect is not found to be significant in developing countries. In contrast, the effect of CO_2 emissions on temperature changes is strongly evident in developed nations, primarily due to higher levels of economic growth, uncontrolled urbanization, and reliance on fossil fuels in developing countries. Successes in reducing carbon emissions have been documented in 18 developed countries through the use of renewable energy sources and adherence to the targets set by the Paris Agreement, which has also contributed to stabilizing temperature changes [61,62]. To prevent problems, foreign direct investments may offer opportunities for firms to shift towards cleaner and greener technologies; for instance, a study using data from Chinese companies has demonstrated that foreign investments support green innovation [63].

The relationship between CO_2 emissions and health expenditures is significant in both developed and developing countries. While CO_2 emissions drive increases in health expenditures in developing countries, this effect is stronger in developed nations. A similar study in G7 countries found that greenhouse gas emissions directly drive health expenditures [51]. In developed countries, this relationship is likely due to the allocation of more resources for combating air pollution and climate change. In developing countries, a study examining the relationships between health expenditures, carbon emissions, economic growth, natural resources, and population found that improved sanitation reduces health expenditures, whereas economic growth, pollution, and resource exploitation increase them [64]. Another study on causal dynamics found bidirectional causality between CO_2 emissions and economic growth, as well as between health expenditures and economic growth for the global panel, though this relationship was absent in low-income countries [65]. These findings highlight the critical role of advanced health infrastructure and technology in treating and preventing pollution-related illnesses in developed nations.

The effects of temperature changes on health expenditures are significant across all countries. However, this relationship is only marginally significant in developing countries and is not significant in developed countries. Nevertheless, the more pronounced effects of temperature changes on health systems in developing countries are likely due to limited infrastructure and adaptation capacity. A study covering 15 countries from 2000 to 2017 found that temperature and air pollution had a long-term and substantially positive relationship with healthcare costs, while rainfall exhibited a negative correlation with health expenditures [66]. Another study involving 38 countries emphasized that national environmental policies could reduce health expenditures [67]. In Sub-Saharan Africa, a study warned of significant public health threats in countries such as Ghana, Nigeria, South Africa, Namibia, Ethiopia, and Kenya if climate change measures were not implemented [68]. Limited access to clean water and sanitation in developing countries further exacerbates the health issues caused by temperature changes [69].

Advanced climate policies and transitions to green energy help mitigate the indirect effects of temperature changes on health in these countries. Additionally, in developed countries, allocating a significant portion of health expenditures to preventive healthcare reduces the costs of health issues associated with temperature changes. However, considering the long-term impacts of climate change, even developed countries are expected to face an increasing burden on their health systems. The aging population's greater vulnerability to environmental changes could further amplify the effects of temperature changes on health expenditures in the coming years [66]. These findings underscore the importance of proactive policies and investments in addressing climate change for both developed and developing countries. Strengthening energy efficiency, promoting renewable energy use, and enhancing environmental health policies are critical steps in mitigating these impacts.

5. Conclusions

This study provides comprehensive evidence on the causal relationships between carbon emissions, temperature increases, and health expenditures, with a particular focus on inequalities between developed and developing countries. It highlights the multifaceted impact of climate change and environmental degradation on public health systems, emphasizing the importance of proactive and targeted strategies.

The findings reveal that population density significantly contributes to both temperature increases and carbon emissions across all countries. However, this relationship is more pronounced in developed countries, likely due to better management of urbanization patterns and industrial activities through sustainable infrastructure. In contrast, in developing countries, inadequate urban planning and uncontrolled urban sprawl exacerbate environmental pressures, leading to increased emissions and temperature fluctuations.

The relationship between temperature increases and health expenditures underscores the critical vulnerability of developing countries. Limited adaptation capacity and inadequate infrastructure make health systems in these countries more susceptible to the impacts of climate change, including vector-borne diseases, heat-related illnesses, and water-borne diseases. While the direct effects on health expenditures appear less significant in developed countries, the long-term implications of an aging population and chronic diseases linked to climate change remain a concern.

The role of economic growth, measured by GNI PPP, demonstrates a consistent link with increased carbon emissions. This finding highlights the need for both developed and developing countries to prioritize decoupling economic growth from carbon intensity. Investments in renewable energy, improvements in energy efficiency, and the adoption of low-carbon technologies are essential in mitigating the environmental impact of economic activities. Accordingly, the following recommendations are proposed:

- Developing countries should focus on enhancing healthcare infrastructure, improving access to clean water and sanitation, and integrating climate adaptation into public health strategies. International funding and technology transfer are critical in supporting these efforts.
- Governments in developing countries should implement policies prioritizing sustainable urban planning, including green infrastructure, efficient public transportation systems, and urban green spaces, to mitigate the environmental impact of population density.
- Both developed and developing countries should increase investments in renewable energy sources and promote the transition to energy-efficient technologies. Developed countries should lead by example and provide financial and technical support to developing nations.
- Policymakers must enforce regulations that limit emissions, incentivize energy efficiency, and support the use of cleaner energy sources. Multilateral agreements like the Paris Agreement should be further reinforced with actionable commitments.
- Developing countries need to allocate resources to preventive healthcare to reduce the burden of climate-related illnesses, while developed countries should expand efforts to address long-term health challenges associated with climate change.

While this study provides significant insights, it does not fully capture the long-term impacts of climate change that may manifest over decades. Additionally, the classification of countries into developed and developing groups does not account for the environmental, legal, political, and economic variations within these broad categories. The causal relationships examined in this study do not fully reflect the long-term progression of these dynamics. Furthermore, critical environmental indicators such as biodiversity loss or air pollution, which could offer deeper insights into the environment–health nexus, were not included, and only unidirectional relationships were evaluated.

Future research should focus on longitudinal analyses to capture the delayed effects of climate change on health systems and include micro-level data from regional or local studies to provide more detailed insights into the causal dynamics explored here. Increasing studies on the intersection of climate change, socioeconomic inequality, and health outcomes can offer valuable multidimensional perspectives for designing equitable and effective climate policies.

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