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Global Dynamics of Environmental Kuznets Curve: A Cross-Correlation Analysis of Income and CO_2 Emissions

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Abstract: The environmental Kuznets curve (EKC) hypothesis posits an inverted U-shaped relationship between economic growth and environmental degradation. However, there is no consensus regarding the EKC hypothesis among countries and regions of different income groups. This study revisits the EKC hypothesis by employing cross-correlation analysis to explore the income–CO_2 emissions relationship across 158 countries and 44 regions from 1990 to 2020. The empirical method utilizes a dynamic cross-correlation coefficient (CCC) approach, allowing for the assessment of lead-lag dynamics between income and CO_2 emissions over time. By categorizing nations into the World Bank's income classifications, we found a heterogeneous EKC pattern highlighting distinct environmental–economic dynamics across different income groups. The findings indicate that high-income countries show a decoupling of economic growth from CO_2 emissions; whereas, low-income countries still exhibit a positive correlation between both variables. This underscores the necessity for tailored policy interventions that promote carbon neutrality, while considering each country's unique development stage. Our research contributes to the ongoing issue of sustainable economic development by providing empirical evidence of the different pathways nations follow in balancing growth with environmental preservation.

Keywords: environmental Kuznets curve; CO_2 emissions; economic growth; cross-correlation analysis; income levels; sustainable development

Citation: Almeida, D.; Carvalho, L.; Ferreira, P.; Dionísio, A.; Haq, I.U. Global Dynamics of Environmental Kuznets Curve: A Cross-Correlation Analysis of Income and CO_2 Emissions. *Sustainability* **2024**, *16*, 9089. https://doi.org/10.3390/su16209089

Academic Editor: Pallav Purohit

Received: 13 September 2024
Revised: 15 October 2024
Accepted: 18 October 2024
Published: 20 October 2024

1. Introduction

For human survival and development, the Earth's climate must be suitable and stable [1,2]. However, according to Berkeley Earth (2024) [3], 2023 was the warmest year, with global surface temperatures having accelerated by ~1.5 °C since the preindustrial period. Human activities and anthropogenic greenhouse gas emissions have been "unequivocally" identified as the main causes of global warming [4]. Considering the identified causality, one issue requires academic and governmental attention: how to change the existing paradigm of development to bring it into line with the principles of climate mitigation [5–9].

In the environmental economics literature, the environmental Kuznets curve (EKC) is widely discussed. The EKC is a reinterpretation, from the economics field, of the nonlinear relationship between per capita income and income inequality, proposed by Kuznets [10]. In the 1990s, Grossman and Krueger [11] proposed the EKC concept to describe the inverted U-shaped relationship between economic growth and environmental degradation. According to these authors, there are three stages in the association between economic development and environmental degradation throughout the growth trajectory, with the phases being impacted by scale, composition, and technological impacts. According to the EKC theory, urbanization and industrialization use natural resources and create urban and industrial waste at the start of economic growth, explaining the negative association between economic growth and environmental quality. As the country's wealth rises, several changes occur in the framework of the economy, and economic development begins to have an environmental composition effect. During this time, environmental quality has become more important, and businesses and industries are concerned about increasing energy efficiency and using cleaner technology. In the later stages of development, environmental safety becomes a key component of economic policy and raises significant concerns for global society. This perspective is reinforced by [12], who posit that there is a notable increase in income levels as economies progress. This, coupled with enhanced institutional quality, a heightened awareness of environmental responsibility, and a greater adoption of innovations and technological advancements, leads to a decrease in environmental degradation. As a result, economic growth and environmental quality experience simultaneous improvement in the later stages of economic development. The relationship between the two follows a bell-shaped or inverted U-shaped curve. This phenomenon is commonly referred to as the EKC hypothesis. According to EKC theory, as GDP per capita rises, environmental degradation initially increases, but after reaching a specific income threshold (the inflection point), further rising income leads to improvements in environmental quality. These interpretations of EKC align with those presented by [13], and our research follows the same explanation throughout the paper.

The EKC links economic development with environmental quality and posits that at the early stages of economic development, due to the higher priority given to income over the environment, both economic growth and environmental pollution would increase. However, after a certain point of economic development, as a greater proportion of the population is willing to pay for a clean environment, and due to more effective environmental policies, this scenario would be reverted, and pollution would start declining. This means that in the early stages of development, there exists a positive relationship between environmental degradation and per capita income (a positive slope), but after a certain level of income, pollution decreases with an increase in per capita income, i.e., a negative slope [14–16]. However, several empirical studies have provided inconclusive results regarding the EKC hypothesis, underscoring the importance of considering both regional and income-level heterogeneity when evaluating the EKC hypothesis.

Given the above, it was expected that most developed countries would have exceeded the turning point of the inverted U and the worsening in environmental degradation would be reduced with growth. However, several recent studies point out that some developed countries are ecologically deficient (see, for example, [17,18]). There are also other countries (such as Germany, The Netherlands, and Austria) that are once again turning to coal for electricity and heating, as they struggle with a European energy crisis triggered by the Russia–Ukraine conflict beginning in 2022 [19,20].

Furthermore, it is important to test the relationship between environmental quality and economic growth, as it allows policymakers to judge the environment's response to economic growth. This is crucial, since growth is an important element in most countries' objective function. Moreover, it is crucial to consider the targets for global carbon neutrality and net zero carbon emissions by 2050, which are central to international climate policies. Many high-income countries have committed to achieving net zero emissions by mid-century, implying significant changes in energy production and consumption. These targets underscore the necessity for sustainable development where economic growth is decoupled from carbon emissions. Integrating these targets into EKC analyses can provide relevant insights into the alignment of economic and environmental policies and identify gaps and opportunities for improvement in climate mitigation strategies. Thus, our research seeks to answer the following key research question:

How does the relationship between economic growth (measured by GDP per capita) and CO_2 emissions evolve globally, and does the cross-correlation coefficient (CCC) analysis from 1990 to 2020 provide evidence supporting the EKC hypothesis across varying income levels?

While the existing literature on the EKC provides a foundational understanding of the income–CO_2 emissions relationship, our research fills several critical gaps by analyzing a broader dataset spanning 158 countries and 44 regions over three decades. This global scope, coupled with the CCC approach of Narayan et al. [13], allows us to explore the temporal dynamics of the relationship between economic growth and environmental impact, offering insights that extend beyond traditional analyses. By employing this methodology, we highlight the heterogeneity among countries at different stages of development, revealing that the EKC pattern is far from uniform. Furthermore, our study emphasizes the need for tailored carbon policies that account for these differences, crucial for effective and equitable climate action. By providing empirical evidence of these diverse trajectories, our research contributes to the global issue of sustainable development, highlighting the nuanced relationship between economic growth and CO_2 emissions.

The novelty of this study lies in its ability to capture the nuanced, dynamic relationship between income growth and CO_2 emissions over time, going beyond static, cross-sectional analyses. Our comparative analysis across various income groups enables us to pinpoint the exact stages at which economic growth begins to decouple from CO_2 emissions, offering valuable insights for policymakers. This level of detail is essential for developing effective carbon mitigation strategies that are tailored to the unique circumstances of each country or region. Furthermore, our findings contribute to the broader discussion on sustainable development by providing new evidence of regional disparities and diverse environmental–economic trajectories. These insights are crucial for creating policies that promote equitable climate action, while balancing economic growth with environmental sustainability.

Our findings reveal that low-income countries display the highest percentage of countries aligned with the EKC hypothesis, while high-income countries display the lowest. However, there are countries whose behavior is partially aligned with the EKC hypothesis, i.e., countries for whom it is expected that CO_2 emissions will reduce in the future with increased GDP. In this case, high-income countries display the highest percentage of alignment, while none of the lower-income countries reveals a trend of CO_2 reduction in the future with an increase in GDP. Across the world, there are significant variations in the alignment with the EKC hypothesis. Generally, Europe and Asia are the world regions whose behavior best fits the EKC hypothesis. Our results also reveal that 11.36% of the world regions are on a carbon neutrality path where economic growth is decoupled from carbon emissions.

This article is organized as follows: Section 1 presents the motivation for this study and the main results; Section 2 provides a brief literature review of the studies related to the EKC hypothesis; Section 3 provides an overview of the analyzed data and the applied methods; Section 4 discusses the results; and Section 5 offers some concluding remarks, policy recommendations, and future research directions.

2. Brief Literature Review

Climate change and its consequences for the global economy have been discussed in the economic literature since the 1980s [21]. In recent years, one of the major concerns of nations has become global warming, particularly its adverse effects on the Earth and, implicitly, on quality of life. The start of the Industrial Revolution contributed to significant changes at the global level (both economically and socially) with subsequent effects on the environment. Thus, reducing the emission of greenhouse gases (GHG), such as CO_2, methane (CH_4), nitrous oxide (N_2O), and a set of fluorinated gases (hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3)), is the key to mitigating climate change.

Grossman and Krueger [22] identified evidence of a nonlinear relationship between income and environmental quality and proposed an inverted U-shaped relationship between both variables. According to their theory, as GDP per capita rises, environmental degradation initially increases, but after reaching a specific income threshold (the inflection point), further rising income leads to improvements in environmental quality.

The EKC theory, which suggests an inverted U-shaped relationship between environmental degradation and income, has been the subject of much debate. (See, for example, [23–27] for extensive and systematic literature reviews in this regard, which are not covered by this research, since we do not aim to review or cite all the rapidly growing number of studies).

For example, Ekins [28] examined the evidence for an EKC relationship between environmental quality and income. They found that some environmental indicators exhibit a monotonically increasing relationship with income, rather than the inverted U-shape suggested by the EKC. Ekins concluded that the income–environment relationship remains problematic from a sustainability perspective, indicating that additional environmental policies are necessary to align income growth with sustainable development. Cole [23] provided a comprehensive analysis of the relationship between economic growth and environmental degradation, highlighting that while some environmental indicators improve with economic growth, others do not, which necessitates careful interpretation of EKC studies. This heterogeneity indicates that economic growth does not uniformly enhance environmental quality, as the EKC hypothesis suggests.

The EKC hypothesis posits that while economic growth initially leads to environmental degradation, it eventually improves environmental quality once a certain income level is reached [24]. However, research results are mixed: some studies, for example [29–39], support the EKC hypothesis, while others [40–42] challenge its validity.

It is important to clarify that the EKC hypothesis is primarily concerned with the relationship between environmental degradation and income per capita rather than economic growth per se. The EKC posits that at lower levels of income, environmental degradation tends to increase as income rises. However, after reaching a certain income threshold—the "turning point"—further increases in income per capita are associated with improvements in environmental quality. This relationship is typically represented by an inverted U-shaped curve. It should also be noted that this relationship is not necessarily monotonic. A country can experience high economic growth but remain within the low-income category, where environmental degradation may continue to increase. Conversely, a country with low growth but high per capita income may already be on the downward slope of the EKC, where environmental improvements are observed. The critical factor is the level of income per capita in relation to the turning point, not the growth rate itself. Therefore, while economic growth can influence environmental outcomes, it is the income level that primarily determines whether a country is moving toward increased or decreased environmental degradation.

Recent events challenge the EKC hypothesis, particularly in advanced economies. For example, the U.S., the world's largest economy, withdrew from the Paris Agreement in 2020 to prioritize reviving polluting industries [43], and several European countries have reverted to coal for energy due to the 2022 Russia–Ukraine conflict [19,20]. This shift raises concerns about the future of global efforts to combat climate change and suggests the need to revisit the global EKC.

An alternative perspective posits that the EKC may follow an N-shaped curve, where environmental pollution could re-emerge even in advanced economies if technological progress does not keep pace with economic growth [44]. The N-shaped model suggests that economic growth initially leads to environmental degradation, which improves after reaching a peak (first turning point). However, pollution levels start to rise again (second turning point) with further economic progress [44]. The most concerning aspect of this model is the rebound of environmental pollution in the third stage, known as the technological obsolescence effect [44,45], attributed to overlooked environmental regulations and sluggish technological innovation.

This emerging paradigm of the N-shaped curve (which has been confirmed in various global and country-specific studies, such as the studies of [46–51]) appears to be more relevant to the current reality than the previously accepted inverted U-shaped EKC, to the fact that carbon emissions may continue to rise even at high levels of economic development if the positive impacts of green innovation fail to keep pace with the negative effects of scale [44]. Hence, an accurate understanding of the current shape of global EKC is critical for different categories of countries to identify their unique drivers of carbon emissions and adopt prompt action. Furthermore, the current situation highlights the intricate nature of carbon emissions regulations. While the EKC framework has traditionally considered variables such as trade openness, institutional quality, and energy consumption [52], recent studies have unveiled new connections between external factors and carbon emissions. Moreover, geopolitical risks and national political, economic, and financial risks have been identified as influential factors that can change a country's economic development and energy consumption patterns [53–55]. Additionally, digital technology and artificial intelligence, pivotal components of the third and fourth industrial revolutions, have been shown to have a positive impact on reducing carbon emissions in certain studies [56,57]. The shift from traditional fossil fuels to alternative energy sources has been empirically proven to effectively combat air pollution and expedite the journey toward carbon neutrality [58,59]. Additionally, social factors such as population aging [60] and food security [61] are also being considered in environmental analyses. The building and transportation sectors, particularly with the rise of electric vehicles (EVs), are critical in achieving carbon neutrality [62,63]. For instance, energy-efficient buildings can reduce both direct and indirect emissions by lowering energy demand, while EVs can significantly cut transportation-related emissions when powered by clean energy sources.

Thus, more studies are needed to understand the relationship between economic growth and sustainability. Policy measures are necessary to promote sustainability, and economic models should incorporate better the physical and ecological aspects of economic activity and the interaction between the economy and the environment.

Following the same line of thinking, Ekis [28] and Aslanidis [64] also questioned the existence of a clear EKC and provided a critical review of the literature on the EKC for carbon emissions. The author found no clear-cut evidence supporting or rejecting the existence of the EKC for carbon emissions, despite using more sophisticated econometric techniques. The assumption of homogeneous income effects across countries is rejected, with the EKC holding true only for some developed countries. Carbon emissions and GDP per capita are integrated variables, although not always cointegrated, which casts doubt on the validity of the EKC [16] and calls for re-evaluating its assumptions.

Given the complexity of the relationship between economic growth and environmental sustainability, more research is necessary to refine economic models that better integrate physical and ecological aspects. Studies such as those by Mbatu and Otiso [65] have expanded the scope of EKC research and highlighted the potential dangers of relying solely on the EKC hypothesis without considering regional socio-political and environmental contexts. Chen et al. [66] argue that the EKC pattern may not be valid for situations of more damaging pollution, given human-bounded rationality and societal uncertainties. Conversely, Purcel [25], in a literature review of the EKC hypothesis, found that recent empirical studies suggest a growing consensus that the pollution–growth nexus and the validity of the EKC hold true in developing and transition economies, particularly where economic growth has surpassed certain thresholds of development. Chen et al. [66] and Purcel [25], thus, provided additional insights into the limitations of the EKC, particularly in the context of severe pollution scenarios. They argue that the EKC pattern may not adequately address the complexities of environmental degradation and the influence of human-bounded rationality and societal uncertainties. Several other studies also found a long-term relationship between pollution and growth, supporting the EKC hypothesis.

Although the EKC knowledge domain has developed substantially since its inception, no consensus exists on the existence, shape, and turning points of the EKC among researchers [27]. While several studies validated the existence of the EKC while dealing with a wide sample of economies, other multicountry studies failed to validate this theory, and some others found mixed evidence (see, for example, [67] for an extensive state-of-the-art review). This divergence underscores the need for further research that includes a broader range of countries and employs more comprehensive datasets.

Furthermore, only a few studies explore the cross-correlation between per capita GDP and indicators of environmental degradation over different periods (the lags and leads), including both past and future trends, in relation to the EKC hypothesis. Nonetheless, there are several exceptions cited in the literature [13,68–71]. These studies have used the EKC framework to analyze the relationship between economic growth, CO_2 emissions, globalization, and environmental degradation. Some of these studies found evidence supporting the EKC hypothesis across countries with varying income levels, suggesting that, beyond certain income thresholds, economic growth can lead to reductions in CO_2 emissions and environmental degradation. However, the influence of additional factors, such as financial development and tourism revenues, differs depending on the income level of the country. Moreover, the impact of international trade was also examined, revealing that exports generally contribute positively to sustainable development in developing countries, while imports tend to have negative effects. Overall, these findings offer valuable insights into how different economic and environmental factors interact in various countries.

While several studies have tested the EKC hypothesis using panel data, most focus on developing and transition economies, often analyzing specific country groups, frequently overlooking the temporal dynamics across diverse economies. This underscores the need to revisit the EKC hypothesis with a broader set of countries and more recent data. Additionally, research on the relationship between GDP per capita and CO_2 emissions, particularly using the cross-correlation approach to examine lag and lead effects, remains limited. Given this empirical gap, expanding this line of inquiry is essential to better understand how GDP per capita may influence CO_2 emissions.

Our study addresses the identified gaps by revisiting the EKC hypothesis with a larger, more diverse sample of countries and regions, incorporating recent data and a cross-correlation approach to examine the lag and lead relationship between GDP per capita and CO_2 emissions. By doing so, we aim to provide a more accurate and nuanced understanding of how economic growth influences environmental outcomes, offering valuable policy development and implementation insights.

Thus, our research offers further insightful findings to the extant literature by providing empirical evidence on the income–CO_2 emissions relationship across a broad sample of countries and regions, adding depth to the ongoing discussions about the EKC. Furthermore, the application of the CCC approach proposed by Narayan et al. [13] allows for a more detailed exploration of the lead–lag (past–future) relationships between GDP and CO_2 emissions, we are able to obtain a better understanding of the heterogeneity of EKC trajectories across different income levels.

From a practical standpoint, the study emphasizes the importance of tailored policy interventions that account for these differences. Policymakers can use these insights to design more effective and equitable carbon-reduction strategies based on the specific economic stages of each country.

3. Data and Methods

3.1. Data

To test the EKC hypothesis, data on GDP per capita (current USD) and CO_2 emissions (metric tons per capita) were retrieved from the World Bank (https://data.worldbank.org/, accessed on 2 September 2024), a data source widely recognized for its accuracy and comprehensiveness in providing long-term, comparable environmental and economic data across countries. Carbon dioxide emissions are a leading indicator of environmental pollution and are used in several studies that test the EKC hypothesis (see, for example, [25] for a survey of studies that use this indicator in this regard). The data include countries and regions for which complete data were available for the entire period, ensuring comparability across income groups, covering 193 countries and 46 world regions.

To analyze a similar period for all the countries and regions, and due to data availability for both variables selected (GDP and CO_2 emissions), the analysis covers 158 countries. As for the world regions South Asia and South Asia (IDA and IBRD), and for Sub-Saharan Africa and Sub-Saharan Africa (IDA and IBRD countries), the values of GDP per capita and CO_2 emissions are the same; therefore, the world regions South Asia (IDA and IBRD) and Sub-Saharan Africa (IDA and IBRD countries) were not considered.

The IDA countries include those countries that receive concessional loans (low or zero interest) from the International Development Association (IDA). On the other hand, the IBRD countries include both middle-income and creditworthy low-income countries that receive loans from the International Bank for Reconstruction and Development (IBRD) for development projects. Thus, 44 world regions were considered.

The chosen categories, while broad, are essential for capturing the complex interactions between economic growth and environmental impact. This approach allows a more nuanced understanding of how income levels influence the relationship between GDP and CO_2 emissions.

The data range from 1990 (the first year for which there are available data on CO_2 emissions) to 2020 (the last year with data on CO_2 emissions for all countries and world regions studied), covering a comprehensive 31-year period. Furthermore, the period considered encompasses critical decades during which many countries, particularly in the upper-middle-income and high-income groups, have reached or are approaching the income thresholds where the turning point of the EKC becomes visible. For many low- and lower-middle-income countries, this period also reflects a significant era of economic growth, providing sufficient data to test whether income growth has been accompanied by increased or decreased carbon emissions. While some countries may have only recently crossed these thresholds, using a 31-year period allows for the observation of both short-term deviations and long-term trends necessary to capture income–emissions dynamics. Additionally, the global COVID-19 pandemic significantly impacted economic activities and emissions patterns, potentially introducing anomalies in post-2020 data that could distort long-term trends. Thus, the used dataset accurately reflects the relationship between GDP and CO_2 emissions during the period analyzed.

The choice of GDP per capita and CO_2 emissions per capita as the main indicators in this study was based on their widespread acceptance and consistent use in the literature on the EKC. GDP per capita is a standard proxy for a country's level of economic development, reflecting its capacity to generate wealth. In contrast, CO_2 emissions per capita are one of the most representative indicators of environmental degradation, particularly in terms of climate impact. Several previous studies investigating the EKC frequently employ these variables (e.g., [22,46,72–82]) due to their direct relevance and the availability of reliable data over time. Moreover, choosing these variables allows for consistent comparison with prior studies, facilitating the verification and extension of existing findings in the literature. Finally, using CO_2 as a pollution indicator aligns with global objectives for climate change mitigation, providing relevant insights for environmental and sustainable development policies.

To compare the results, the countries were then grouped into categories based on their income level (which evolves over time). For this classification, the last year of available data (2020) was considered, as detailed in Table 1. These categories follow the World Bank Group assignments, which are widely used and recognized in economic literature. Specifically, the countries were grouped into low, lower-middle, upper-middle, and high-income levels. This classification is based on the Gross National Income (GNI) per capita (in USD, converted from the local currency using the Atlas method). This classification provides a standardized and reliable framework for comparing economic and environmental data across different income levels.

Table 1. Classification of countries by income level.

Country Categories (Panels)	Acronym	GNI (USD)	Number of Countries by Category
High income	H	>12.695	47
Upper-middle income	UM	4.096–12.695	44
Lower-middle income	LM	1.046–4.095	49
Low income	L	≤1.045	18

As countries are at different stages of development, their incomes per capita are different. Thus, and as hypothesized by the EKC hypothesis, this has direct implications for the magnitude of carbon emissions, meaning it is relevant to their classification by income level.

3.2. Methods

The EKC hypothesis is tested using the cross-correlation coefficient (CCC) proposed by Narayan et al. [13], a mature method for analyzing the temporal dynamics between GDP per capita and CO_2 emissions, applied, for example, by [13,68,83]. In this study, a country's or region's consistency and inconsistency with the EKC is determined based on the interpretations and criteria established by [13], specifically: (i) if there is a positive cross-correlation between the current level of income and the past (lag) level of CO_2 emissions, and (ii) if there is a negative cross-correlation between the current level of income and the future (lead) level of CO_2 emissions. This cross-correlation coefficient is estimated according to Equation (1):

$$CCC = \frac{\sum_{t=1}^{n}\left(GDP_t - \overline{GDP}\right)\left(CO2_{t+k} - \overline{CO2}\right)}{\sum_{t=1}^{n}\left(GDP_t - \overline{GDP}\right)^2\left(CO2_{t+k} - \overline{CO2}\right)^2} \tag{1}$$

where $\overline{GDP}$ and $\overline{CO2}$ are, respectively, the mean GDP and CO_2 emissions per capita, t ranges from 1 to 31 (since we have yearly observations for the 31 years from 1990 to 2020), and k represents the lags $(k < 0)$ and leads $(k > 0)$.

To avoid spurious correlations between the analyzed variables, both time series are detrended with the Hodrick–Prescott (HP) filter, which uses a mathematical equation that minimizes the sum of the squared differences between the original time series (cyclical component) and the trend component (which represents the long-term underlying growth or decline in the series), subject to a constraint on the smoothness of the trend component. This filter is, among the data-smoothing techniques, one of the most commonly used in the literature [84,85] and uses a lambda (λ) parameter to control the trade-off between smoothing the trend and preserving the data fluctuations.

Considering the annual frequency of the data used, the λ parameter was set as λ = 100, following the suggestions of [86] for the λ parameter. After detrending the series, the CCC was estimated for the lags $-20 \leq k \leq 20$, which are sufficient to gauge the behavior of CO_2 emissions in response to changes in income [13]. Where $k > 0$, we obtain the CCC between GDP_t and k lead or future values of CO_2 $(CO2_{t+k})$; where $k = 1$, we obtain the CCC between GDP_t and the one-period lead or future value of CO_2 $(CO2_{t+1})$; and $k = -1$ indicates the CCC between GDP_t and the one-period lag or past value of CO_2. Where $k = 0$, the CCC between GDP_t and $CO2_t$ is obtained, which is the contemporaneous correlation between both variables. On the other hand, where $k < 0$, we obtain the CCC between GDP_t and the k period lag values of CO_2. All the estimations were made in software R—version 4.4.1 (the code is available upon request) and double-checked in Excel®.

The EKC hypothesis is considered correct if there exists: (i) a negative cross-correlation between the current level of GDP (GDP_t) and future levels (leads) of CO_2 emissions $(CO2_{t+k},\ \forall\ 0 < k \leq 20)$, and (ii) a positive cross-correlation between the current level of GDP (GDP_t) and past levels (lags) of CO_2 emissions $(CO2_{t+k}, \forall -20 \leq k < 0)$. CO_2 emissions will decline with the progression of GDP over time after a certain point. While the CCC analysis is a fundamental statistical tool, its application in this study serves a specific purpose. By focusing on the temporal lead–lag relationships between GDP and CO_2 emissions, the applied CCC approach allows us to observe patterns that are often overlooked in more complex models.

To enhance the methodological applicability of our study, it is important to highlight that the CCC proposed by Narayan et al. [13] was selected to test the EKC hypothesis due to its ability to capture the dynamic relationship between economic growth (GDP) and CO_2 emissions over time, offering insights into the lead–lag relationships that are not easily identified using other methods. Traditional econometric models, such as panel data regressions or Granger causality tests, often provide a static view of the relationship or require causality assumptions that may not apply in heterogeneous samples of countries with varying income levels. Mature methods, such as fixed-effect models or dynamic panel data models, are commonly used in EKC research, but these approaches often overlook the dynamic nature of the relationship, especially in terms of how rising income levels have led, or will lead to, environmental outcomes, i.e., CO_2 emissions. In contrast, the applied approach, by incorporating both lags and leads, allows for an analysis of how changes in GDP affect CO_2 emissions with different temporal lags, making it particularly suitable for understanding the temporal evolution of the EKC in a global context. This method allows us to detect not only contemporaneous relationships but also delayed effects that might emerge due to shifts in policy, technology adoption, or economic structure. This analysis is crucial for understanding sustainability dynamics in economies with varying levels of development. Furthermore, our method does not require strict assumptions about the homogeneity of the countries or regions, making it more flexible and adaptable to a diverse dataset such as ours. Moreover, the HP filter, applied to detrend the GDP and CO_2 time series, is a widely accepted practice in economic and environmental studies. It facilitates the identification of underlying trends by eliminating short-term noise that may distort results. By applying the HP filter to detrend the series, we ensure that short-term fluctuations do not obscure the long-term trends of income–emissions relationships, further strengthening the robustness of our findings. Combining these approaches provides a robust framework for analyzing the economies studied, offering valuable insights into sustainable development trajectories.

Although the cross-correlation coefficient (CCC) analysis does not directly establish causality, it is a valuable tool for exploring temporal associations between economic growth and CO_2 emissions across a wide range of countries and regions. This approach aligns with the exploratory nature of our study, which aims to identify patterns and trends rather than establish direct causal relationships. While methods such as the panel Granger causality test could be employed in a more targeted study, our broad, comparative analysis across 158 countries and 44 regions benefits from the flexibility and applicability of the CCC method. The applied approach has been effectively used to test the EKC hypothesis (for example, [13,68,87]) and in environmental economics to reveal significant associations that inform further research and policy considerations.

4. Results and Discussion

4.1. Preliminary Results

Tables 2–6 present some descriptive statistics, namely the mean and standard deviation (Std.Dev.) for both time series. Tables 2–5 report the results for the countries (which are grouped according to the categories in Table 1), and Table 6 reports the results for the world regions. The penultimate column of each table shows the values of the unconditional correlation between GDP and CO_2 emissions per capita. The null hypothesis of unconditional correlation equal to zero was tested (with a *t*-test using the t-statistics), and the results are displayed in the last column.

Table 2. Summary and descriptive statistics for the panel of high-income (H) countries.

Country	Code	GDP		CO_2 Emissions		Corr.	t-Statistic	
		Mean	Std.Dev.	Mean	Std.Dev.			
Andorra	AND	33,513.756	12,730.017	6.991	0.490	−0.458	−2.773	***
Antigua and Barbuda	ATG	12,606.951	3440.824	4.598	0.810	0.955	17.249	***
Australia	AUS	37,398.457	17,743.386	16.917	1.153	0.003	0.018	
Austria	AUT	37,669.077	11,201.962	7.948	0.671	−0.160	−0.872	
Bahamas, The	BHS	23,617.698	7225.189	6.170	0.647	−0.491	−3.039	***
Bahrain	BHR	16,955.385	6683.277	22.059	0.870	−0.034	−0.184	
Barbados	BRB	13,513.067	3910.232	4.526	0.676	0.681	5.003	***
Belgium	BEL	35,184.785	10,319.811	10.040	1.391	−0.875	−9.748	***
Brunei Darussalam	BRN	25,144.941	10,539.514	16.086	2.534	0.685	5.067	***
Canada	CAN	34,749.151	12,273.542	15.834	0.826	0.058	0.313	
Chile	CHL	8897.364	4712.158	3.641	0.845	0.945	15.542	***
Czechia	CZE	13,257.629	7453.118	11.342	1.448	−0.814	−7.558	***
Denmark	DNK	45,961.280	13,673.947	9.186	2.439	−0.786	−6.842	***
Finland	FIN	36,981.853	11,611.069	10.455	1.791	−0.514	−3.223	***
France	FRA	32,848.105	8406.669	5.564	0.675	−0.755	−6.203	***
Germany	DEU	35,496.418	9128.758	9.855	1.029	−0.838	−8.275	***
Greece	GRC	18,240.602	6296.672	7.683	1.214	0.187	1.023	
Hong Kong SAR, China	HKG	30,551.181	9719.464	5.233	0.582	−0.822	−7.767	***
Iceland	ISL	44,024.655	15,999.350	6.845	1.212	−0.708	−5.400	***
Ireland	IRL	43,305.016	21,700.216	9.292	1.401	−0.437	−2.619	**
Italy	ITA	28,779.928	6980.172	6.865	1.001	−0.344	−1.973	*
Japan	JPN	37,999.932	4955.627	9.187	0.396	0.204	1.120	
Korea, Rep.	KOR	19,019.393	8642.434	9.940	1.841	0.913	12.061	***
Kuwait	KWT	28,096.194	13,518.981	23.522	5.081	0.584	3.873	***
Luxembourg	LUX	80,509.712	33,061.083	21.268	4.711	−0.587	−3.902	***
Malta	MLT	17,272.450	8152.843	5.696	1.282	−0.724	−5.647	***
Monaco	MCO	135,307.698	45,555.805	3.585	1.829	−0.433	−2.590	**
Netherlands	NLD	39,411.272	12,443.167	9.900	0.788	−0.675	−4.920	***
New Zealand	NZL	26,995.219	11,864.834	7.232	0.605	−0.171	−0.932	
Norway	NOR	61,278.249	26,302.374	7.710	0.516	0.045	0.243	
Oman	OMN	13526.097	6821.440	12.861	3.694	0.920	12.600	***
Poland	POL	8593.375	4888.651	8.191	0.543	−0.607	−4.111	***
Portugal	PRT	16,996.778	5512.428	5.089	0.670	−0.102	−0.552	
Qatar	QAT	47,103.477	28,177.851	38.361	5.684	−0.177	−0.968	
Saudi Arabia	SAU	14,270.104	6556.716	13.351	2.091	0.937	14.440	***
Seychelles	SYC	10,653.678	3435.597	4.314	1.172	0.906	11.512	***
Singapore	SGP	36,894.723	17,488.764	9.076	1.038	−0.806	−7.337	***
Slovak Republic	SVK	11,405.345	6464.644	7.034	1.124	−0.868	−9.392	***
Spain	ESP	23,038.405	7321.656	6.241	0.974	−0.042	−0.225	
St. Kitts and Nevis	KNA	13,298.978	5711.927	4.223	0.804	0.917	12.393	***
Sweden	SWE	42,712.338	12,272.594	5.342	1.162	−0.859	−9.033	***
Switzerland	CHE	61,599.929	19,686.175	5.694	0.730	−0.866	−9.306	***
Trinidad and Tobago	TTO	11,092.989	6105.806	11.292	3.038	0.886	10.303	***
United Arab Emirates	ARE	35,667.627	7996.840	24.926	4.130	−0.796	−7.086	***
United Kingdom	GBR	34,866.662	9954.021	8.046	1.554	−0.658	−4.712	***
United States	USA	43,131.007	12,689.830	17.986	2.094	−0.855	−8.884	***
Uruguay	URY	9796.516	5645.954	1.782	0.326	0.671	4.876	***

Note: (i) "***", "**", and "*" correspond to statistical significance at 1%, 5%, and 10% significance levels, respectively; (ii) "Std.Dev." corresponds to the standard deviation; (iii) "Corr." corresponds to the unconditional correlation between both variables.

Table 3. Summary and descriptive statistics for the panel of upper-middle-income (UM) countries.

Country	Code	GDP		CO_2 Emissions		Corr.	t-Statistic	
		Mean	Std.Dev.	Mean	Std.Dev.			
Albania	ALB	2665.109	1800.928	1.298	0.444	0.804	7.282	***
Argentina	ARG	8518.593	3227.707	3.715	0.411	0.786	6.852	***
Armenia	ARM	2123.591	1619.682	1.812	1.141	0.054	0.291	
Azerbaijan	AZE	2930.402	2657.006	3.901	1.439	−0.433	−2.590	**
Botswana	BWA	4690.513	1590.257	2.280	0.423	0.430	2.567	**
Brazil	BRA	6549.213	3415.845	1.837	0.328	0.857	8.942	***
Bulgaria	BGR	4718.178	3114.510	6.182	0.642	−0.306	−1.730	*
China	CHN	3620.801	3476.529	4.655	2.182	0.945	15.529	***
Colombia	COL	4277.592	2226.098	1.543	0.125	0.198	1.089	
Costa Rica	CRI	6470.315	3710.129	1.419	0.200	0.737	5.870	***
Dominica	DMA	5740.121	1653.786	1.895	0.612	0.928	13.457	***
Dominican Republic	DOM	4227.287	2222.225	1.961	0.376	0.724	5.645	***
Ecuador	ECU	3632.565	1851.646	2.060	0.340	0.874	9.678	***
Equatorial Guinea	GNQ	7175.954	6775.226	3.837	1.786	0.708	5.405	***
Fiji	FJI	3441.352	1376.748	1.144	0.204	0.731	5.770	***
Gabon	GAB	6318.011	2019.434	3.803	0.892	−0.785	−6.820	***
Georgia	GEO	2342.236	1625.935	2.097	1.365	0.117	0.634	
Grenada	GRD	5909.886	2169.873	2.021	0.462	0.922	12.842	***
Guatemala	GTM	2490.587	1210.400	0.805	0.195	0.856	8.910	***
Guyana	GUY	2956.967	2353.561	2.331	0.569	0.837	8.226	***
Iraq	IRQ	3077.271	2547.821	3.702	0.681	−0.099	−0.536	
Jamaica	JAM	3971.723	1238.576	3.310	0.616	−0.371	−2.153	**
Jordan	JOR	2696.632	1223.568	2.946	0.354	−0.429	−2.558	**
Kazakhstan	KAZ	5512.682	4348.579	11.822	2.339	0.459	2.785	***
Libya	LBY	8345.772	2814.005	8.323	1.018	0.313	1.772	*
Malaysia	MYS	6631.129	3043.872	5.963	1.403	0.896	10.872	***
Maldives	MDV	5069.865	3375.597	2.132	0.954	0.970	21.379	***
Marshall Islands	MHL	2915.601	1028.386	2.206	0.773	0.773	6.566	***
Mauritius	MUS	6343.081	3021.857	2.328	0.752	0.940	14.778	***
Mexico	MEX	8056.363	2420.964	3.809	0.303	0.653	4.646	***
North Macedonia	MKD	3519.998	1618.463	4.119	0.412	−0.633	−4.408	***
Panama	PAN	7398.370	4574.470	2.075	0.521	0.848	8.625	***
Paraguay	PRY	3421.072	1963.058	0.835	0.207	0.779	6.680	***
Peru	PER	3746.250	2082.419	1.281	0.319	0.969	21.244	***
Romania	ROU	5752.380	4257.793	4.486	0.868	−0.634	−4.414	***
Russian Federation	RUS	6902.982	4683.833	11.461	1.068	0.018	0.099	
South Africa	ZAF	5226.971	1825.468	7.108	0.890	0.853	8.791	***
St. Lucia	LCA	7379.675	2389.200	2.430	0.496	0.905	11.485	***
St. Vincent and the Grenadines	VCT	5227.806	2141.860	1.781	0.558	0.915	12.199	***
Suriname	SUR	4408.957	2894.728	3.911	0.901	−0.132	−0.715	
Thailand	THA	3857.679	1909.120	3.103	0.658	0.833	8.109	***
Turkey	TUR	6980.295	3622.281	3.695	0.814	0.889	10.438	***
Turkmenistan	TKM	3117.179	2706.998	9.776	1.692	0.664	4.786	***
Tuvalu	TUV	2481.515	1242.141	0.859	0.148	−0.149	−0.814	

Note: (i) "***", "**", and "*" correspond to statistical significance at 1%, 5%, and 10% significance levels, respectively; (ii) "Std.Dev." corresponds to the standard deviation; (iii) "Corr." corresponds to the unconditional correlation between both variables.

Table 4. Summary and descriptive statistics for the panel of lower-middle-income (LM) countries.

Country	Code	GDP		CO_2 Emissions		Corr.	t-Statistic	
		Mean	Std.Dev.	Mean	Std.Dev.			
Algeria	DZA	3136.814	1432.914	3.061	0.542	0.817	7.616	***
Angola	AGO	1982.430	1586.901	0.888	0.169	0.226	1.251	
Bangladesh	BGD	774.193	588.449	0.281	0.154	0.944	15.452	***
Belize	BLZ	4962.751	929.042	1.742	0.228	−0.615	−4.201	***

Table 4. *Cont.*

Country	Code	GDP Mean	GDP Std.Dev.	CO_2 Emissions Mean	CO_2 Emissions Std.Dev.	Corr.	t-Statistic	
Benin	BEN	775.224	344.346	0.340	0.198	0.951	16.531	***
Bolivia	BOL	1679.277	990.356	1.359	0.328	0.842	8.390	***
Cabo Verde	CPV	2337.745	1192.087	0.803	0.227	0.868	9.416	***
Cameroon	CMR	1173.040	320.181	0.361	0.068	0.040	0.214	
Comoros	COM	1136.511	327.103	0.232	0.076	0.653	4.638	***
Congo, Rep.	COG	1838.393	998.058	1.135	0.148	−0.005	−0.026	
Cote d'Ivoire	CIV	1432.329	506.953	0.326	0.069	0.703	5.325	***
Djibouti	DJI	1321.574	779.032	0.486	0.055	−0.690	−5.132	***
Egypt, Arab Rep.	EGY	1814.874	960.204	1.934	0.350	0.812	7.494	***
El Salvador	SLV	2564.978	1034.958	0.983	0.200	0.776	6.625	***
Eswatini	SWZ	2666.611	1105.311	1.015	0.190	−0.702	−5.304	***
Ghana	GHA	990.185	732.772	0.340	0.138	0.930	13.615	***
Haiti	HTI	881.238	425.613	0.206	0.071	0.921	12.689	***
Honduras	HND	1522.123	590.852	0.867	0.212	0.765	6.400	***
India	IND	944.063	604.968	1.133	0.380	0.986	31.738	***
Indonesia	IDN	1990.622	1323.478	1.519	0.390	0.909	11.776	***
Kenya	KEN	860.717	562.280	0.290	0.061	0.927	13.351	***
Kiribati	KIR	1104.692	386.045	0.476	0.104	0.754	6.184	***
Kyrgyz Republic	KGZ	735.667	393.812	1.624	0.976	0.079	0.425	
Lao PDR	LAO	988.265	866.027	0.676	0.897	0.902	11.226	***
Lesotho	LSO	762.700	309.704	0.970	0.155	0.859	9.035	***
Mauritania	MRT	1223.134	459.310	0.547	0.153	0.830	7.999	***
Micronesia, Fed. Sts.	FSM	2445.629	614.171	1.292	0.421	0.018	0.099	
Mongolia	MNG	1946.519	1588.169	5.102	1.162	0.802	7.225	***
Morocco	MAR	2345.155	867.836	1.396	0.317	0.967	20.350	***
Myanmar	MMR	582.229	527.164	0.254	0.164	0.763	6.358	***
Nepal	NPL	490.987	347.138	0.183	0.143	0.933	13.921	***
Nicaragua	NIC	1261.086	549.009	0.715	0.125	0.737	5.873	***
Nigeria	NGA	1601.920	829.271	0.686	0.122	−0.695	−5.211	***
Pakistan	PAK	873.978	417.101	0.694	0.102	0.915	12.222	***
Papua New Guinea	PNG	1493.388	791.845	0.615	0.097	0.551	3.553	***
Philippines	PHL	1812.246	892.837	0.925	0.174	0.758	6.253	***
Samoa	WSM	2537.854	1294.011	0.898	0.199	0.892	10.602	***
Senegal	SEN	1059.197	308.972	0.491	0.134	0.825	7.849	***
Solomon Islands	SLB	1465.966	579.793	0.546	0.076	−0.146	−0.795	
Sri Lanka	LKA	1981.855	1442.738	0.635	0.252	0.889	10.473	***
Tajikistan	TJK	525.295	317.412	0.617	0.432	0.102	0.550	
Tanzania	TZA	564.769	319.562	0.137	0.058	0.961	18.803	***
Tunisia	TUN	2998.875	992.619	2.250	0.316	0.931	13.781	***
Ukraine	UKR	2115.424	1183.604	6.610	2.278	−0.396	−2.322	**
Uzbekistan	UZB	1175.693	790.401	4.412	0.726	−0.823	−7.798	***
Vanuatu	VUT	2063.623	716.584	0.451	0.079	0.483	2.968	***
Vietnam	VNM	1257.278	1157.203	1.322	0.959	0.973	22.813	***
Zambia	ZMB	900.692	521.524	0.261	0.084	0.226	1.252	
Zimbabwe	ZWE	876.170	442.966	1.024	0.357	−0.337	−1.930	*

Note: (i) "***", "**", and "*" correspond to statistical significance at 1%, 5%, and 10% significance levels, respectively; (ii) "Std.Dev." corresponds to the standard deviation; (iii) "Corr." corresponds to the unconditional correlation between both variables.

Table 5. Summary and descriptive statistics for the panel of low-income (L) countries.

Country	Code	GDP Mean	GDP Std.Dev.	CO_2 Emissions Mean	CO_2 Emissions Std.Dev.	Corr.	t-Statistic	
Burkina Faso	BFA	483.356	211.656	0.123	0.065	0.873	9.628	***
Burundi	BDI	189.134	46.069	0.036	0.010	0.376	2.182	**
Central African Republic	CAF	372.932	87.692	0.049	0.010	−0.574	−3.779	***
Chad	TCD	538.884	305.413	0.081	0.017	0.882	10.068	***

Table 5. *Cont.*

Country	Code	GDP		CO_2 Emissions		Corr.	t-Statistic	
		Mean	Std.Dev.	Mean	Std.Dev.			
Ethiopia	ETH	334.374	249.384	0.080	0.039	0.945	15.608	***
Gambia, The	GMB	620.288	122.167	0.209	0.030	0.417	2.469	**
Guinea	GIN	587.920	207.676	0.207	0.052	0.834	8.146	***
Guinea-Bissau	GNB	438.391	194.574	0.155	0.015	0.002	0.012	
Madagascar	MDG	386.385	99.034	0.099	0.020	0.576	3.793	***
Malawi	MWI	425.618	157.423	0.077	0.008	−0.477	−2.921	***
Mali	MLI	518.234	231.972	0.120	0.049	0.935	14.198	***
Niger	NER	380.385	132.584	0.071	0.019	0.813	7.528	***
Rwanda	RWA	446.082	227.983	0.079	0.015	0.615	4.204	***
Sierra Leone	SLE	340.939	170.745	0.098	0.033	0.894	10.773	***
Sudan	SDN	1122.105	782.028	0.351	0.133	0.741	5.942	***
Togo	TGO	548.882	234.301	0.273	0.064	0.326	1.854	*
Uganda	UGA	483.754	278.287	0.082	0.035	0.937	14.498	***
Yemen, Rep.	YEM	931.176	398.789	0.735	0.246	0.105	0.570	

Note: (i) "***", "**", and "*" correspond to statistical significance at 1%, 5%, and 10% significance levels, respectively; (ii) "Std.Dev." corresponds to the standard deviation; (iii) "Corr." corresponds to the unconditional correlation between both variables.

Table 6. Summary and descriptive statistics for the world regions.

World Region	Code	GDP		CO_2 Emissions		Corr.	t-Statistic	
		Mean	Std.Dev.	Mean	Std.Dev.			
Arab World	ARB	4409.764	1994.329	3.687	0.551	0.958	18.087	***
Caribbean small states	CSS	7079.385	2907.295	4.930	0.592	0.797	7.101	***
Central Europe and the Baltics	CEB	8716.471	5125.355	6.933	0.641	−0.677	−4.953	***
Early-demographic dividend	EAR	2145.871	997.383	1.758	0.324	0.983	29.132	***
East Asia and Pacific	EAS	6277.222	2971.174	4.279	1.426	0.965	19.857	***
East Asia and Pacific (excluding high income)	EAP	3102.089	2735.300	3.707	1.582	0.953	17.009	***
East Asia and Pacific (IDA and IBRD countries)	TEA	3137.219	2765.625	3.719	1.614	0.953	16.953	***
Euro area	EMU	30,041.323	8329.311	7.521	0.813	−0.701	−5.290	***
Europe and Central Asia	ECS	18,426.500	6185.380	7.558	0.741	−0.664	−4.787	***
Europe and Central Asia (excluding high income)	ECA	5074.851	3165.363	7.606	0.940	−0.156	−0.850	
Europe and Central Asia (IDA and IBRD countries)	TEC	5449.408	3331.387	7.473	0.857	−0.220	−1.213	
European Union	EUU	26,145.894	7939.703	7.460	0.770	−0.752	−6.151	***
Fragile and conflict-affected situations	FCS	1426.060	602.529	1.282	0.335	−0.645	−4.540	***
Heavily indebted poor countries (HIPC)	HPC	632.022	278.419	0.205	0.046	0.973	22.850	***
High income	HIC	32,361.412	8926.937	10.915	0.730	−0.660	−4.728	***
IBRD only	IBD	3222.182	2068.898	3.339	0.791	0.987	33.038	***
IDA and IBRD total	IBT	2652.901	1627.332	2.667	0.556	0.985	31.048	***
IDA blend	IDB	1183.662	567.481	0.897	0.067	−0.901	−11.179	***
IDA only	IDX	744.650	324.124	0.289	0.060	0.968	20.673	***
IDA total	IDA	890.843	399.954	0.491	0.025	0.747	6.049	***
Late-demographic dividend	LTE	4487.925	3304.814	4.735	1.390	0.982	27.865	***
Latin America and Caribbean	LCN	6267.761	2639.431	2.443	0.260	0.897	10.935	***
Latin America and Caribbean (excluding high income)	LAC	5966.245	2463.491	2.258	0.238	0.912	11.967	***
Latin America and the Caribbean (IDA and IBRD countries)	TLA	6169.196	2624.209	2.459	0.265	0.897	10.910	***
Least developed countries: UN classification	LDC	620.251	326.348	0.218	0.074	0.957	17.747	***
Low and middle income	LMY	2540.821	1573.965	2.599	0.568	0.985	30.271	***
Low income	LIC	649.790	214.273	0.394	0.094	−0.386	−2.252	**
Lower middle income	LMC	1210.648	676.003	1.283	0.222	0.980	26.532	***
Middle East and North Africa	MEA	5109.302	2336.851	4.648	0.749	0.956	17.448	***
Middle East and North Africa (excluding high income)	MNA	2817.581	1229.723	3.156	0.442	0.914	12.099	***
Middle East and North Africa (IDA and IBRD countries)	TMN	2825.307	1235.171	3.190	0.449	0.913	12.054	***
Middle income	MIC	2730.098	1733.156	2.807	0.654	0.986	31.420	***
North America	NAC	42,300.725	12,518.295	17.770	1.927	−0.837	−8.239	***
OECD members	OED	29,249.160	7759.829	9.912	0.773	−0.725	−5.669	***
Other small states	OSS	8366.543	4673.966	5.300	0.742	0.972	22.326	***
Pacific island small states	PSS	2619.201	952.894	1.020	0.112	0.505	3.152	***
Post-demographic dividend	PST	33,151.302	9035.017	11.068	0.906	−0.755	−6.203	***
Pre-demographic dividend	PRE	1009.993	490.465	0.474	0.040	0.065	0.353	
Small states	SST	7761.159	4095.455	4.950	0.666	0.968	20.902	***
South Asia	SAS	916.023	574.025	0.968	0.313	0.988	33.776	***
Sub-Saharan Africa	SSF	1177.861	470.510	0.768	0.029	−0.030	−0.162	
Sub-Saharan Africa (excluding high income)	SSA	1176.860	470.380	0.768	0.029	−0.032	−0.171	
Upper middle income	UMC	4323.453	2930.511	4.360	1.210	0.981	27.082	***
World	WLD	7700.699	2545.740	4.263	0.322	0.945	15.611	***

Notes: (i) "***" and "**", correspond to statistical significance at 1% and 5% significance levels, respectively; (ii) "Std.Dev." corresponds to the standard deviation; (iii) "Corr." corresponds to the unconditional correlation between both variables.

As was expected, high-income countries report higher mean GDP (and standard deviation) values and generally higher mean CO_2 emissions. However, it is curious to observe that the Principality of Monaco reports the highest mean GDP value but does not report one of the highest values of mean CO_2 emissions. Monaco's highest mean value of GDP per capita can be explained by its robust financial sector, luxury tourism, and the presence of wealthy residents. Unlike countries with high industrial output, Monaco's economy does not rely on heavy manufacturing or large-scale industrial activities that typically result in significant CO_2 emissions. Thus, despite its high economic wealth, Monaco has a low carbon footprint, which may reflect Monaco's implementation of stringent environmental regulations and sustainable practices. This combination of a service-oriented economy and proactive environmental policies could explain why Monaco enjoys a high GDP per capita without correspondingly high CO_2 emissions.

On the other hand, Qatar is the country that reports the highest mean value of CO_2 emissions, which can be explained by the extensive oil and gas industry, which is a major contributor to the country's economy. Despite the significant revenues from hydrocarbons, Qatar's wealth distribution, population size, and economic structure result in a lower GDP per capita compared to other countries with diversified and technologically advanced economies. Qatar's economic model, which is heavily reliant on fossil fuels, could explain its high CO_2 emissions but without a corresponding high GDP per capita.

The countries with the highest levels of CO_2 emissions are Bahrain, Kuwait, Qatar, and the United Arab Emirates, all of which are countries with large reserves of oil and natural gas (the exploitation of these natural resources being fundamental pillars of their economies) and economies that are heavily dependent on the production and export of hydrocarbons, which can explain their higher values of mean CO_2 emissions.

Considering the values of the estimated unconditional correlation (between the mean GDP per capita and the mean CO_2 emissions per capita), the relationship between GDP and CO_2 emissions per capita varies significantly between the different groups of countries, according to their stage of economic development. Except for the high-income countries, most of the correlations are positive and statistically significant, meaning that, on average, incomes have led to increased emissions over the 1990–2020 period; this is in line, for example, with the findings of Narayan et al. [13].

For the high-income countries, 24 unconditional correlations (of the 47 possible) are negative and statistically significant, which could mean these countries passed the inflection point of the EKC. These results seem to be not only in agreement with the EKC hypothesis but also with the energetic transition theory, which suggests that, as countries develop, they pass from traditional energy sources to renewable and clean energy sources.

From high-income countries to low-income countries (as the income levels decline), the percentage of positive and statistically significant correlations increases. This preliminary evidence seems to agree with the EKC hypothesis, i.e., countries of high-income levels seem to have reached a point where their economic growth is not strongly associated with an increase in CO_2 emissions.

The evidence found for the upper-middle and lower-middle-income countries (Tables 3 and 4) could be a sign that these countries are still in the ascending phase of the EKC, where economic growth results in higher levels of CO_2 emissions.

Concerning low-income countries (Table 5), although this category has the smallest number of countries, 77.78% of these countries display positive and statistically significant unconditional correlations, suggesting that even in the early stages of development, there exists a clear positive relationship between economic growth and CO_2 emissions.

Among world regions (Table 6), North America, post-demographic dividend regions (mostly high-income countries where fertility has transitioned below replacement levels), and high-income regions are the ones that report the highest level of mean GDP per capita and, simultaneously, the highest mean values of CO_2 emissions. The Euro area ranks similarly in terms of mean GDP per capita but shows lower mean CO_2 emissions compared to the broader OECD membership. This could mean that countries outside the Euro area are the major ones responsible for CO_2 emissions among the OECD members (as only 19 of the 38 OECD members are from the Euro area). This could also be a sign that the Euro area could have implemented more effective policies and technologies in terms of the reduction in CO_2 emissions than other members of the OECD. Thus, the Euro area could be viewed as an example of how high levels of development can coexist with lower levels of emissions through strict environmental policies. Regarding the OECD countries, our results do not seem to support the EKC hypothesis, which contradicts the findings of Galeotti et al. [88], who found evidence supporting the EKC. This discrepancy suggests that OECD countries may need to reassess their approach to environmental issues.

The relationship between GDP and CO_2 emissions per capita also varies between the different world regions, with most of the correlations being positive and statistically significant, meaning that, on average, incomes have led to increased emissions over the 1990–2020 period. The world, as a whole, displays a positive and statistically significant correlation between the analyzed variables, meaning that global economic growth and CO_2 emissions are still strongly associated, which could mean that the world as a whole is still at an early or intermediate stage on the EKC.

Globally, 40 out of the 158 countries (25.3%) and 11 of the 44 world regions (25%) display a negative and statistically significant unconditional correlation between GDP and CO_2 emissions per capita. This percentage is higher than the one found by Narayan et al. [13], which, considering the period 1960–2008, found 20 countries (of 181 analyzed) with this pattern. These results indicate that, as GDP per capita increases, CO_2 emissions decrease, reflecting a significant change in the traditional relationship between economic growth and CO_2 emissions, which could mean that economic growth is no longer necessarily associated with higher CO_2 emissions in many countries. At the same time, and considering the perspective of the EKC, this could mean that more countries have reached the inflection point or are in the process of reaching it. However, this transition is not yet universal, which is confirmed by the different results for the world regions.

4.2. Cross-Correlation Coefficient Analysis

The correlations obtained in the previous sub-section are static and do not allow us any insight into how these relationships will behave in the future. Thus, to obtain some insights in this respect and evaluate how GDP per capita is negatively or positively correlated with CO_2 emissions over the past (lags), and in the future (leads), the CCC proposed by Narayan et al. [13] was estimated, and the results are displayed in Tables 7–10 for countries (which are grouped according to the categories in Table 1) and in Table 11 for world regions. To ascertain whether a country's or region's relationship between per capita income and carbon emissions aligns with the EKC, this research follows interpretations presented by [13] based on lag/lead relationships.

Table 7. Cross-correlation coefficient results for the panel of high-income (H) countries.

Country	Code	Lags		Leads		(Aver. CCC Lags)/(Aver. CCC Leads)			
		Σ of CCC	Aver. CCC	Σ of CCC	Aver. CCC	(+)/(−)	(−)/(−)	(−)/(+)	(+)/(+)
Andorra	AND	−7.042	−0.352	3.093	0.155			X	
Antigua and Barbuda	ATG	1.640	0.082	3.098	0.155				X
Australia	AUS	−6.409	−0.320	6.783	0.339			X	
Austria	AUT	−7.123	−0.356	5.411	0.271			X	
Bahamas, The	BHS	1.416	0.071	−3.417	−0.171	X			
Bahrain	BHR	−5.458	−0.273	6.009	0.300			X	
Barbados	BRB	−2.998	−0.150	4.982	0.249			X	
Belgium	BEL	−4.467	−0.223	0.149	0.007			X	
Brunei Darussalam	BRN	1.482	0.074	1.873	0.094				X
Canada	CAN	−6.774	−0.339	6.410	0.320			X	
Chile	CHL	1.603	0.080	3.273	0.164				X
Czechia	CZE	−3.458	−0.173	−1.595	−0.080		X		

Table 7. *Cont.*

Country	Code	Lags		Leads		(Aver. CCC Lags)/(Aver. CCC Leads)			
		Σ of CCC	Aver. CCC	Σ of CCC	Aver. CCC	(+)/(−)	(−)/(−)	(−)/(+)	(+)/(+)
Denmark	DNK	−4.665	−0.233	0.072	0.004			X	
Finland	FIN	−6.599	−0.330	2.805	0.140			X	
France	FRA	−5.332	−0.267	0.943	0.047			X	
Germany	DEU	−2.401	−0.120	−2.587	−0.129		X		
Greece	GRC	−8.195	−0.410	4.505	0.225			X	
Hong Kong SAR, China	HKG	−1.112	−0.056	−3.821	−0.191		X		
Iceland	ISL	−5.115	−0.256	0.536	0.027			X	
Ireland	IRL	−5.985	−0.299	3.257	0.163			X	
Italy	ITA	−7.367	−0.368	3.658	0.183			X	
Japan	JPN	−6.023	−0.301	4.230	0.211			X	
Korea, Rep.	KOR	0.578	0.029	4.455	0.223				X
Kuwait	KWT	−4.113	−0.206	4.203	0.210			X	
Luxembourg	LUX	−3.479	−0.174	−1.592	−0.080		X		
Malta	MLT	−4.985	−0.249	0.753	0.038			X	
Monaco	MCO	2.582	0.129	−6.264	−0.313	X			
Netherlands	NLD	−6.040	−0.302	1.540	0.077			X	
New Zealand	NZL	−6.196	−0.310	6.340	0.317			X	
Norway	NOR	−6.793	−0.340	5.898	0.295			X	
Oman	OMN	1.103	0.055	2.717	0.136				X
Poland	POL	0.528	0.026	−5.257	−0.263	X			
Portugal	PRT	−6.901	−0.345	5.672	0.284			X	
Qatar	QAT	−6.852	−0.343	5.832	0.292			X	
Saudi Arabia	SAU	1.557	0.078	2.515	0.126				X
Seychelles	SYC	2.038	0.102	3.242	0.162				X
Singapore	SGP	−1.033	−0.052	−3.481	−0.174		X		
Slovak Republic	SVK	−1.767	−0.088	−3.144	−0.157		X		
Spain	ESP	−7.544	−0.377	5.409	0.270			X	
St. Kitts and Nevis	KNA	0.452	0.023	4.513	0.226				X
Sweden	SWE	−3.878	−0.194	−0.355	−0.018		X		
Switzerland	CHE	−3.793	−0.190	−0.711	−0.036		X		
Trinidad and Tobago	TTO	0.151	0.008	2.131	0.107				X
United Arab Emirates	ARE	−3.084	−0.154	−1.219	−0.061		X		
United Kingdom	GBR	−6.325	−0.316	1.431	0.072			X	
United States	USA	−4.803	−0.240	0.309	0.015			X	
Uruguay	URY	−1.334	−0.067	5.689	0.284			X	

Notes: (i) "CCC" corresponds to the cross-correlation coefficient estimated according to the method proposed by Narayan et al. [13]; (ii) "Aver." corresponds to the mean of the CCC. The (+) means the average CCC for the lags and leads is positive, while the (−) means the average CCC is negative.

Table 8. Cross-correlation coefficient results for the panel of upper-middle-income (UM) countries.

Country	Code	Lags		Leads		(Aver. CCC Lags)/(Aver. CCC Leads)			
		Σ of CCC	Aver. CCC	Σ of CCC	Aver. CCC	(+)/(−)	(−)/(−)	(−)/(+)	(+)/(+)
Albania	ALB	2.572	0.129	1.421	0.071				X
Argentina	ARG	−1.809	−0.090	5.497	0.275			X	
Armenia	ARM	3.980	0.199	−6.273	−0.314	X			
Azerbaijan	AZE	2.142	0.107	−5.760	−0.288	X			
Botswana	BWA	5.719	0.286	−1.355	−0.068	X			
Brazil	BRA	1.226	0.061	2.794	0.140				X
Bulgaria	BGR	−0.522	−0.026	−4.344	−0.217		X		
China	CHN	0.601	0.030	3.943	0.197				X
Colombia	COL	6.090	0.304	−5.558	−0.278	X			
Costa Rica	CRI	−1.143	−0.057	5.850	0.292			X	
Dominica	DMA	0.782	0.039	3.851	0.193				X
Dominican Republic	DOM	−0.984	−0.049	5.961	0.298			X	
Ecuador	ECU	−0.369	−0.018	4.789	0.239			X	
Equatorial Guinea	GNQ	−3.124	−0.156	3.915	0.196			X	

Table 8. *Cont.*

Country	Code	Lags		Leads		(Aver. CCC Lags)/(Aver. CCC Leads)			
		Σ of CCC	Aver. CCC	Σ of CCC	Aver. CCC	(+)/(−)	(−)/(−)	(−)/(+)	(+)/(+)
Fiji	FJI	1.171	0.059	4.052	0.203				X
Gabon	GAB	−3.635	−0.182	0.720	0.036			X	
Georgia	GEO	4.636	0.232	−7.120	−0.356	X			
Grenada	GRD	1.276	0.064	3.933	0.197				X
Guatemala	GTM	0.667	0.033	4.708	0.235				X
Guyana	GUY	2.944	0.147	1.842	0.092				X
Iraq	IRQ	5.283	0.264	−6.099	−0.305	X			
Jamaica	JAM	−6.906	−0.345	3.431	0.172			X	
Jordan	JOR	−6.571	−0.329	3.835	0.192			X	
Kazakhstan	KAZ	1.546	0.077	−2.976	−0.149	X			
Libya	LBY	−4.513	−0.226	6.170	0.309			X	
Malaysia	MYS	0.258	0.013	4.560	0.228				X
Maldives	MDV	1.493	0.075	3.479	0.174				X
Marshall Islands	MHL	−0.372	−0.019	5.549	0.277			X	
Mauritius	MUS	0.781	0.039	4.087	0.204				X
Mexico	MEX	−4.029	−0.201	4.495	0.225			X	
North Macedonia	MKD	−4.714	−0.236	1.115	0.056			X	
Panama	PAN	−0.258	−0.013	5.076	0.254			X	
Paraguay	PRY	3.121	0.156	1.264	0.063				X
Peru	PER	1.919	0.096	2.436	0.122				X
Romania	ROU	0.232	0.012	−5.237	−0.262	X			
Russian Federation	RUS	2.822	0.141	−6.041	−0.302	X			
South Africa	ZAF	−0.629	−0.031	3.504	0.175			X	
St. Lucia	LCA	0.297	0.015	4.700	0.235				X
St. Vincent and the Grenadines	VCT	0.318	0.016	4.420	0.221				X
Suriname	SUR	5.648	0.282	−6.308	−0.315	X			
Thailand	THA	−0.578	−0.029	5.583	0.279			X	
Turkey	TUR	3.570	0.179	0.906	0.045				X
Turkmenistan	TKM	−0.722	−0.036	3.844	0.192			X	
Tuvalu	TUV	−6.195	−0.310	5.766	0.288			X	

Notes: (i) "CCC" corresponds to the cross-correlation coefficient estimated according to the method proposed by Narayan et al. (2016); (ii) "Aver." corresponds to the mean of the CCC. The (+) means the average CCC for the lags and leads is positive, while the (−) means the average CCC is negative.

Table 9. Cross-correlation coefficient results for lower-middle-income (LM) countries.

Country	Code	Lags		Leads		(Aver. CCC Lags)/(Aver. CCC Leads)			
		Σ of CCC	Aver. CCC	Σ of CCC	Aver. CCC	(+)/(−)	(−)/(−)	(−)/(+)	(+)/(+)
Algeria	DZA	4.102	0.205	−0.346	−0.017	X			
Angola	AGO	−4.264	−0.213	5.273	0.264			X	
Bangladesh	BGD	0.686	0.034	3.729	0.186				X
Belize	BLZ	1.398	0.070	−4.353	−0.218	X			
Benin	BEN	2.272	0.114	2.525	0.126				X
Bolivia	BOL	3.386	0.169	−1.245	−0.062	X			
Cabo Verde	CPV	0.743	0.037	3.582	0.179				X
Cameroon	CMR	4.937	0.247	−7.669	−0.383	X			
Comoros	COM	2.943	0.147	1.325	0.066				X
Congo, Rep.	COG	4.618	0.231	−5.458	−0.273	X			
Cote d'Ivoire	CIV	1.507	0.075	3.856	0.193				X
Djibouti	DJI	−3.880	−0.194	2.471	0.124			X	
Egypt, Arab Rep.	EGY	−0.120	−0.006	4.455	0.223			X	
El Salvador	SLV	−1.105	−0.055	5.670	0.283			X	
Eswatini	SWZ	0.549	0.027	−3.841	−0.192	X			
Ghana	GHA	1.088	0.054	3.561	0.178				X
Haiti	HTI	2.643	0.132	2.221	0.111				X
Honduras	HND	−1.539	−0.077	6.070	0.303			X	
India	IND	1.776	0.089	2.878	0.144				X
Indonesia	IDN	0.794	0.040	4.129	0.206				X
Kenya	KEN	2.843	0.142	0.968	0.048				X

Table 9. *Cont.*

Country	Code	Lags		Leads		(Aver. CCC Lags)/(Aver. CCC Leads)			
		Σ of CCC	Aver. CCC	Σ of CCC	Aver. CCC	(+)/(−)	(−)/(−)	(−)/(+)	(+)/(+)
Kiribati	KIR	−0.374	−0.019	4.338	0.217			X	
Kyrgyz Republic	KGZ	3.337	0.167	−7.047	−0.352	X			
Lao PDR	LAO	3.118	0.156	0.419	0.021				X
Lesotho	LSO	0.641	0.032	3.001	0.150				X
Mauritania	MRT	2.926	0.146	0.907	0.045				X
Micronesia, Fed. Sts.	FSM	−2.482	−0.124	4.009	0.200			X	
Mongolia	MNG	3.658	0.183	−2.346	−0.117	X			
Morocco	MAR	2.354	0.118	2.396	0.120				X
Myanmar	MMR	3.740	0.187	0.539	0.027				X
Nepal	NPL	2.907	0.145	1.167	0.058				X
Nicaragua	NIC	−1.402	−0.070	5.709	0.285			X	
Nigeria	NGA	−1.219	−0.061	−2.816	−0.141		X		
Pakistan	PAK	1.766	0.088	3.367	0.168				X
Papua New Guinea	PNG	−1.266	−0.063	5.309	0.265			X	
Philippines	PHL	2.785	0.139	1.786	0.089				X
Samoa	WSM	1.870	0.094	3.248	0.162				X
Senegal	SEN	0.628	0.031	3.601	0.180				X
Solomon Islands	SLB	−5.705	−0.285	5.866	0.293			X	
Sri Lanka	LKA	1.283	0.064	3.779	0.189				X
Tajikistan	TJK	4.742	0.237	−7.472	−0.374	X			
Tanzania	TZA	2.741	0.137	2.177	0.109				X
Tunisia	TUN	2.682	0.134	1.322	0.066				X
Ukraine	UKR	−0.118	−0.006	−4.406	−0.220		X		
Uzbekistan	UZB	−1.843	−0.092	−2.292	−0.115		X		
Vanuatu	VUT	4.250	0.212	−0.697	−0.035	X			
Vietnam	VNM	2.030	0.102	2.504	0.125				X
Zambia	ZMB	7.000	0.350	−5.704	−0.285	X			
Zimbabwe	ZWE	2.766	0.138	−7.409	−0.370	X			

Notes: (i) "CCC" corresponds to the cross-correlation coefficient estimated according to the method proposed by Narayan et al. (2016); (ii) "Aver." corresponds to the mean of the CCC. The (+) means the average CCC for the lags and leads is positive, while the (−) means the average CCC is negative.

Table 10. Cross-correlation coefficient results for the panel of low-income (L) countries.

Country	Code	Lags		Leads		(Aver. CCC Lags)/(Aver. CCC Leads)			
		Σ of CCC	Aver. CCC	Σ of CCC	Aver. CCC	(+)/(−)	(−)/(−)	(−)/(+)	(+)/(+)
Burkina Faso	BFA	3.388	0.169	0.836	0.042				X
Burundi	BDI	4.111	0.206	−3.874	−0.194	X			
Central African Republic	CAF	2.653	0.133	−1.602	−0.080	X			
Chad	TCD	3.009	0.150	0.231	0.012				X
Ethiopia	ETH	0.550	0.027	3.212	0.161				X
Gambia, The	GMB	1.928	0.096	1.590	0.079				X
Guinea	GIN	0.931	0.047	3.144	0.157				X
Guinea-Bissau	GNB	5.180	0.259	−6.979	−0.349	X			
Madagascar	MDG	3.746	0.187	0.645	0.032				X
Malawi	MWI	3.356	0.168	−4.334	−0.217	X			
Mali	MLI	1.907	0.095	2.875	0.144				X
Niger	NER	1.254	0.063	1.030	0.051				X
Rwanda	RWA	3.432	0.172	0.806	0.040				X
Sierra Leone	SLE	3.057	0.153	1.047	0.052				X
Sudan	SDN	0.858	0.043	1.852	0.093				X
Togo	TGO	−3.624	−0.181	7.107	0.355			X	
Uganda	UGA	2.133	0.107	2.301	0.115				X
Yemen, Rep.	YEM	−3.368	−0.168	3.962	0.198			X	

Notes: (i) "CCC" corresponds to the cross-correlation coefficient estimated according to the method proposed by Narayan et al. (2016); (ii) "Aver." corresponds to the mean of the CCC. The (+) means the average CCC for the lags and leads is positive, while the (−) means the average CCC is negative.

Table 11. Cross-correlation coefficient results for the world regions.

World Region	Code	Lags		Leads		(Aver. CCC Lags)/(Aver. CCC Leads)			
		Σ of CCC	Aver. CCC	Σ of CCC	Aver. CCC	(+)/(−)	(−)/(−)	(−)/(+)	(+)/(+)
Arab World	ARB	1.4163	0.0708	2.7020	0.1351				X
Caribbean small states	CSS	−0.7673	−0.0384	3.3647	0.1682			X	
Central Europe and the Baltics	CEB	−0.7807	−0.0390	−4.2701	−0.2135		X		
Early-demographic dividend	EAR	1.7162	0.0858	2.9637	0.1482				X
East Asia and Pacific	EAS	0.9762	0.0488	3.6751	0.1838				X
East Asia and Pacific (excluding high income)	EAP	0.6940	0.0347	3.8910	0.1945				X
East Asia and Pacific (IDA and IBRD countries)	TEA	0.6817	0.0341	3.9099	0.1955				X
Euro area	EMU	−5.7828	−0.2891	1.4026	0.0701			X	
Europe and Central Asia	ECS	−2.8028	−0.1401	−2.1610	−0.1081		X		
Europe and Central Asia (excluding high income)	ECA	1.8913	0.0946	−5.7348	−0.2867	X			
Europe and Central Asia (IDA and IBRD countries)	TEC	1.7816	0.0891	−5.7382	−0.2869	X			
European Union	EUU	−5.1135	−0.2557	0.4929	0.0246			X	
Fragile and conflict-affected situations	FCS	−0.8084	−0.0404	−3.5588	−0.1779		X		
Heavily indebted poor countries (HIPC)	HPC	2.3229	0.1161	1.8006	0.0900				X
High income	HIC	−6.3282	−0.3164	2.5069	0.1253			X	
IBRD only	IBD	1.6665	0.0833	2.6546	0.1327				X
IDA and IBRD total	IBT	1.6870	0.0843	2.5757	0.1288				X
IDA blend	IDB	−0.8144	−0.0407	−3.8206	−0.1910		X		
IDA only	IDX	2.6625	0.1331	1.9562	0.0978				X
IDA total	IDA	4.0536	0.2027	0.1180	0.0059				X
Late-demographic dividend	LTE	1.4871	0.0744	2.8646	0.1432				X
Latin America and Caribbean	LCN	−0.4408	−0.0220	4.1896	0.2095			X	
Latin America and Caribbean (excluding high income)	LAC	−0.0048	−0.0002	3.9480	0.1974			X	
Latin America and the Caribbean (IDA and IBRD countries)	TLA	−0.4764	−0.0238	4.2045	0.2102			X	
Least developed countries: UN classification	LDC	1.9338	0.0967	2.6043	0.1302				X
Low and middle income	LMY	1.6198	0.0810	2.6587	0.1329				X
Low income	LIC	−3.5011	−0.1751	−0.2927	−0.0146		X		
Lower middle income	LMC	2.8035	0.1402	1.4232	0.0712				X
Middle East and North Africa	MEA	1.0904	0.0545	3.0532	0.1527				X
Middle East and North Africa (excluding high income)	MNA	1.1766	0.0588	2.4594	0.1230				X
Middle East and North Africa (IDA and IBRD countries)	TMN	1.2038	0.0602	2.4229	0.1211				X
Middle income	MIC	1.6087	0.0804	2.7081	0.1354				X
North America	NAC	−5.0336	−0.2517	0.6449	0.0322			X	
OECD members	OED	−6.0581	−0.3029	1.9011	0.0951			X	
Other small states	OSS	1.7261	0.0863	2.2628	0.1131				X

Table 11. *Cont.*

World Region	Code	Lags		Leads		(Aver. CCC Lags)/(Aver. CCC Leads)			
		Σ of CCC	Aver. CCC	Σ of CCC	Aver. CCC	(+)/(−)	(−)/(−)	(−)/(+)	(+)/(+)
Pacific island small states	PSS	−1.9978	−0.0999	6.6179	0.3309			X	
Post-demographic dividend	PST	−5.8276	−0.2914	1.5317	0.0766			X	
Pre-demographic dividend	PRE	5.8432	0.2922	−4.6393	−0.2320	X			
Small states	SST	1.4265	0.0713	2.5121	0.1256				X
South Asia	SAS	1.7308	0.0865	2.9572	0.1479				X
Sub-Saharan Africa	SSF	−6.5806	−0.3290	4.2205	0.2110			X	
Sub-Saharan Africa (excluding high income)	SSA	−6.5758	−0.3288	4.1991	0.2100			X	
Upper middle income	UMC	1.3743	0.0687	3.0030	0.1502				X
World	WLD	1.2405	0.0620	2.8374	0.1419				X

Notes: (i) "CCC" corresponds to the cross-correlation coefficient estimated according to the method proposed by Narayan et al. [13]; (ii) "Aver." corresponds to the mean of the CCC; (iii) "X" represents the world regions for which the relationship between the average of the CCC for the lags/leads displayed in the top of each column is verified. The (+) means the average CCC for the lags and leads is positive, while the (−) means the average CCC is negative.

The third and fifth columns of each table report the sum of the cross-correlation coefficients over the past 20 lags and the future 20 leads of CO_2 emissions, respectively. The fourth and sixth columns report the mean values of the same lags and leads, respectively. If past/future values of CO_2 emissions per capita, i.e., lags/leads, are positively/negatively correlated with the current values of GDP per capita, there is evidence of an inverted U-shaped relationship (identified with an "X" in the seventh column of Tables 7–11). This means that the CO_2 emissions increased with GDP in the past but will decline in the future, supporting the EKC hypothesis.

However, in addition to this scenario, another three can be observed:

(i) Negative cross-correlation between both past and future values of CO_2 emissions (lags and leads) and the current level of GDP per capita (identified with an "X" in the eighth column of Tables 7–11), meaning, in this case, increasing GDP per capita has led in the past, and could lead in the future, to a reduction in carbon emissions, which partially supports the EKC hypothesis;

(ii) Past/future values of CO_2 emissions per capita, i.e., lags/leads, could be negatively/positively correlated with the current values of GDP per capita, meaning that, although in the past an increase in the GDP level led to a reduction in CO_2 emissions per capita, in the future, it will not happen (identified with an "X" in the ninth column of Tables 7–11);

(iii) Positive cross-correlation between both past and future values of CO_2 emissions (lags and leads) and the current level of GDP per capita, meaning, in this case, increasing GDP per capita has led in the past, and will probably lead in the future, to an increase in carbon emissions (identified with an "X" in the tenth column of Tables 7–11).

To verify whether our results are consistent, we begin our analysis by verifying whether the sign of the sum of the CCC for the lags and leads and their averages are similar, i.e., whether they are both (sum and average) negative or positive. As displayed in Tables 7–11, they are. Thus, we can consider the values of the averages of the CCC in our analysis to be valid. Considering the results of the average CCC (that can soften outliers and provide a clearer view of the general pattern), displayed in Table 7, only 3 of the 47 countries categorized as high-income countries (namely, The Bahamas, Monaco, and Poland) show signs of an inverted U-shaped relationship between the current levels of GDP per capita and past and future values of CO_2 emissions. On the other hand, Czechia, Germany, Hong Kong, Luxembourg, Singapore, the Slovak Republic, Sweden, Switzerland, and the United Arab Emirates (a total of nine countries), reveal negative mean values of the CCC over the lags and leads, which may be a sign that, for these countries, the CO_2 decreased in the past and will continue to decrease in the future, with the increase in GDP per capita. These results corroborate the results of Narayan et al. [13] in the cases of Czechia, Luxembourg, the Slovak Republic, Sweden, and Switzerland.

For the majority of high-income countries (26 countries), we find a negative cross-correlation for the lags and a positive for the leads, which could mean that, although in the past an increase in GDP level led to a reduction in CO_2 emissions per capita, it will not happen in the future. The remaining countries of this panel (precisely, nine countries) display positive cross-correlation for the lags and leads, meaning that increasing GDP per capita has led in the past, and will probably lead in the future, to an increase in carbon emissions.

Considering the 44 upper-middle-income countries, the results suggest that 10 countries (namely, Armenia, Azerbaijan, Botswana, Colombia, Iraq, Kazakhstan, Romania, the Russian Federation, and Suriname) agree with the EKC hypothesis; although, Bulgaria is only in partial agreement. For the remaining countries in this panel, 17 reveal negative/positive cross-correlations for the lags/leads and 16 positive cross-correlations for the lags and leads.

For the lower middle-income countries, twelve (namely, Algeria, Belize, Bolivia, Cameron, the Congo Republic, Eswatini, the Kyrgyz Republic, Mongolia, Tanzania, Vanuatu, Zambia, and Zimbabwe) show evidence of an inverted U-shaped relationship, and three (Nigeria, Ukraine, and Uzbekistan) are only in partial agreement with the EKC hypothesis, displaying negative average CCC for the leads. For the remaining countries (34), the results do not provide any support for the EKC hypothesis.

For the panel of 18 lower-income countries, 4 (namely, Burundi, the Central African Republic, Guinea-Bissau, and Malawi) show an inverted U-shaped relationship. For the remaining 14 countries, 2 (Togo and the Yemen Republic) reveal negative/positive cross-correlations for the lags/leads and 12 positive cross-correlations for the lags/leads.

If we compare our results with those of Shahbaz et al. [68], who explored, using the same approach, the nexus between globalization and energy demand for 86 high-, middle-, and low-income countries over the period 1970–2015, we can highlight that (i) some countries have changed, in relation to the income level criteria, their category/classification; (ii) several countries of different income levels (but mostly from high-income levels) have maintained or improved the relationship between the mean GDP per capita and the mean CO_2 emissions for the lags but have displayed a similar pattern for the leads. However, there are four countries, namely Denmark, the United States, Gabon, and the Philippines, which, although revealing a similar pattern for the lags, display a positive (sum and average) CCC for the leads (while, in the study of Shahbaz et al. [68], they displayed a negative CCC (sum and average) for the lags and leads), indicating an undesirable inversion on their pathway to sustainable development; (iii) on the other hand, Botswana, Algeria, Bolivia, and the Congo Republic, although revealing a similar pattern for the lags, display a negative (sum and average) CCC for the leads (while, in the study of Shahbaz et al. [68], they displayed a positive CCC (sum and average)), also indicating an inversion on their pathway to sustainable development. However, for these countries, it is a desirable one, since a reduction in CO_2 emissions is expected with increasing GDP; (iv) for Albania, Ghana, and Sudan, increasing GDP has led in the past, and will lead in the future, to rising CO_2 emissions, entirely contradicting the findings of Shahbaz et al. [68]; (v) on the other hand, for Sweden and Nigeria, increasing GDP has led in the past, and will lead in the future, to decreasing CO_2 emissions, also entirely contradicting the findings of Shahbaz et al. [68].

Considering the results of the average CCC displayed in Table 11, for the 44 regions, only 3 (namely, Europe, and Central Asia (excluding high income), Europe and Central Asia (IDA and IBRD countries), and pre-demographic dividend) show signs of an inverted U-shaped relationship between the current levels of GDP per capita and past and future values of CO_2 emissions. This evidence suggests that these regions are managing to balance economic growth with effective environmental policies.

On the other hand, Central Europe and the Baltics, Europe and Central Asia, fragile and conflict-affected situations, IDA blends, and low-income regions, reveal negative mean values of the CCC over the lags and leads, not fully supporting the EKC hypothesis. For fragile and low-income regions, it may be a positive sign that economic growth is not being achieved at the expense of increasing carbon emissions, but these results may also reflect the economic challenges that limit growth.

For 13 regions, the results reveal negative cross-correlation for the lags and positive ones for the leads, which could mean that, although in the past an increase in GDP level has led to a reduction in CO_2 emissions per capita, in the future, this will not happen. These results may indicate that these regions may face the risk of reversing the environmental gains they have achieved in the past, which may be due to a possible lack of continuity in environmental policies or new economic challenges. Thus, for these regions, there is an urgent need to implement or reinforce environmental policies that ensure that future economic growth does not increase CO_2 emissions. The new economic challenges can include a range of factors. Economic downturns or recessions, for example, may result in decreased investments in green technologies and infrastructure, impeding efforts to address environmental issues.

Furthermore, shifts in global trade patterns and increased reliance on nonrenewable resources due to economic pressures can worsen environmental degradation. Conversely, sustainable economic growth driven by investments in renewable energy, circular economies, and green innovations can play a crucial role in preserving and enhancing environmental outcomes. The response of countries to these challenges largely depends on the strength of their environmental policies, the availability of financial resources, and the extent to which their economies are intertwined with global markets that prioritize sustainability.

Finally, the majority of regions (23) display positive cross-correlation for the lags and leads, meaning that increasing GDP per capita has led in the past, and probably will lead in the future, to an increase in carbon emissions. In these regions, the growth of per capita GDP has historically led, and will probably continue to lead, to a rise in CO_2 emissions, which may indicate that these economies are at an early stage of the EKC. It is, therefore, essential that these regions adopt strict environmental policies and promote clean technologies to reverse this trend.

Table 12 summarizes all the above results for a brief and easier analysis. The first column ((+)/(−)) identifies the number and percentage of countries and regions that, considering the average CCC for the 20 lags and 20 leads, reveal a pattern in agreement with the EKC hypothesis. The second column identifies the number and percentage of countries and regions that reveal a pattern in partial agreement with the EKC hypothesis. The last two columns show the number and percentage of countries and regions for which it is expected that, in the future, there will be an increase in CO_2 emissions with GDP per capita. It is interesting to note that high-income countries are the ones that are in least agreement with the EKC hypothesis. It was expected that these countries, being economically well-established and having the necessary infrastructure and resources to maintain and promote a cleaner environment, would be in greater agreement with the EKC hypothesis, but this is not verified.

Table 12. Summary of the average CCC of the lags and leads for each panel of countries and world regions.

	(Average CCC Lags)/(Average CCC Leads)				**Total**
	(+)/(−)	**(−)/(−)**	**(−)/(+)**	**(+)/(+)**	
Panel A: High-income (H) countries					
Number of countries	3	9	26	9	47
Percentage of countries	6.38%	19.15%	55.32%	19.15%	100%
Panel B: Upper middle-income (UM) countries					
Number of countries	10	1	17	16	44
Percentage of countries	22.73%	2.27%	38.64%	36.36%	100%
Panel C: Lower middle-income (LM) countries					
Number of countries	12	3	10	24	49
Percentage of countries	24.49%	6.12%	20.41%	48.98%	100%
Panel D: Lower-income (L) countries					
Number of countries	4	0	2	12	18
Percentage of countries	22.22%	0.00%	11.11%	66.67%	100%
World regions					
Number of regions	3	5	13	23	44
Percentage of regions	6.82%	11.36%	29.55%	52.27%	100%

Note: The (+) means the average CCC for the lags and leads is positive, while the (−) means the average CCC is negative.

Generally, the results suggest that 18.35% of the countries (29 out of 158) and 6.82% of the world regions (3 out of 44) support the EKC hypothesis. Comparing our results with the ones of Narayan et al. [13], which found 12% with clear evidence supporting the EKC hypothesis, the percentage of countries in agreement with this hypothesis has increased. Considering the countries/regions that are in partial agreement, i.e., the ones in which it is expected that an increase in the GDP will be accompanied by a reduction in CO_2 emissions in the future, our results reveal that only 8.23% of countries, and 11.36% of world regions, seem to be aligned with this pattern. If we compare this result with the one of Narayan et al. [13], which found that 27% of the countries partially agree with the EKC hypothesis, our results are not very encouraging regarding CO_2 reductions in the future. According to our results, it is expected that 73.42% of countries and 81.82% of world regions will see an increase in CO_2 emissions with an increase in GDP.

For a more accurate analysis of which countries and regions agree with the EKC hypothesis using the CCC proposed by Narayan et al. [13], it is crucial to consider both the average values of the lags and leads as well as the detailed graphical representation of these coefficients over the 20 lags and 20 leads. Although the average values of the lags and leads provide a simplified and aggregated view of the relationship between GDP and CO_2 emissions, we must not forget some possible limitations related to this analysis. Using averages can mask significant variations and trends within the individual lag and lead periods. Furthermore, a graphical presentation of the CCC for each of the 20 lags and leads allows for a more nuanced and detailed analysis. The graphs will enable us to highlight the specific periods where the relationship changes, providing relevant information about the temporal dynamics that the average values cannot capture. For instance, a graph might show that the correlation is positive for the initial few lags/leads but starts to decline and eventually turns negative as we approach the 20th lag/lead. This transition is critical in understanding how economic activities can influence environmental outcomes over time and supports a more robust interpretation of whether a country/region agrees with the EKC hypothesis. Moreover, graphical analysis can help us identify any anomalies or outliers that could significantly affect the average values. Visualizing the CCC over time can also illustrate the consistency or volatility of the relationship between the analyzed variables, providing context essential for interpreting the results accurately. This dual approach ensures that we capture the full complexity of the relationship between the analyzed variables, allowing more accurate conclusions about agreement of countries/regions with the EKC hypothesis. For these reasons, Figure 1 displays the plots for the countries/regions whose behavior seems to agree with the EKC hypothesis (with reference to the positive sign (+) for the average CCC for the lags, and the negative (-) one for the average CCC for the leads), and Figure 2 displays the graphs for the countries/regions that seem to be in partial agreement with the EKC hypothesis, i.e., the ones that display negative sign ($-$) for the average CCC for the leads. We plotted the graphs for the 20 lags and leads for all the countries and regions (a total of 202 graphs). However, due to space constraints, it is not possible to present all of them here, but they are all available upon request.

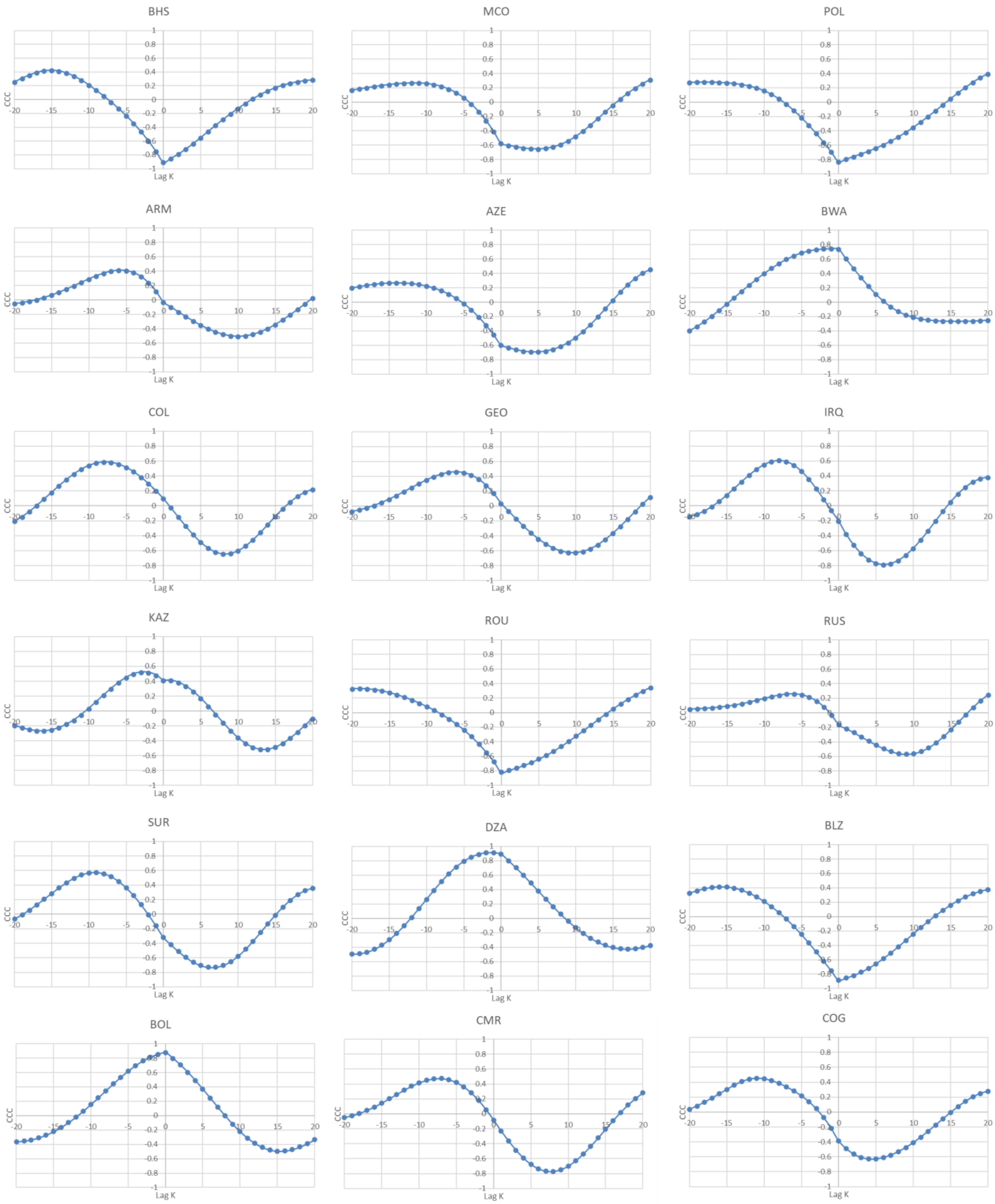

Figure 1. *Cont.*

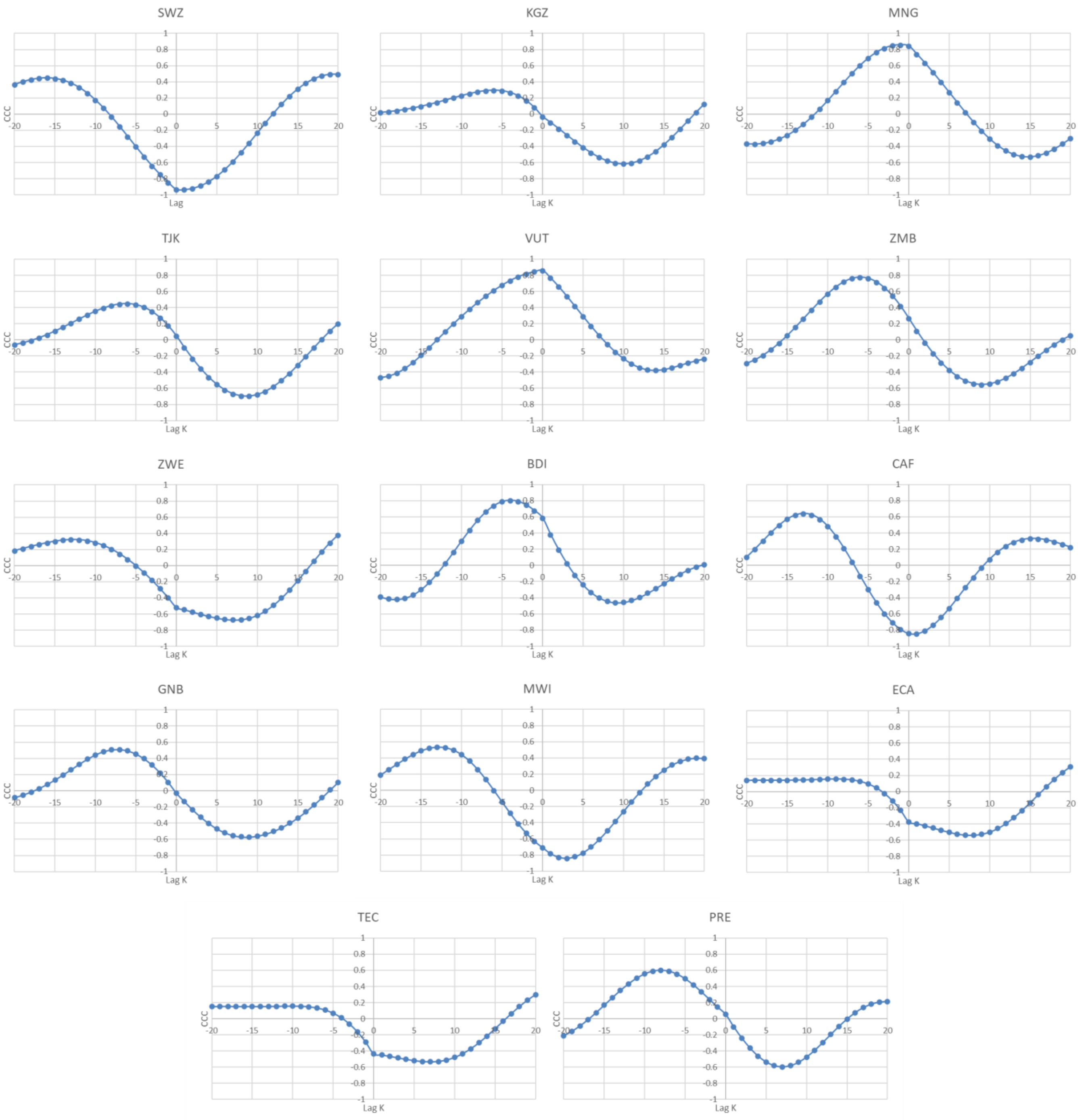

Figure 1. Plots of the cross-correlation coefficient (CCC) for countries/regions in agreement with the EKC hypothesis. Note: (i) the figure displays the plots for the countries/regions whose behavior seems to agree with the EKC hypothesis, with reference to the positive sign (+) for the average CCC for the lags and the negative (−) one for the average CCC for the leads; (ii) *k* negative/positive values correspond, respectively, to the lags (past)/leads(future).

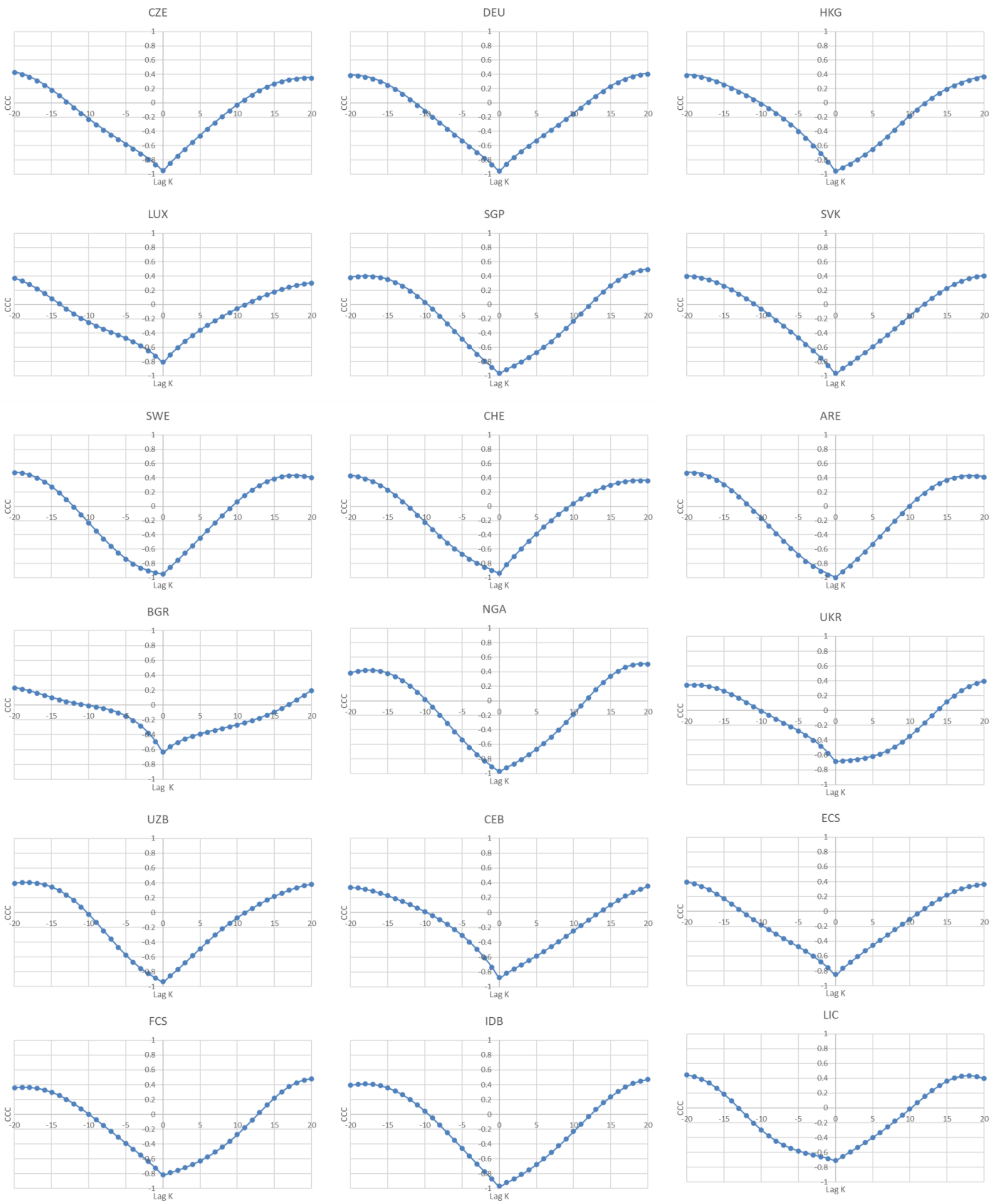

Figure 2. Plots of the cross-correlation coefficient (CCC) for countries/regions in partial agreement with the EKC hypothesis. Note: (i) *k* negative/positive values correspond, respectively, to the lags (past)/leads(future); (ii) for countries/regions in partial agreement with the EKC hypothesis, the ones that display negative sign (−) for the average CCC for the leads are those where an increase in income will reduce (expectantly) CO_2 emissions in the future.

5. Conclusions, Policy Recommendations, and Future Research Directions

Due to concerns about global climate change, the number of studies related to CO_2 emissions has increased in recent decades. Although most studies empirically identify a relationship between economic growth and environmental negative indicators in the context of the EKC, the results do not always agree, highlighting the need for deeper analysis.

This study looked at GDP and CO_2 emissions per capita from 1990 to 2020 in 158 countries and 44 world regions, grouping countries by income levels. Consistent with the EKC hypothesis, lower-income and lower-middle-income countries showed a positive correlation between economic growth and CO_2 emissions, indicating that, as per capita GDP increases, carbon emissions tend to rise. This pattern reflects the early stages of the EKC, where economic development is typically accompanied by environmental degradation. In contrast, high-income countries generally displayed either a negative or mixed cross-correlation, suggesting that these nations have either surpassed the inflection point of the EKC, where further economic growth leads to reduced CO_2 emissions, or are in a transitional phase. The mixed results across income levels suggest that there is no one-size-fits-all policy approach to tackling CO_2 emissions. Policymakers must consider the specific economic contexts of each country when designing interventions to mitigate climate change. Decoupling economic growth from emissions in lower-income countries, where emissions continue to rise with GDP, is particularly urgent to ensure sustainable development.

For high-income countries, while some showed a negative cross-correlation consistent with the EKC hypothesis, a significant portion exhibited a mixed pattern—negative correlations for past CO_2 emissions and positive for future projections. This finding implies that, while these countries have historically decoupled rising income levels from CO_2 emissions, future growth may not continue this trend without reinforced environmental policies and greater investment in green technologies. Upper-middle-income countries, which often find themselves at a critical juncture in the EKC, may similarly require significant efforts to ensure that economic growth does not lead to further environmental degradation. To address this, policymakers in upper-middle- and high-income countries should focus on advancing sustainable practices, including renewable energy adoption and energy efficiency improvements, to sustain the decoupling of economic growth from carbon emissions.

Regarding world regions, it is possible to conclude that there are significant variations in the agreement with the EKC hypothesis. Regions such as Europe and Central Asia (excluding high income countries), Europe and Central Asia (IDA and IBRD countries), and pre-demographic dividend, i.e., 6.82% of the analyzed regions, reveal a pattern that is aligned with the EKC hypothesis, suggesting that these regions have reached the turning point of the EKC, where economic growth starts contributing to environmental improvement. Of the world regions, 11.36% are in partial agreement with the EKC hypothesis, suggesting they are on a sustainable development path, where economic growth is decoupled from carbon emissions. For 29.55% of world regions, CO_2 levels have decreased with GDP growth in the past but are projected to increase with future GDP growth, meaning emerging challenges exist. This shift implies potential backsliding in environmental gains and indicates the need for stronger policy interventions to obtain decoupling. For the majority of world regions, 52.27%, both past and future GDP growth are accompanied by increases in CO_2 emissions, meaning there remains a situation where economic growth is highly carbon-intensive. This reveals significant challenges in transitioning towards sustainable growth and underscores the need for urgent and robust environmental policies.

In the literature, there are contradictory results regarding the EKC. The different findings depend on many criteria (e.g., the pollutants considered, the dataset, the selection of variables, and the choice of methodology). In this regard, our analyses should be perceived as empirical, and they do not disprove the validity of the EKC. Although our results support the EKC hypothesis for some countries (in the different panels) and regions, this could also be considered problematic, i.e., the EKC hypothesis posits that economic growth could be a way to reduce environmental degradation, which could mean that the exploration of natural resources for the sake of economic growth may be acceptable until reaching the turning point of the curve. This means that the irreversibility of ecological damage, and the ecosystem's capacity for resilience, are apparently overlooked. Thus, actions to slow down the release of CO_2 emissions should not wait until reaching high income, i.e., independently from the income level, global, regional, and local policies are needed now to combat climate change, or at least to adapt to climate change.

Based on our research, we propose that investments be directed towards advancing energy efficiency and renewable energy in countries that do not align with the EKC hypothesis. Additionally, we advise policymakers to enhance environmental regulations, particularly for industries that are energy-intensive and contribute to pollution. These measures can, thereby, stimulate economic growth and lead to a critical juncture where the correlation between GDP and CO_2 emissions shifts to a negative trajectory. A global, coordinated effort is crucial to mitigate future emissions and to ensure that all countries and regions contribute equitably to achieving carbon neutrality. This effort must be supported by international collaboration, with developed nations leading in financing the transition in developing regions through climate funds and technology transfers.

Furthermore, to operationalize the findings of this study, we also suggest some other policy recommendations:

(i) Governments should implement carbon pricing strategies that are progressively scaled based on the GDP per capita of the regions. (For example, Sweden implemented a carbon tax in 1991, which has been widely recognized as one of the most effective tools for reducing CO_2 emissions, while allowing the economy to grow. This policy sets a clear price on carbon emissions, incentivizing businesses and individuals to adopt greener practices [89]). This ensures that higher-income areas, which typically have higher emissions, bear a proportionate cost, incentivizing both corporations and individuals to reduce their carbon footprint;
(ii) Policies should prioritize significant investments in renewable energy infrastructure, especially in regions with rising GDP per capita. This could include subsidies for renewable energy projects, tax incentives for businesses adopting green technologies, and public–private partnerships to accelerate the deployment of solar, wind, and other clean energy sources;
(iii) To introduce or tighten energy efficiency standards across sectors, particularly in industries and buildings. This could be complemented by government-sponsored programs that offer financial support for retrofitting existing structures to meet these standards, thereby reducing overall energy consumption;
(iv) To ensure the long-term success of these policies, there should be an emphasis on public awareness and education regarding the importance of sustainable practices.

Considering our findings, we also propose several specific strategies tailored to different regional contexts:

(i) For high-income countries, where technological advancements and financial resources are more accessible, we recommend the implementation of strict carbon pricing mechanisms and the promotion of green technologies through subsidies and tax incentives. These measures should be complemented by robust monitoring systems to ensure compliance and continuous improvement. For high-income countries that have decoupled economic growth from CO_2 emissions, policymakers should focus on maintaining this trend by incentivizing further technological innovation, promoting renewable energy sources, and strengthening international climate agreements to support carbon neutrality goals;
(ii) For middle-income countries, a phased approach to adopting cleaner technologies is advised. Initially, investments should focus on improving energy efficiency in key sectors, such as manufacturing and transportation. International cooperation (mechanisms such as the Green Climate Fund (GCF) and the Clean Development Mechanism (CDM) provide financial assistance and promote technology transfer, allowing developing countries to access cleaner technologies and to finance renewable

energy projects) and financial support will be crucial in facilitating this transition, particularly through technology transfer and capacity-building initiatives;

(iii) In low-income countries, policy efforts should prioritize sustainable development that aligns with poverty alleviation goals.

In low- and middle-income countries, where the positive correlation between GDP growth and emissions remains strong, targeted policies should aim at facilitating the transition to green technologies without stifling economic development. Governments in these regions could benefit from implementing carbon pricing mechanisms, offering subsidies for clean energy investments, and promoting industrial modernization that aligns with environmental sustainability. Moreover, policies should focus on strengthening institutions to effectively manage environmental programs and ensure that growth is not achieved at the expense of environmental degradation. The diverse trajectories observed across regions imply that a one-size-fits-all approach to climate policy is unlikely to succeed. Policymakers must, therefore, prioritize flexible frameworks that allow for the adaptation of climate mitigation strategies based on local economic conditions, available resources, and technological capacities. The alignment of national policies with global targets, such as the Paris Agreement's carbon neutrality goals, will require coordinated efforts that account for each country's varying capabilities and development stages. Ultimately, fostering international collaboration in both financial and technological exchanges will be crucial to ensuring equitable progress toward a sustainable future.

These targeted recommendations are tailored to specific income groups and regions to address their unique environmental challenges. For high-income countries, stricter carbon pricing and investments in green technologies are essential to sustaining the decoupling of economic growth from emissions. Middle-income countries should focus on advancing renewable energy and improving energy efficiency, while low-income countries require support for sustainable development initiatives that align with poverty alleviation. These region-specific strategies are critical to ensuring that each country can meet its economic and environmental goals. By considering the unique economic and social contexts of each region, we believe these strategies will enhance the feasibility and effectiveness of policy implementation, thereby contributing to more sustainable outcomes globally.

Our findings in this paper are not without limitations. While our study primarily focuses on describing the dynamic relationship between GDP per capita and CO_2 emissions through the lens of the EKC, we recognize the importance of exploring the underlying drivers of this inverted U-shaped relationship. Several potential factors could influence this dynamic, such as technological advancements, shifts in energy consumption, regulatory frameworks, and changes in public awareness regarding environmental issues. For instance, in high-income countries, the decoupling of economic growth from emissions may be driven by stronger environmental regulations, higher adoption of clean technologies, and a greater societal focus on sustainability. Conversely, in lower-income countries, reliance on fossil fuels and limited regulatory enforcement may explain the positive correlation between economic growth and emissions. Future research should delve deeper into these drivers to provide a more comprehensive understanding of what propels countries to transition through the different stages of the EKC. Investigating how factors such as green innovation, renewable energy adoption, and government policies interact with economic development can offer more practical guidance for policymakers aiming to reduce CO_2 emissions. By identifying the key drivers behind these patterns, future studies can also contribute to more tailored and effective strategies for addressing the environmental impacts of economic growth.

Furthermore, although "carbon emissions" have great significance in theory and practice, they may not fully capture environmental degradation or environmental sustainability as a whole. The selection of CO_2 emissions as the primary environmental indicator, while reliable, does introduce a limitation in that it does not capture the full spectrum of environmental impacts, such as air quality or biodiversity loss. However, given the focus on climate change and carbon neutrality targets, CO_2 emissions remain a crucial and relevant metric for assessing the sustainability of economic growth.

The third limitation is related to obtaining data for analysis. In this regard, the series for analyzing all countries and variables was only available up to 2020.

Future research may explore other response variables, such as ecological footprints, air pollution, and negative-environmental-sustainability-related indicators. It should also explore positive-environmental-sustainability-related indicators to reinvestigate with macroeconomic indicators other than economic growth to test our findings' reliability and resilience, which will enhance generalizability.

Fourth, our analysis is conducted at the national level, which provides a broad overview of the relationship between GDP per capita and CO_2 emissions across a wide range of countries and regions. However, it is important to acknowledge (i) the potential heterogeneity among different types of economies; (ii) the fact that, while this approach offers valuable insights into global and regional patterns, it may not fully capture intracountry variations, such as differences in emissions between urban and rural areas or between different industrial sectors. These internal disparities could be significant, especially in large and economically diverse countries. Despite this limitation, the significance of our study lies in its ability to reveal macroeconomic trends crucial for informing national and international climate policies. By identifying overarching patterns in the income–CO_2 emissions relationship, our research provides a foundation for more targeted studies at subnational or sectoral levels. Future research could complement our findings by exploring intracountry differences, allowing for a more granular understanding of the drivers behind carbon emissions within countries.

Future research could benefit from a split-sample analysis that distinguishes between resource-dependent, manufacturing-led, and service-led economies. Such an approach would allow for a more nuanced understanding of the EKC hypothesis and how different economic structures influence the relationship between economic growth and environmental outcomes. This could provide valuable insights into tailoring environmental policies to the specific needs and challenges of different types of economies.

Another potential avenue for future research involves exploring alternative country classifications, such as categorizing nations into developed, emerging, and developing economies. While our study employs a widely accepted GDP per capita classification to analyze the EKC, further studies could examine whether using these broader developmental categories yields different insights. Evaluating how varying definitions of economic development influence the relationship between economic growth and environmental outcomes may offer additional perspectives, especially in terms of policy implications for sustainable development.

Lastly, the CCC results show association or correlation, but not causation. To address this, future research should explore the causal relationship between economic growth and environmental sustainability or degradation indicators. Using panel Granger causality can contribute to this line of research and enhance the generalizability of our findings.

Author Contributions: Conceptualization, L.C., D.A., A.D., P.F. and I.U.H.; methodology, L.C., D.A., A.D., P.F. and I.U.H.; validation, L.C., D.A., A.D., P.F. and I.U.H.; formal analysis, L.C., D.A., A.D., P.F. and I.U.H.; data curation, L.C., D.A., A.D., P.F. and I.U.H.; writing—original draft preparation, L.C., D.A., A.D., P.F. and I.U.H.; writing—review and editing, L.C., D.A., A.D., P.F. and I.U.H. All authors have read and agreed to the published version of the manuscript.

Funding: Luísa Carvalho acknowledges financial support from Fundação para a Ciência e a Tecnologia (grant UIDB/04312/2020). Dora Almeida, Andreia Dionísio, and Paulo Ferreira are pleased to acknowledge financial support from Fundação para a Ciência e a Tecnologia (grant UIDB/04007/2020). Dora Almeida and Paulo Ferreira also acknowledge financial support from Fundação para a Ciência e a Tecnologia (grant UIDB/05064/2020).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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