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Nuclear Energy and Financial Development for a Clean Environment: Examining the N-Shaped Environmental Kuznets Curve Hypothesis in Top Nuclear Energy-Consuming Countries

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Abstract: This research aims to reassess the impact of nuclear energy consumption and financial development on environmental quality using annual data from 1993 to 2019 for 11 countries with the highest nuclear energy consumption. Additionally, the study seeks to test the validity of the N-shaped EKC hypothesis. The findings of this study indicate a long-term cointegration relationship between the variables. According to the PCSE model results, increased nuclear energy consumption among the top 11 countries leads to decreased carbon emissions. Furthermore, the study reveals an N-shaped relationship between economic growth and environmental degradation. There is a strong recommendation for enhancing investments and grants directed towards research and development endeavours to identify and implement innovative solutions to reduce carbon emissions and improve environmental quality, particularly in less technologically advanced countries. Such efforts could include allocating more substantial funding to new technologies and encouraging collaborations between academic institutions and industry. Furthermore, considering regulatory adjustments like the liberalization of the energy market with the pro-ecological initiatives mainly carried out by public utilities is crucial as part of a comprehensive strategy to address environmental challenges.

Keywords: nuclear energy; financial development; carbon dioxide emissions; N-shaped environmental Kuznets curve; top nuclear energy-consuming countries

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1. Introduction

The increasing global concern for environmental degradation has led researchers to investigate the potential impact of nuclear energy as a viable solution for reducing carbon emissions and promoting sustainable development. While adopting nuclear energy has been hailed as a way to meet growing energy demands and mitigate the negative effects of fossil fuels, its impact on environmental degradation remains a subject of debate. Several studies have explored the complex relationships between nuclear energy, carbon dioxide (CO_2) emissions, economic growth, and other factors, presenting a multifaceted picture of the effects of nuclear energy on the environment [1–6]. Consequently, policymakers and stakeholders must comprehensively comprehend the diverse elements at work in varying situations to formulate successful energy and environmental strategies.

This study aims to re-evaluate the role of nuclear energy consumption on environmental quality by examining the impact of both nuclear energy consumption and financial development on environmental quality. Additionally, the study seeks to test the validity of the N-shaped Environmental Kuznets Curve (EKC) hypothesis in order to better understand the role of economic growth on environmental quality at different stages. To achieve these objectives, this research utilizes annual data from 1993 to 2019 for 11 countries with the highest nuclear energy consumption, including the United States, China, France, Russia, South Korea, Canada, Ukraine, Germany, Japan, Spain, and Sweden.

This research aims to contribute to the current knowledge surrounding the connections between nuclear energy, financial growth, and environmental quality. Firstly, it extends the current body of research on the EKC hypothesis by focusing on the lesser-explored N-shaped EKC hypothesis in the context of nuclear energy. In doing so, this study examines the direction of nuclear power generation and its impact on the environment, especially for the countries with the highest nuclear energy consumption, which account for around 80% of the world's nuclear energy consumption. This approach is expected to yield more precise and more realistic results on the effects of nuclear energy on environmental quality. Secondly, by testing the N-shaped EKC hypothesis, the study aims to provide insights into the relationship between gross domestic product (GDP) and environmental degradation at different income levels. Lastly, the findings of this research have the potential to contribute to policy development aimed at reducing CO_2 emissions and enhancing environmental quality in line with the sustainable development goals. This study can provide valuable information for policymakers to develop more accurate and realistic strategies to address environmental concerns by identifying factors such as GDP, financial development, and nuclear energy consumption which affect carbon emissions.

This paper is organized into five main sections to comprehensively analyse the relationship between nuclear energy, financial development, and environmental quality in the N-shaped EKC hypothesis. First, the introduction sets the stage by highlighting the importance of understanding the complex effects of nuclear energy on environmental degradation and the motivation behind this study. Next, the literature review synthesises existing research on nuclear energy and its environmental impact, emphasizing the need for further investigation. The Section 3, Materials and Methods, outlines this study's data sources, variables, and statistical techniques to examine the N-shaped EKC hypothesis. In the Section 4, Results and Discussion, the analysis findings are presented and discussed, focusing on the implications of the results for the relationship between nuclear energy, financial development, and environmental quality. Finally, the paper concludes with a summary of the main findings.

2. Literature Review

Various studies have investigated the relationships between nuclear energy, CO_2 emissions, economic growth, and other factors to determine nuclear power's potential benefits and drawbacks in addressing environmental concerns. Nuclear energy has been found to have different impacts on environmental degradation in countries that produce nuclear energy. Several studies have investigated the impact of nuclear energy production on carbon emissions and environmental quality in these countries. Jahanger et al. [7] found that the top nuclear energy-producing countries had achieved environmental sustainability despite significant economic growth. The study revealed the validity of the N-shaped EKC hypothesis, indicating that the energy sectors in these countries were still heavily reliant on fossil fuels. However, nuclear energy generation was found to have a positive impact on environmental quality in the examined countries.

Within the same group of countries, Sadiq et al. [8] evaluated how nuclear energy efficiency and technological innovation could reduce environmental costs in the context of globalization. Their findings suggest that nuclear energy and technological innovation decrease environmental costs by reducing carbon emissions. However, globalization leads to increased environmental costs due to higher carbon emissions. The study highlights the importance of leveraging nuclear energy efficiency in managing environmental costs and pursuing a cost-effective transition to a low-carbon economy. Similarly, Baek [9] measured the impact of nuclear energy, energy consumption, and income on CO_2 emissions in 12 major nuclear power-generating countries. The results indicate that nuclear energy typically reduces CO_2 emissions, with CO_2 emissions decreasing consistently with income growth. This finding offers no support for the Environmental Kuznets Curve in relation to CO_2 emissions.

Pan et al. [3] investigated the impact of nuclear energy on CO_2 emissions in countries with high nuclear power consumption. Their findings indicate that nuclear energy reduces environmental degradation in most countries, including the USA, France, Russia, South Korea, Canada, Ukraine, Germany, and Sweden. However, Spain and, unexpectedly, China showed that nuclear energy consumption could worsen environmental conditions. The study also found that nuclear energy and CO_2 emissions can often predict one another across most quantiles.

China, as an example of a country with high nuclear energy production, has been found to benefit from nuclear energy in reducing environmental degradation. Ali et al. [10] found that energy innovation, specifically in nuclear energy efficiency, had a significant negative impact on the ecological footprint, suggesting that it could contribute positively to reducing environmental degradation. Similarly, Dong et al. [6] demonstrated that nuclear and renewable energy significantly contributes to reducing CO_2 emissions in the short and long term. However, the CO_2 emission mitigation impact of nuclear energy consumption is smaller than that of renewable energy consumption, suggesting that renewable energy will be the key factor in reducing CO_2 emissions in China. In contrast, fossil fuel consumption remains the primary driver for increasing CO_2 emissions.

Likewise, in France and South Korea, which are also examples of countries with high nuclear energy production, studies by Pata et al. [4] and Pata et al. [11] have shown that nuclear energy has a positive impact on reducing environmental degradation. In France, nuclear energy contributes to decreasing CO_2 emissions and enhancing the load capacity factor, improving environmental quality, while renewable energy does not exhibit a long-term effect on the environment. On the other hand, South Korea, a leading country in producing and consuming nuclear energy, has also experienced a positive impact on environmental quality through nuclear energy consumption, focusing on CO_2 emissions, ecological footprint, and load capacity factor. These findings highlight the significance of nuclear energy in promoting green sustainability and reducing environmental degradation in both France and South Korea.

Nuclear energy has been found to have a positive impact on environmental degradation in the Organisation for Economic Co-operation and Development (OECD) countries, as demonstrated by studies conducted by Danish et al. [12], Lau et al. [13], and Hassan et al. [14]. These studies show that nuclear energy contributes to a decrease in production-based CO_2 emissions, while also supporting the validity of the environmental Kuznets curve hypothesis in the OECD countries. Nuclear energy significantly contributes to environmental protection, and electricity generated from nuclear sources leads to reduced CO_2 emissions without hindering long-term growth. Furthermore, high scores on the economic complexity index can intensify the pressure on the ecological footprints of OECD countries, emphasizing the crucial role of nuclear energy production in fostering ecologically sustainable development in these nations.

Also, other advanced economies have been shown to benefit significantly from nuclear energy in reducing environmental degradation. According to Usman et al. [5], nuclear energy usage in 12 advanced economies significantly reduces the ecological footprint by conserving water, land, and forest resources while reducing carbon emissions. Similarly, Murshed et al. [2] found that nuclear energy consumption helps reduce CO_2 emissions and carbon footprints in the long term among G7 countries, whereas renewable energy consumption contributes to environmental degradation. Wang et al. [15] discovered that nuclear energy and renewable energy contribute to reducing carbon emissions in 24 countries with nuclear energy, with some countries experiencing more significant reductions due to nuclear energy compared to renewable energy. The studies collectively suggest that incorporating nuclear energy into energy and environmental policies could help address environmental degradation and energy security issues in advanced economies.

Similar results were observed in some emerging economies, where studies conducted by Naimoğlu [16] and Sadiq et al. [17] have shown that nuclear energy positively impacts environmental degradation. The findings indicate that an increase in nuclear energy use and energy prices reduces CO_2 emissions in emerging economies that import energy and use nuclear energy. Furthermore, nuclear energy and financial globalization support human development in the BRICS countries, while external debt hinders it. Nuclear energy and external debt encourage environmental sustainability, while financial globalization exacerbates environmental degradation. The research also reveals two-way causal relationships between human development, carbon emissions, and nuclear energy consumption, emphasizing the potential benefits of nuclear energy in addressing environmental challenges in emerging economies. India is a perfect example. Because of India's rapidly rising population, the environment is being severely strained. However, with 22 operational nuclear reactors, India boasts tremendous nuclear energy potential to cut down on CO_2 emissions [18].

As an example of a developing country, Pakistan has been found to benefit from nuclear energy in reducing environmental degradation. Majeed et al. [1] discovered that nuclear energy significantly reduces carbon emissions in both the short and long term, with an uneven long-term relationship and a two-way causal link between nuclear energy and CO_2 emissions. However, Rehman et al. [19] found that while fossil fuel energy, renewable energy usage, CO_2 emissions, and GDP per capita positively correlate with economic development, electric power consumption, electricity generated from nuclear sources, and energy use negatively impact economic growth in the long term. Despite this negative relationship with economic growth, nuclear energy remains essential in mitigating environmental degradation in Pakistan.

The impact of nuclear energy on environmental degradation has garnered increasing attention, with studies examining its relationship with CO_2 emissions, economic growth, and other factors in countries producing nuclear power. Findings generally show that nuclear energy contributes to reducing environmental degradation across different contexts, including OECD countries, advanced economies, and emerging and developing countries like Pakistan. While the relationship between nuclear energy and economic growth may vary, its potential for reducing CO_2 emissions and improving environmental quality has been consistently demonstrated. This highlights the importance of incorporating nuclear power into energy and environmental policies to address environmental challenges and promote ecologically sustainable development.

3. Materials and Methods

This research utilized annual data from 11 countries (United States, China, France, Russia, South Korea, Canada, Ukraine, Germany, Japan, Spain, and Sweden) which had the highest nuclear energy consumption (measured in exajoules) between 1993 and 2019. Environmental quality was gauged using CO_2 emissions (metric tons per capita) following the existing literature [12,19–22]. Nuclear energy consumption (exajoules) served as the independent variable [3,21]. The second independent variable was the financial development index, sourced from the International Monetary Fund's (IMF) database [23–25]. The last independent variable, GDP per capita, represented economic growth and was employed to test the N-shaped EKC curve [26,27]. To refine the results all variables in the model were converted to their logarithms. Building upon the empirical study conducted by Jahanger et al. [7], which incorporated the dependent and independent variables in question, the following three models were developed:

$$CO_{2i,t} = \beta_0 + \beta_1 NUC_{i,t} + \beta_2 FI_{i,t} + \beta_3 Y + \varepsilon_{i,t} \tag{1}$$

$$CO_{2i,t} = \beta_0 + \beta_1 NUC_{i,t} + \beta_2 FI_{i,t} + \beta_3 Y + \beta_4 Y^2 + \varepsilon_{i,t} \tag{2}$$

$$CO_{2i,t} = \beta_0 + \beta_1 NUC_{i,t} + \beta_2 FI_{i,t} + \beta_3 Y + \beta_4 Y^2 + \beta_5 Y^3 + \varepsilon_{i,t} \tag{3}$$

In accordance with Equation (1), the indices $i = 1, \ldots, N$ represent the cross-sectional units, while $t = 1, \ldots, T$ signifies the time periods under consideration. The term ε_{it} denotes the error terms associated with the model. The parameters $\beta_1, \ldots\ldots, \beta_5$ are employed to quantify the impact of the independent variables on the carbon emissions. A comprehensive list of the variables utilized in this study can be found in Table 1.

Table 1. Data description.

Variable(s)	Pictogram	Unit Measurement(s)	Source
Carbon emissions	CO_2	CO_2 emissions (metric tons per capita)	World Bank
Nuclear energy	NUC	Nuclear Energy Consumption (Exajoules)	BP Statistical Review of World Energy
Financial development	FD	Financial Development Index	IMF Database
Income	Y	GDP per capita (constant 2010 USD)	World Bank

This study employed a three-stage panel data methodology to investigate the relationship between nuclear energy consumption, financial development, economic growth, and carbon emissions. In the initial stage, tests for slope homogeneity and cross-section dependence (CSD) were conducted. In the second stage, second-generation unit root and cointegration tests were administered. In the final stage, the causality of the variables and the long-term elasticity coefficients were estimated.

In order to evaluate cross-section dependence, the current study utilized four tests: the Pesaran scaled Lagrange Multiplier (LM) test (CD_{LM}), along with the Pesaran CD test developed by Pesaran [28]; the Breusch-Pagan LM test, crafted by Breusch and Pagan [29]; and the Bias-Corrected Scaled LM (LM_{adj}) test, introduced by Pesaran, Ullah, and Yamagata [30]. These tests are denoted by Equations (4)–(7), respectively:

$$LM = T \sum_{=1}^{N-1} \sum_{j=i+1}^{N} \hat{\rho}_{ij}{}^2 \tag{4}$$

$$CD_{LM} = \sqrt{\frac{1}{N(N-1)}} \sum_{=1}^{N-1} \sum_{j=i+1}^{N} \left(T\hat{\rho}_{ij}{}^2 - 1 \right) \tag{5}$$

$$CD = \sqrt{\frac{2T}{N(N-1)}} \left(\sum_{i=1}^{N-1} \sum_{j=1+1}^{N} \hat{\rho}_{ij} \right) \tag{6}$$

$$LM_{adj} = \left(\frac{2}{N(N-1)} \right)^{\frac{1}{2}} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \hat{\rho}_{ij}^2 \frac{(T-K-1)\hat{\rho}_{ij} - \hat{\mu}_{Tij}}{v_{Tij}} \sim N(0,\ 1) \tag{7}$$

Following the CSD test, Δ tests were employed to evaluate slope homogeneity, as formulated by Pesaran, Ullah, and Yamagata [30]. In instances of serial correlation and heteroskedasticity within regression errors, Δ tests devised by Blomquist and Westerlund [31] were utilized. The heteroskedasticity and autocorrelation consistent (HAC) version of the homogeneity test, based on the delta test, is illustrated in Equations (8)–(11):

$$\Delta_{HAC} = \sqrt{N} \left(\frac{N^{-1} S_{HAC} - k}{\sqrt{2k}} \right) \tag{8}$$

$$S_{HAC} = \sum_{i=1}^{N} T \big(\hat{\beta}_i - \hat{\beta} \big)' \left(\hat{O}_T V_T^{-1} \hat{O}_T \right) \big(\hat{\beta}_i - \hat{\beta} \big) \tag{9}$$

$$\hat{\beta} = \left(\sum_{i=1}^{N} T\hat{O}_T V_T^{-1} \hat{O}_T \right)^{-1} \sum_{i=1}^{N} \hat{O}_T \hat{V}_T^{-1} X_i' M_T y_i \tag{10}$$

$$\hat{V}_T = \hat{\Gamma}_i(0) + \sum_{j=1}^{T-1} K\left(\frac{j}{M_T}\right)\left[\hat{\Gamma}_i(j) + \hat{\Gamma}_i(j)'\right] \tag{11}$$

In the presence of cross-section dependence, it is essential to employ second-generation panel unit root tests. Consequently, in this study, the Cross-Sectionally Augmented Im, Pesaran, and Shin (CIPS) and the Cross-Sectionally Augmented Dickey–Fuller (CADF) panel unit root tests, developed by Pesaran [32], were utilized. Equations (12) and (13) were implemented for these tests, respectively:

$$\Delta y_{it} = \alpha_i + \beta_i y_{i,t-1} + u_{it} \tag{12}$$

$$u_{it} = \gamma f_t + \varepsilon_{it} \tag{13}$$

In the absence of autocorrelation within the factor or error term, Equation (14) represents the CADF regression. Conversely, when autocorrelation is present, the first-order differences of y_{it} and $\overline{y}_{it}$, are incorporated, as demonstrated in Equation (15):

$$\Delta y_{it} = \alpha_i + \rho_i y_{i,t-1} + d_0 \overline{y}_{t-1} + d_1 \Delta \overline{y}_t + \varepsilon_{it} \tag{14}$$

$$\Delta y_{i,t} = \alpha_i + \rho_i y_{i,t-1} + c_i \overline{y}_{t-1} + \sum\nolimits_{j=0}^{p} d_{i,j} \Delta \overline{y}_{t-j} + \sum\nolimits_{j=0}^{p} \beta_{i,j} \Delta y_{i,t-j} + \mu_{i,t} \tag{15}$$

To compute the CIPS statistic, as depicted in Equation (16), the average of the t-statistics of the lagged variables is taken:

$$CIPS = \frac{1}{N} \sum_{i=1}^{N} CADF_i \tag{16}$$

In this phase of the investigation, the second-generation Westerlund and Edgerton Panel LM bootstrap cointegration test [33], which accounts for cross-section dependence, was utilized. This test is based on the Lagrange Multiplier test, initially devised by McCoskey and Kao [34]. Equations (17) and (18) elucidate the foundation of the panel cointegration test.

$$\gamma_{it} = \alpha_i + x_{it}' \beta_{it} + Z_{it} \tag{17}$$

$$Z_{it} = \mu_{it} + V_{it} \; V_{it} = \sum\nolimits_{J=1}^{t} \eta_{ij} \tag{18}$$

In Equation (18), the partial sum of the error term, Z_{it} is denoted as S_{it}^2 while $\hat{\omega}_i^{-2}$ represents the long-run variance of μ_{it}. The LM statistics used by Westerlund and Edgerton [33] to test for cointegration, employing bootstrap critical values and accounting for cross-section dependence, are illustrated in Equation (19):

$$LM_N^+ = \frac{1}{NT^2} \sum_{i=1}^{N} \sum_{t=1}^{t} \hat{\omega}_i^{-2} \, S_{it}^2 \tag{19}$$

Standard errors were adjusted using the robust estimator developed by Beck and Katz [35], which is resistant to heteroskedasticity, autocorrelation, and cross-section dependence issues, and yields consistent results when T < N. The panel-corrected standard error (PCSE) approach, as devised by Beck and Katz [35], is displayed in Equation (20):

$$y_{it} = x_{it}\beta + \varepsilon_{it} \tag{20}$$

where $i = 1, \ldots, m$ is the number of panels; $t = 1, \ldots, T_i$; T_i is the number of periods in panel i; and ε_{it} is a disturbance that may be autocorrelated along t or contemporaneously correlated across i. The representation of this model as a panel is demonstrated in Equation (21):

$$\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_m \end{bmatrix} = \begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_m \end{bmatrix} \beta + \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_m \end{bmatrix} \tag{21}$$

In a model displaying heteroskedastic disturbances and contemporaneous correlation, without autocorrelation, it is assumed that the disturbance covariance matrix takes the following form:

$$\sum[\varepsilon\varepsilon'] = \Omega = \begin{bmatrix} \sigma_{11}I_{11} & \sigma_{12}I_{12} & \ldots & \sigma_{1m}I_{1m} \\ \sigma_{21}I_{21} & \sigma_{22}I_{22} & \ldots & \sigma_{2m}I_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ \sigma_{m1}I_{m1} & \sigma_{m2}I_{m2} & \ldots & \sigma_{mm}I_{mm} \end{bmatrix} \tag{22}$$

where σ_{ii} denotes the variance of the disturbances for panel i; σ_{ij} signifies the covariance of the disturbances between panel i and panel j when the periods of the panels are aligned; and I is a Γ_i by Γ_i identity matrix applicable to balanced panels.

The Dumitrescu and Hurlin [36] causality test is applicable in scenarios where either N > T or T > N, and cross-section dependence is present within heterogeneous panels examining the relationship between X and Y. The test is formulated as follows:

$$y_{i,t} = \alpha_i + \sum_{k=1}^{K} \beta_{ik} y_{i,t-k} + \sum_{k=1}^{K} \gamma_{i,k} X_{i,t-k} + \varepsilon_{it} \tag{23}$$

In Equation (23), $X_{i,t}$ and $y_{i,t}$ denote the stationary variable observations in period t for each cross-sectional unit (i). It is assumed that the coefficients vary across each unit (i) but remain constant over time, the lag length is the same for each (i), and the panel is balanced.

4. Results and Discussion

Table 2 presents the descriptive statistics of the variables utilized in this study, pertaining to countries with the highest nuclear energy consumption. According to the findings, the average CO_2 emissions, denoted in metric tons per capita, for these 11 countries stand at 9.34. The mean nuclear energy consumption (NUC), expressed in exajoules, is recorded at 1.97, while the average financial development index (FD) is noted to be 0.65. Moreover, the GDP per capita for these countries is ascertained to be 26,323.21.

Table 2. Descriptive statistics.

Variable(s)	Obs.	Mean	Std. Dev.	Min	Max
CO_2	297	9.34	4.38	2.24	20.47
NUC	297	1.97	2.13	0.02	8.29
FD	297	0.65	0.21	0.09	0.90
Y	297	26,323.21	17,240.90	377.39	65,120.39

Table 3 showcases the correlation matrix results between CO_2 and the variables NUC, FD, and Y. The matrix reveals that all explanatory variables display a weak positive correlation with the dependent variable, CO_2. This similar degree of correlation renders the variables apt for joint modelling in assessing their impact on carbon emissions within the selected countries.

Table 3. Correlation matrix.

Variable(s)	CO_2	NUC	FD	Y
CO_2	1.0000			
NUC	0.5262	1.0000		
FD	0.4217	0.3450	1.0000	
Y	0.3034	0.3911	0.7876	1.0000

Table 4 displays the results of the CDS test. The results for the variables CO_2, NUC, FD, and Y are evidently statistically significant. In other words, the null hypothesis H_0, which posits "no cross-sectional dependence", is rejected, signifying the presence of cross-section dependence for all series.

Table 4. Cross-sectional dependence test results.

Variable(s)	CO_2	NUC	FD	Y
Breusch—Pagan LM	540.405 *** (0.000)	396.389 *** (0.000)	922.985 *** (0.000)	1034.799 *** (0.000)
Pesaran scaled LM	45.232 *** (0.000)	31.501 *** (0.000)	81.710 *** (0.000)	92.371 *** (0.000)
Bias-corrected scaled LM	45.021 *** (0.000)	31.289 *** (0.000)	81.498 *** (0.000)	92.159 *** (0.000)
Pesaran CD	3.4211 *** (0.000)	1.733 * (0.083)	29.801 *** (0.000)	31.388 *** (0.000)

Note: The *p*-values are given in parentheses. * and *** denote significance at 10% and 1% level, respectively.

Based on the outcomes from the Blomquist and Westerlund [31] test, the null hypothesis H_0, which asserts the presence of slope homogeneity for the models developed in the research, is rejected. This indicates that slope heterogeneity was observed in the models constructed within the study. Table 5 presents the results of the slope homogeneity test.

Table 5. Test of slope homogeneity.

Models	Statistics	*p*-Values
$\widetilde{\Delta}$	11.538	<0.000
$\widetilde{\Delta}$adj	9.752	<0.000

Table 6 displays the results of the examination on the stationarity of CO_2, NUC, FD, and Y variables using the CADF and CIPS tests. Both tests are second-generation panel unit root tests utilized in the presence of cross-section dependence. The analysis reveals that all variables are stationary at the first difference, meaning the null hypothesis H_0, which posits that "series have unit roots", is rejected.

Table 6. CADF and CIPS unit root test results.

Variable(s)	CADF (Constant)		CIPS (Constant)	
	Level	First Difference	Level	First Difference
CO_2	2.034 **	5.164 ***	2.314 ***	6.644 ***
NUC	1.205	3.573 ***	0.973	4.176 ***
FD	0.971	2.264 ***	0.875	3.584 ***
Y	1.165	2.764 ***	1.201	5.784 ***

Note: ** and *** denote significance at 5% and 1% level, respectively.

Upon establishing the stationarity of the dependent and independent variables, a long-term cointegration relationship was ascertained using the second-generation method: the Westerlund−Edgerton LM Bootstrap test [33] (Table 7). Given the presence of cross-section dependence among the variables, the Bootstrap p-value should be considered. In the model assessing the impact of the NUC, FD, and Y independent variables on the dependent variable CO_2, the Bootstrap p-value exceeds 0.10. Consequently, the null hypothesis H_0 of the Westerlund–Edgerton LM Bootstrap test is accepted. From these findings, it can be inferred that the series are collectively moving in the long term, indicating the presence of a cointegration relationship.

Table 7. Westerlund–Edgerton's LM Bootstrap Cointegration Test Results.

Test	LM Statistics	Asymptotic-*p* Value	Bootstrap *p*-Value
LMNT	9.882	0.0000	0.811

Note: the number of bootstrap iterations is 1000. The test result is obtained with the constant and trend models.

Table 8 delineates the outcomes of three Panel-Corrected Standard Error (PCSE) models developed in this study. These models concentrate on the impacts of nuclear energy consumption (NUC), financial development (FD), and economic growth (Y) on carbon dioxide emissions (CO_2). Furthermore, the validity of the N-shaped EKC hypothesis was assessed by incorporating the variables of economic growth (Y), the square of economic growth (Y^2), and the cube of economic growth (Y^3) into these models.

Table 8. Findings of long-run elasticity estimates.

	(Model 1)	**(Model 2)**	**(Model 3)**
Variable(s)	**CO_2**	**CO_2**	**CO_2**
NUC	−6.34 *** (0.13)	−6.35 *** (0.12)	−5.63 *** (0.13)
FD	12.92 *** (0.69)	7.57 *** (0.86)	5.35 *** (0.93)
Y	2.34 ** (0.0001)	4.95 *** (0.0003)	5.80 *** (0.0007)
Y2	-	−4.30 *** (5.14)	−4.65 *** (2.38)
Y3	-	-	3.85 *** (2.36)
Observations	297	297	297
R-squared	0.7544	0.7690	0.7761
Number of groups	11	11	11

Note: ** and *** denote significance at 5% and 1% level, respectively.

According to the outcomes derived from the PCSE models, there exists a negative association between nuclear energy consumption and CO_2 emissions across all three formulated models. In essence, an augmentation in nuclear energy consumption among the leading 11 countries corresponds to a diminution in CO_2 emissions levels. These results postulate that nuclear energy consumption plays a pivotal role in ameliorating environmental quality. Such findings resonate with the assertions made in the ensuing studies: Anwar et al. [37] for 15 Asian countries; Usman et al. [5] for 12 advanced economies; Pata and Samour [4] for France; Ali et al. [10] for China; Danish et al. [12] for 15 OECD countries; Sadiq et al. [8] for BRICS countries; Murshed et al. [2] for G7 countries; Kartal [38] for the top-five carbon-producing countries; Ozgur et al. [18] for India; and Majeed et al. [1] for Pakistan.

The aforementioned result demonstrates that financial development, as the second independent variable in the models, plays a significant role in influencing environmental quality. Across all models, it has been observed that financial development is associated with an increase in CO_2 emissions, thereby contributing to environmental degradation. This finding implies that as the financial sector develops and expands, it may inadvertently lead to higher levels of carbon emissions, potentially due to increased industrial activities, investments in carbon-intensive sectors, or other related factors. As a result, this negative relationship between financial development and environmental quality underscores the importance of implementing environmentally conscious policies and practices in the financial sector. The findings regarding the negative influence of financial development on the environment corroborate the results of the following studies: Shahbaz et al. [39] for Pakistan; Pata [40] for Turkey; Ibrahiem [41] for Egypt; Shoaib et al. [42] for D8 and G8 countries; Tahir et al. [43] for South Asian economies; Kihombo et al. [44] for the West Asia and Middle East countries; and Ahmed, Zhang, and Cary [45] for Japan.

The final independent variable in this study examines the impact of economic growth on environmental quality. The findings suggest that economic growth (Y) negatively affects environmental quality in the top 11 nuclear energy-producing countries across all models analyzed. The negative coefficient associated with the square of GDP per capita (Y^2) indicates an inverted U-shaped Kuznets curve across all models, implying that as economic growth (Y) increases, environmental degradation initially intensifies, peaks, and then declines with further economic growth. This turning point occurs when the negative impact of (Y^2) surpasses the positive impact of the linear term Y, resulting in a decrease in environmental degradation as economic development progresses. Maduka et al. [46] attribute the improvement in environmental quality to the adoption of various technologies and innovations that significantly contribute to sustainability.

The positive coefficient correlated with Y^3 denotes an N-shaped trajectory between economic growth and environmental degradation. In economic terms, as the trajectory surpasses the turning point of the inverted U-shaped curve, the positive externality of Y^3 supersedes the negative externality of Y^2, ushering in a renewed exacerbation of environmental degradation. Jahanger et al. [7] articulate that at this phase of economic expansion (Y^3), the rate of innovation notably dwindles relative to earlier stages, and the endeavors to amplify revenue supersede the advancement in innovation. In this context, the results are consistent with those of other previously reported studies: Zhang [47] with respect to China; Bisset [48] encompassing 41 Sub-Saharan African countries; Gao et al. [49] concerning high-polluting economies; and Fakher et al. [27] in relation to OPEC countries. This N-shaped trajectory accentuates that the relation between economic growth and environmental quality embodies a more intricate complexity than initially postulated by the EKC hypothesis.

Engaging new research outcomes have been disclosed by Abbasi et al. [50]. The revelations exhibit an inverted N-shape EKC, illustrating that both nuclear and renewable energy sources contribute to pollution mitigation in contrast to non-renewable energy which exacerbates it. Notably, the positive impact exerted by nuclear and renewable energy is more pronounced at lower quantiles compared to higher ones. These insights underscore the importance of fostering nuclear and renewable energy adoption to address environmental adversities. Consequently, a well-conceived strategy advocating for renewable energy utilization ought to be devised to facilitate a smooth energy transition and harness its advantages in fostering economic growth and safeguarding the environment.

Comparable deductions were made by Awan et al. [51], albeit with distinct test outcomes. They scrutinized the veracity of the EKC hypothesis within the five most impacted economies of the G-20 spanning from 1993 to 2017, employing GDP per capita and CO_2 emissions as indicators, alongside other variables such as technological progress, financial development, energy consumption, and social globalization. The results affirm that economies with veto power exhibit an N-shaped EKC relation between CO_2 emissions and GDP per capita. Additionally, empirical evidence demonstrates a positive association between technological progression and energy consumption with CO_2 emissions, while financial development and social globalization serve to mitigate environmental deterioration.

A compelling delineation of the elements contributing to the enhancement of environmental quality depicted in the N-shaped EKC was articulated by Tsujimoto [52] while scrutinizing the Japanese economy. The pivotal factors underpinning the inverted N-shaped EKC emerged from the synergy of the ensuing five aspects, which have garnered endorsement and promotion in Japan in the recent years: regulatory modifications such as the liberalization of the energy market; investors' accentuation of environmental, social, and governance (ESG) criteria; directives and evaluations by economic entities, rating agencies, and environmental non-profit organizations; the professional ethos of citizens and their inclination towards environmental preservation and societal benefaction; and endogenous initiatives undertaken by public utilities in their capacity as societal constituents.

Table 9 exhibits the outcomes of the Dumitrescu–Hurlin test. Per the results, a unidirectional causality relationship was discerned, originating from nuclear energy consumption and leading to carbon emissions (CO_2). This one-way causality suggests that for countries with the highest nuclear energy consumption, the use of nuclear energy contributes to reducing carbon pollution and improving environmental quality. These findings align with the findings of Menyah and Wolde-Rufael [53] and Pata and Samour [4]. This finding also highlights the potential benefits of increasing the use of nuclear energy as a strategy to address climate change and reduce greenhouse gas emissions.

Table 9. Dumitrescu–Hurlin panel causality test results.

	W-Bar	Z-Bar	*p*-Values
CO $\nrightarrow$ NUC	0.962	0.948	0.335
NUC $\nrightarrow$ CO	3.414	5.661	0.000
CO $\nrightarrow$ FD	0.730	0.695	0.594
FD $\nrightarrow$ CO	3.754	2.910	0.000
CO $\nrightarrow$ Y	5.940	11.58	0.000
Y $\nrightarrow$ CO	6.047	4.942	0.000

Note: The maximum lag length is taken as 1.

This study discerned a unidirectional causality relationship emanating from financial development to carbon emissions. This observation is in alignment with the findings of preceding studies, such as Abbasi and Riaz [54], Shahzad et al. [55], Ibrahiem [41], and Tahir et al. [43], which substantiated a one-way causality nexus from financial development to carbon emissions. Additionally, a bidirectional causality relationship between economic growth and carbon emissions was identified, resonating with the conclusions drawn by Zhang [56], Shahbaz et al. [57], and Shahbaz et al. [58].

5. Conclusions

This study's main goal was to explore the impact of nuclear energy consumption and financial development on environmental quality. Additionally, the research sought to evaluate the accuracy of the N-shaped Environmental Kuznets Curve hypothesis to understand the influence of economic growth on environmental quality.

The findings indicate that the null hypothesis H_0 of the Westerlund–Edgerton LM Bootstrap test is accepted, revealing a cointegration relationship between the series in the long term. According to the PCSE model results, an increase in nuclear energy consumption among the top 11 countries leads to a decrease in carbon emissions, demonstrating the negative impact of nuclear energy consumption on CO_2 levels across all three developed models. Furthermore, the study uncovers an N-shaped relationship between economic growth and environmental degradation, as indicated by the positive coefficient associated with the Y^3 term. This finding suggests that after the initial inverted U-shaped Kuznets curve, environmental degradation starts to increase again with further economic growth. As the economy grows beyond the turning point of the inverted U-shaped curve, the positive impact of the Y^3 term outweighs the negative effect of the Y^2 term, resulting in a renewed rise in environmental degradation. Additionally, a unidirectional causality relationship was identified, running from nuclear energy consumption to carbon emissions, and a unidirectional causality relationship from financial development to carbon emissions.

Based on the findings and the literature review, it is strongly recommended that investments and grants for research and development endeavours be augmented, with the aim of identifying and executing innovative solutions to diminish carbon emissions and ameliorate environmental quality. These efforts may encompass the provision of more robust funding for new technologies and the fostering of collaborations between academia and industry. Additionally, regulatory modifications such as liberalization of the energy market, and endogenous initiatives undertaken by public utilities in their capacity as societal constituents, should be considered as vital components of a holistic strategy to tackle environmental challenges and promote sustainable energy practices.

Although insightful, the research faced certain constraints, such as focusing on a limited number of countries and using data spanning from 1993 to 2019. Future studies could benefit from expanding the analysis to include more countries and explore more recent data. Additionally, the research could be further developed by examining the potential mediating effects of other variables, such as technological innovation, governance, and international cooperation. This would provide a more comprehensive understanding of the factors driving the relationship between nuclear energy consumption, financial development, economic growth, and environmental quality. It is essential to consider these limitations when interpreting the study's results and formulating policies based on its findings. By addressing these constraints, future research can contribute to a more nuanced understanding of the complex interplay between nuclear energy, financial development, environmental quality, and economic growth, ultimately providing more robust policy recommendations.

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