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Article

The Triple Threat to Our Environment: Economic, Non-Economic, and Demographic Factors Driving Ecological Footprint in Nuclear-Power Countries

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Abstract: This study examines how economic growth, travel, global connection, and changes in population impact the environmental footprint in seven countries, including Russia, the US, China, France, the UK, Pakistan, and India, from 1995 to 2023. The results show a significant link between Granger’s environmental impact and some economic, non-economic, and population factors in these countries. According to the study, environmental impacts result primarily from economic expansion and tourism revenue generation. The essential activities in economic development frequently result in significant ecological deficits through natural resource depletion, land alterations, and environmental releases. Business enlargement and tourism income commonly bring about deforestation while causing both pollution and habitat damage, thus showing why sustainable practices must exist to protect nature during economic development. We also have to consider factors other than economics, such as total income from natural resources and using nuclear power early. Additionally, how many people live in a particular area and the number of children born contribute to these footprints. Also, this study shows how economic, non-economic and demographic issues can indicate what harm the environment might face later. This is especially important in countries that use nuclear energy extensively. The report suggests different ways to solve this problem. These include advocating for sustainable tourism practices, directing research efforts towards nuclear energy, supporting renewable energy initiatives, promoting family planning and education, and raising public awareness. The aim is to reduce the environmental harm caused by nuclear energy and promote a more sustainable future.

Keywords: ecological footprint; Dumitrescu–Hurlin Granger causality test; economic factors; non-economic factors; demographic factors; nuclear energy



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1. Introduction

The fast-paced economic growth and industrialization in developing countries have brought both progress and challenges (Chen et al., 2021; S. Khan & Majeed, 2023). These developments have significantly boosted economies, improved people’s lives, and reduced energy poverty. However, they have also taken a toll on the environment, affecting natural ecosystems negatively (Danish & Wang, 2019; Hassan et al., 2019; Zhao et al., 2022). Many nations are now dealing with higher CO₂ levels in the atmosphere and working hard to

deal with the severe risks of climate change. The G-7 nations—UK, US, Italy, France, Japan, Canada, and Germany—control a considerable share of the world’s wealth and economy (H. Qiao et al., 2019). China, a substantial energy user and a significant source of CO₂ emissions (Z. Liu et al., 2022; Qin et al., 2021), is estimated to reach its highest pollution level by 2030. At the same time, Pakistan’s share of worldwide emissions went from a small amount to a more critical share between 1974 and 2016. This shows its role in causing climate change (Kamal et al., 2021). To cultivate hope for a promising and long-lasting future, people need to use natural resources carefully while thinking about their effect on nature (Ke et al., 2021; Q. Wang et al., 2022). One of the problems in reaching sustainability is discovering how to use resources without hurting nature. This can be seen from research on ecological footprints (EF).

The ecological footprint (EF) measures the entire resource requirement of population waste capabilities by determining necessary biologically productive land areas expressed through global hectares (gha). Mathis Wackernagel and William Rees created the ecological footprint model by assembling six analyzed elements, which combine cropland and grazing land, forest land, and fishing grounds with built-up land and carbon footprints to measure human ecosystem use against natural regeneration power. The EF differentiates itself from other measurement standards, since it integrates multiple environmental sectors through its land-use assessment, energy evaluation, and waste-management system. The calculation method transforms resource usage and emissions into units of productive areas through standard global yield and equivalence standards. Through this instrument, policymakers can determine the extent of resource utilization of biocapacity to identify ecological overshoot conditions to develop sustainable development approaches (GFPN, 2024).

EF calculates the space required for human activities like using energy and throwing away trash (Boleti et al., 2021). To deal with growing emissions, we need to know their main reasons and start using green policies. Some studies say that CO₂ emissions might not be the only cause of pollution from actions like mining and cutting down trees (Usman & Makhdum, 2021; Yang et al., 2021). To address this limitation, the existing literature suggests using EF, which assesses the total environmental effect caused by human activity in six categories: woodland areas, fish hunting areas, farm fields, and carbon footprint, along with grasslands for livestock to graze. It also includes built-up places like cities or factories. Ecological footprint, as shown by Ramzan et al. (2022) and Usman et al. (2021), is a better way to look at how beneficial we are for the Earth, while also looking at problems with nature’s beauty—the issue of sustainability and damage to our planet seems to be composed of many parts that interact in different ways.

The tourism business has grown economically and is criticized for hurting the environment. The rise in pollution from carbon emissions makes it worse, as pointed out in recent studies (Kotz et al., 2024; Razzaq et al., 2021; Robaina-Alves et al., 2016). A recent assessment showed more CO₂ emissions from the tourism industry, jumping from 3.90 to 4.55 units between 2009 and 2011. This is a cause for concern because it is terrible for the earth’s environment, as too much carbon dioxide causes problem, with world temperatures increasing quickly, which is called global warming. In studying the economy and the environment, people often argue about how world trade changes pollution (Kotz et al., 2024). Some people think that as economies interact worldwide, pollution and production increase because of the scale effect. However, scientists such as Le et al. (2016) and Ahmed et al. (2019) think that when the whole world becomes more connected, it might decrease pollution levels. The effect of economic globalization on the environment changes depending on where international investments are made (Yameogo et al., 2024; Zarsky, 1999). Their research shows that the impact of these investments is based on if they are put into green industries or not. In addition, Rudolph and Figge (2017) suggest that governments might

start carrying out international trade deals if the need for nature's resources changes. This could affect a country's level of global economic integration (J. Wang et al., 2023).

Nuclear power, natural resources, and financial resources make a big difference because they affect how we use the Earth. Advocates like Baek (2015), Bandyopadhyay and Rej (2021), and Lau et al. (2019), along with Lau et al., suggest using nuclear power as a way of solving problems for nature while also making energy safety stronger. Setting up nuclear power stations requires financial resources and building work. This can be challenging, especially in less-developed countries like Pakistan (Mahmood et al., 2020). People worry about more than just dirty air. Researchers demonstrate concern for water and soil standards, because global resource-usage trends demand additional attention to natural resource usage. Research organizations assess environmental damage through the ecological footprint (EF) analysis, according to Kumar et al. (2023).

Figure 1 shows that nuclear and renewable energies like wind and solar are the safest and cleanest, with the lowest death rates and greenhouse gas emissions, while fossil fuels like coal and oil are the most dangerous and polluting.

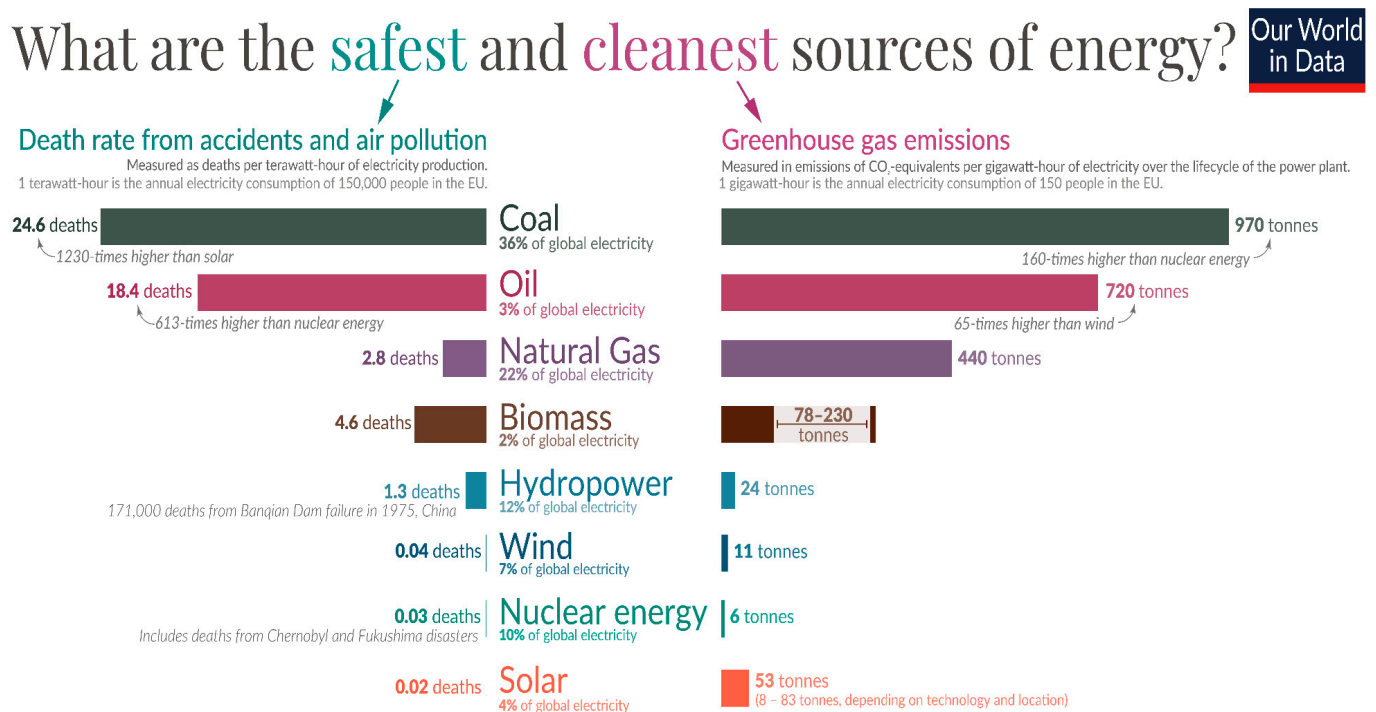


Figure 1. The safest and cleanest sources of energy. Source: Our World in Data.

Demographic factors have been important to Asia's economy in recent times (Jayawardhana et al., 2023; Sahoo, 2006). The fast-growing population density in the area has drawn investment attention, but more people can cause problems like too many people in one place, more household waste, and an overabundance of industry. Cities like Delhi, Faisalabad, and Jakarta have suffered from air pollution because too many people live there. As Greenpeace Southeast Asia (2019) have reported, this has raised pollution levels. Water and soil quality remains vital to scientists, especially during global-resource prioritization, which maximizes natural resource consumption. Scientists measure environmental damage by applying ecological footprints (EF) according to J. Liu et al. (2024). The natural way of life faces additional strain because of it.

Better access to energy, stemming from population growth and financial capital investments, has driven expansion within different sectors of the economy, including production and worldwide trade (Okolo et al., 2024). Improved disposable incomes because of eco-

economic expansion result in enhanced consumer spending, which result in greater market demand (Wei et al., 2024). The consumption pattern creates additional manufacturing pressure, maintaining high energy consumption while sustaining environmental stress (M. Qiao et al., 2024). These are sometimes called SDGs (Sustainable Development Goals). Most importantly, it matches goal 7 of the global targets—which is all about obtaining cheap and clean energy. Also, it aligns with goals eight to thirteen for decent jobs, plus the economic growth in step nine, while aiming for better energy use and saving—in line with goal twelve—and handling climate action. Furthermore, the research also includes particular goals about reproductive health and family planning. These are vital parts of SDG 3 that help everyone have a good life without illness or injury.

The study examines how economic, non-economic, and demographic factors affect the ‘Ecological footprint’ of countries with nuclear power. Employing panel-data analysis, the students analyze the stationarity of variables using unit-root tests and explore cointegration to unveil long-term relationships between these factors. The study employs more robust regression methods by employing cointegration on stationary data, ensuring increased reliability while conducting the Granger causality test to discern causal relationships among the variables.

Research efforts on environmental sustainability have produced limited results because major areas still lack adequate investigation. Studies dealing with CO₂ emissions and isolated environmental measurements tend to disregard the overall ecological footprint assessment, including cropland and grazing land, forest areas, and built-up land-use categories. Research about nuclear energy’s ability to lower the ecological footprint fails to address countries whose energy production is predominantly achieved through this source. Nuclear power is commonly believed to be an EF-friendly source of power. Still, building its facilities alongside its resource usage creates reverse EF impacts, which have not been subject to sufficient investigation. The research examines demographic factors (such as population density, urbanization, and economic globalization) independently as they work together to generate environmental pressure. An analysis of the tourism industry’s carbon emissions has furthered understanding, yet scientists still lack comprehension of its full EF impact, which includes land modification and development-related pollution and infrastructure requirements.

The research studies the entire range of EF elements to extend beyond carbon emission analysis. The research investigates how nuclear energy functions as a low-carbon power generator and as a factor that may increase EF through its use of resource-intensive infrastructure. The study presents a complete picture of the effects of environmental pressure by combining various demographic, economic, and trade elements within one analytical structure. The research uses strong econometric methods, including unit-root tests and cointegration and Granger causality, to validate long-term relationships and causal effects despite other studies lacking these methods. The new findings from this research help authorities operate between economic progress energy stability, and ecological sustainability within nuclear energy systems. This research contributes to the Sustainable Development Goals (SDGs) by establishing relationships between the clean energy targets in SDG 7, the responsible consumption elements in SDG 12, and the climate action measures from SDG 13, with demographic patterns under SDG 3 and 11.

Research Significance

This research analyzes the “Triple Threat” phenomenon, representing three simultaneous factors connecting economic development to population changes and energy use against natural environmental sustainability. The literature research indicates that these three factors remain the main drivers of ecological footprints (EF); thus, the researchers

selected them as critical variables. Economic growth is the main factor that drives resource usage and industrial growth, which causes EF to increase because of scale effects. Demographic elements, which include urban population density, urbanization, and consumption patterns, directly control land-use requirements and waste amounts. The consumption of fossil fuels alongside energy remains the main factor that generates carbon footprints and affects the EF dimensions of cropland and grazing land. These elements (technological innovation and trade policies) and environmental factors were chosen due to their leading influence on environmental outcomes while remaining key components of international sustainability dialogues. The study uses three factors as its framework to maintain analytical clarity while preserving an explicit research scope by the design principle of parsimony.

Russia, along with the United States, China, France, United Kingdom, Pakistan, and India, Seven countries made up the list of nuclear-powered nations, which was established based on multiple assessment standards. These chosen countries have a combination of developed nations like France and the United States alongside the developing powers Pakistan and India, which allows researchers to make cross-national comparisons of their nuclear energy utilization. The selected seven countries combined produce significant amounts of nuclear-generated energy and CO₂ emissions, which makes them pivotal for investigating nuclear power and EF mitigation relationships. A comprehensive data-collection process existed for all essential variables regarding EF components, demographic indicators, and energy statistics, since these nations demonstrated superior data accessibility compared to other countries. The “Triple Threat” establishes its connection with these countries because all nations face environmental challenges that result from urbanization constraining the land in Pakistan and India and economic growth generating energy-related emissions in the US and Russia. The research focuses on a balanced number of countries to offer specific recommendations for policymakers across nuclear nations without creating an analysis that becomes too complex due to an overly large sample size.

2. Literature Review

According to the Environmental Kuznets Curve (EKC) hypothesis, the evidence shows that pollution rises in correlation with income increases before declining as wealth creates better technology and stronger environmental regulation (Kuznets, 2019). Several scholars continue to challenge the EKC hypothesis in different situations. The EKC became widespread thanks to Grossman and Krueger (1991). Yet, most assessments dismiss its effectiveness because it fails to address non-CO₂ pollutants and land-use changes, including deforestation and urban sprawl, which substantially contribute to the ecological footprint (EF). According to the author, EKC studies focus their research on carbon emissions without recognizing the complex nature of EF (He et al., 2023; Iheonu et al., 2021). Authors propose an eco-friendly infrastructure as a sustainable tourism approach to decrease EF (Katircioğlu, 2014; Uddin et al., 2024), yet the other side depicts tourism development as an environmental pressure factor due to power-intensive resort facilities (I. Khan & Hou, 2021; Kongbuamai et al., 2020) and transportation systems. Local policies and technological adoption in Singapore led to the unusual outcome of rising tourism accompanied by decreasing emissions, according to Kumail et al. (2024).

Researchers debate the environmental impact of global processes to a similar extent. The research by Ahmed et al. (2019) demonstrates that globalization produces limited changes in pollution levels. Still, Haseeb et al. (2018); Xu et al. (2018) establish that trade in pollution-intensive goods intensifies EF. The article shows how globalization affects emissions through different countries' income levels, because developed nations like G7 send their emissions to emerging economies (Pata & Yilanci, 2020; Zafar et al., 2019). The authors emphasize technology transfer and efficiency benefits as they question the

“pollution haven” hypothesis in their study—Zafar et al. (2019). The environmental impact of nuclear energy produces conflicting perspectives, because Hassan et al. (2020) support atomic power as a fossil fuel alternative. Still, Rehman et al. (2022) suggest problems stemming from waste-disposal and infrastructure requirements. Life-cycle assessments become the main focus of disagreement, because nuclear power plants emit minimal pollution during operation, yet uranium extraction and decommissioning activities might erase all advantages.

Population statistics serve as additional obstacles that affect environmental results. The research of Alola et al. (2019) documents that North American birth rate increases produce more air pollution, yet Downey and Hawkins (2008) discovered that smaller homes with female leadership decrease EF. According to Huo and Peng (2023), population growth results in fewer resources due to behavioral modifications accompanying education and urbanization developments. However, Dietz et al. (2007) identify growing populations such as resource depletion. Research by Cafaro (2012) and Campbell et al. (2024) shows that family structure elements (such as single-parent homes) affect environmental pollution, while there is a lack of comprehensive analysis between demographics, energy policies, and globalization.

The existing literature reveals critical gaps. The analysis of EKC typically excludes CO₂ alternative pollutants together with land-use effects. Yet, studies on tourism and globalization fail to account for EF complexity—studies about environmental consequences of nuclear energy exhibit limited integration with complete environmental factors’ frameworks. The separate analysis of demographic economic and energy influences fails to show how these elements affect one another in their cumulative impact on EF. Different research methods that employ cross-sectional designs and longitudinal methodologies reduce the ability to match study results when studies are compared against one another. This research widens EF evaluation to include an assessment of land-utilization waste production and carbon emissions, while uniting the tourism and energy sectors and population trends and employing statistical tests for causal relation analysis. The study presents a complete examination of EF drivers through combined research elements, expanding theoretical knowledge while delivering practical guidance to nuclear energy governing bodies.

3. Methodology

3.1. Theoretical Framework

The research bases its findings on the Environmental Kuznets Curve (EKC) hypothesis and ecological economics. It uses ecological footprint (EF) as the environmental degradation measure that shows an inverted U relationship with economic growth. The EKC demonstrates that economic expansion at the initial stages intensifies environmental strain because of increased production (scale effect). Yet, intensive development later creates less pressure through technological innovation and regulatory changes (technique effect). This research builds upon the EKC model by analyzing coterminous influences from economic and non-economic variables and demographic elements on EF. The study of sustainable development helps identify how economic, social, and environmental systems connect, based on which they assess how nuclear energy and globalization affect environmental quality in nuclear-powered nations.

3.2. Hypotheses

H1a: *Economic growth significantly influences the ecological footprint.*

H1b: *Ecological footprint significantly influences economic growth.*

H2a: *Tourism significantly influences the ecological footprint.*

H2b: *Ecological footprint significantly influence tourism.*

H3a: *Globalization significantly influences the ecological footprint.*

H3b: *Ecological footprint significantly influences globalization.*

H4a: *Total natural resource rent significantly influences the ecological footprint.*

H4b: *Ecological footprint significantly influences total natural resource rent.*

H5a: *Nuclear energy uses significantly influence the ecological footprint.*

H5b: *Ecological footprint significantly influences nuclear energy use.*

H6a: *Population density significantly influences the ecological footprint.*

H6b: *Ecological footprint significantly influences population density.*

H7a: *Fertility rate significantly influences the ecological footprint.*

H7b: *Ecological footprint significantly influence fertility rate.*

3.3. Data

Between 1995 and 2023, we focused on exploring how different factors relate to the ecological footprint in seven countries with nuclear power: Russia, the US, China, France, the UK, Pakistan, and India. We looked at various economic, non-economic, and demographic factors. The financial side covered aspects like economic growth, tourism, and globalization. Non-economic factors delved into total natural resource rent and nuclear energy. On the demographic front, we considered population density and fertility rate. You can find more details about the data in Table 1.

Table 1. Measurement and data sources.

Variable	Symbols	Unit of Measurement	Source
Ecological footprint	EF	Global hectares (gha)	Global Footprint Network (GFPN, 2024)
Economic Factors			
Economic Growth	EG	constant USD	WDI (World Bank, 2024)
Tourism	T	number of tourists arriving during a year	WDI (World Bank, 2024)
Globalization	G	(Range between 1 and 100)	KOF Globalization Index (Gygli et al., 2019)
Non-Economic Factors			
Nuclear Energy Use	NE	Terawatt hours	British Petroleum (British Petroleum, 2024)
Total Natural Resource Rent	TNRR	percentage of GDP	WDI (World Bank, 2024)
Demographic Factors			
Population Density	PD	people p./sq.km. of land area	WDI (World Bank, 2024)
Fertility Rate	FR	births per woman	WDI (World Bank, 2024)

3.4. Econometric Methodology

A panel-data analysis enabled us to thoroughly study the time-based relations and sequential cause–effect relationships between studied variables, which produced reliable conclusions about the influence of economic conditions alongside population dynamics and energy-sector variables on the ecological footprint of different nations. We had to check if the data worked well to ensure our results were accurate. First, we made sure that the parts of the data stayed the same over time by performing tests to check if they were “steady”. After confirming this, we looked at “co-movement”, which helped us see long-term connections between different bits of information. This step was essential for ensuring the reliability and validity of the analysis, enabling a more accurate assessment of the relationships among the variables. We made our study more trustworthy by running these tests on the parts of data that stayed unchanged over time. Ultimately, we used a Granger causality test to see how these different parts affected each other.

3.4.1. Panel Unit-Root Analysis

When examining their connection, checking if variables have the same root characteristics is essential. Tests for unit roots are critical in checking if variables stay the same and stopping bad regression outcomes. This study employed three unit-root methods: Levin, Lin, and Chu’s LLC method ([Levin et al., 2002](#)), Fisher-ADF, and Im-Pesaran-IPS Shin’s method.

$$\Delta y_{it} = \varphi_i y_{it-1} + \sum_{l=1}^k \theta_{il} \Delta y_{i,t-1} + \gamma_i c_{it} + \mu_{it} \quad (1)$$

The equation used in the study incorporates various components like fixed effects, time trends (denoted by c_{it}), lag orders (represented by k), error terms (symbolized by μ_{it}), and a constant autoregressive coefficient (φ) across cross-sections. The null hypothesis in these tests posits that each time series is non-stationary, while the alternative hypothesis suggests the opposite.

The LLC test extends the Augmented Dickey–Fuller specification, assuming independence across cross-sections and homogeneity in the panel. It evaluates whether the panel series of each variable is non-stationary versus stationary. On the other hand, the Fisher-ADF unit-root tests accommodate heterogeneity by assuming different unit-root processes across various cross-sections. Like the LLC test, these tests examine the null and alternative hypotheses. Performing unit-root tests is a crucial step in panel-data analysis as it ensures the reliability and validity of subsequent studies.

3.4.2. Cross-Sectional Dependence Test

All panel-data models base their assumptions on independent error terms between individual units. Certain circumstances could lead to errors in developing correlations across individual units. The deviation from standard model assumptions points to non-unitary correlation matrices, since separate autocorrelation or heteroscedasticity patterns do not cause correlation. The research examined if units maintained separate functioning statuses. Different well-known methods were used to evaluate cross-sectional dependence (CSD), such as the Pesaran, Friedman, and Breusch–Pagan tests. Several tests were used in the analysis, including the Pesaran CD test ([Udemba & Keleş, 2022](#)), Pesaran scaled LM test ([Wu et al., 2021](#)), the Breusch–Pagan LM test ([Voumik & Sultana, 2022](#)) and the Friedman test ([Raihan, 2023](#)). The adopted methods successfully identify CSD problems, which deepen our knowledge of complex cross-sectional dependencies. The interpretation and reliability of panel-data models increase when this essential factor receives attention.

$$CSD = \frac{\sqrt{2T}}{N^2(N-1)} \left(\sum_{i=1}^{N-1} \sum_{K=i+1}^N \widehat{Corr}_{i,t} \right)^{\frac{1}{2}} \quad (2)$$

3.4.3. Cointegration Tests

When panel data shows unit roots, it suggests that individual datasets can be linked to establish a long-term balance using cointegration tests. This study used a specific kind of test (Pedroni, 1999). These tests involved creating equations for each set of data and estimating the differences between the expected and actual values, expressed as $\hat{\varepsilon}_{it} = \rho_i \hat{\varepsilon}_{it-1} + \sum_{j=1}^k \varphi_{ik} \Delta \hat{\varepsilon}_{it-k} + v_{it}$. Calculating these differences was a crucial part of the Pedroni tests. When conducting cointegration tests, the null hypothesis, $H_0 : \rho_i = 1$, indicated no cointegration, while the alternative hypothesis suggested the presence of cointegration ($H_0 : \rho_i < 1$).

3.4.4. Granger Causality

The Granger causality test is a widely used tool in econometrics to assess whether adding past values of one variable improves forecasting in a model with another variable. However, this test has limitations, especially in examining Granger causality across different frequencies. To overcome this challenge, (Geweke, 1982) proposed the Wald test, which explores Granger causality in distinct frequency domains, focusing on frequency-related time-series variations rather than time itself. Breitung and Candelon (2006) expanded on Geweke's test, but its use in tourism literature has been constrained due to limited data availability. Croux and Reusens (2013) introduced a multi-country examination for causality within the frequency domain to address this gap.

In our study, we worked with a set of seemingly unrelated equations formulated as follows:

$$X_{i,t} = \sum_{j=1}^p \beta_{ij} X_{i,t-j} + \sum_{j=1}^p \gamma_{ij} Y_{i,t-j} + \varepsilon_{i,t} \quad (3)$$

With $i = 1, 2, 3, \dots, C$,

With each country i at time t , $X_{i,t}$ as well as $Y_{i,t}$ symbolize the variables for country i variables at time t , and the error term i at time t is $\varepsilon_{i,t}$. The researchers used a feasible generalized least-squares estimator to assess the SUR model. The researchers placed restrictions on β_{ij} and tested them to use an incremental R^2 test to test the no Granger causality null hypothesis from y_t to x_t at frequency w . A null hypothesis was rejected at frequency w throughout all countries at level α if:

$$\sum_{j=1}^p \beta_{ij} \cos(jw) = 0 \text{ for } i = 1, \dots, C, \quad (4)$$

$$\sum_{j=1}^p \beta_{ij} \sin(jw) = 0 \text{ for } i = 1, \dots, C, \quad (5)$$

$$R_L^2 = R^2 - R_*^2 \quad (6)$$

$$R_L^2 > F_{(2C, C(T-2p), 1-\alpha)} \frac{2C}{C(T-2p)} (1 - R^2) \quad (7)$$

In this context, R^2 and R_*^2 represent the McElroy R^2 values for unrestricted and restricted SUR models. Additionally, $F_{(2C, C(T-2p), 1-\alpha)}$ signifies the critical value derived from the F distribution.

4. Results

The descriptive statistics from Table 2 display information about ecological footprint (EF) along with economic growth (EG), tourism (T), globalization (G), natural resource rent (NRR), nuclear energy use (NE), and population density (PD) and fertility rate (FR) among 169 observations. Statistical data show that EF ratifies an average value of 20.388, but EG and NE exceed that figure at 28.148 and 26.296, respectively. The dispersion of data extends further for tourism (T) and nuclear energy use (NE) compared to other variables. The

minimum and maximum values from the dataset demonstrate NRR as the variable with the smallest recorded value at -3.245 , which indicates changes in resource dependency levels: the distribution shape and asymmetry levels of EF exhibit right-tailed skewness (0.862) based on the statistics. Only one variable (0.151) shows non-statistical significance, while other variables demonstrate p -values below 0.05, which indicates their importance. These results suggest the possible non-stationary behavior of the variable. The statistical test results reveal vital information about data distribution patterns and variability and normality distributions needed for future econometric analysis.

Table 2. Descriptive statistics.

Variable	EF	EG	T	G	TNRR	NE	PD	FR
Observation	169	169	169	169	169	169	169	169
Std. Dev.	1.071	1.401	1.945	0.233	1.555	1.885	1.317	0.369
Mean	20.388	28.148	16.989	4.195	0.283	26.296	4.714	0.741
Max	23.505	33.634	22.929	4.783	4.581	30.929	7.647	1.725
Min	17.438	23.397	12.561	3.597	-3.245	21.191	1.014	-0.223
Kurtosis	1.236	0.785	1.029	0.654	0.892	1.346	0.979	0.723
Skewness	0.862	0.246	0.457	0.328	0.1987	0.568	0.432	0.289
p Value	0.000	0.151	0.000	0.000	0.026	0.000	0.000	0.000

Note: ecological footprint is represented by EF, economic growth is represented by EG, tourism is represented by T, globalization is represented by G, nuclear energy use is represented by NE, total natural resource rent is represented by TNRR, population density is represented by PD, and fertility rate is represented by FR.

We kicked off the analysis by checking the stationarity of the variables using various unit-root tests: [Im et al. \(2003\)](#) and [Phillips and Perron \(1988\)](#) Fisher-type panel unit-root tests, as well as the [Levin et al. \(2002\)](#) LLC test. We aimed to see if the panel exhibited a unit root based on the null hypothesis. The summarized results in Table 3 reveal that all other variables show stationarity after the first few differences, except EG, G, NE, FR, and PD.

Table 3. Unit-root test results.

Variables	IPS Test		ADF-Fisher Test		Levin-Lin-Chu Test	
	Level	1st diff:	Level	1st diff:	Level	1st diff:
EF	0.993	-6.938^{***}	-2.026	-9.088^{***}	-1.026	-3.523^{***}
EG	-0.276	-4.914^{***}	0.628	-7.778^{***}	-3.115^{***}	-----
T	1.295	-6.926^{***}	-1.816	-10.301^{***}	0.645	-5.231^{***}
G	3.046^{*}	-6.931^{***}	-2.825^{***}	-----	-3.441^{***}	-----
TNRR	-0.468	-5.516^{**}	2.931^{*}	-9.201^{***}	-0.582	-7.957^{***}
NE	-0.468	-9.826^{***}	-0.451	-8.583^{***}	-4.919^{***}	-----
PD	3.158^{*}	-9.449^{***}	0.135	-9.203^{***}	-3.656^{**}	-5.921^{***}
FR	1.534	-7.124^{***}	-2.849^{***}	-----	-0.606	-2.885^{**}

Note: ecological footprint is represented by EF, economic growth is represented by EG, tourism is represented by T, globalization is represented by G, nuclear energy use is represented by NE, total natural resource rent is represented by TNRR, population density is represented by PD, and fertility rate is represented by FR. ***, **, and * demonstrate the levels of significance at 1%, 5%, and 10%, respectively.

Table 4 contains the cross-sectional dependence (CSD) test outcomes based on the Pesaran CD test, the Pesaran Scaled LM test, the Friedman test, and the Breusch–Pagan (BP) LM test. The results from all cross-sectional dependence (CSD) tests produce p -values exceeding 0.05, thus demonstrating no significant relationship between variables during the cross-section. The Pesaran CD test reports a value of 0.988 at $p = 0.325$, and the Pesaran scaled LM test shows 1.543 at $p = 0.287$, indicating independence across the cross-sections. Two tests demonstrating the lack of strong cross-sectional correlation are the Friedman test,

with a score of 2.188 and $p = 0.198$, and the BP LM test at 1.765 and $p = 0.254$. The observed data support independent unit operation, since variations or shocks affecting a single cross-section does not generate systematic effects throughout other sections. Standard panel-estimation methods can continue to be applied for additional analyses because the assumption of cross-sectional independence holds.

Table 4. CSD test results.

Test Statistics	Value	<i>p</i> -Value
Pesaran CD test	0.988	0.325
Pesaran scaled LM	1.543	0.287
Friedman test	2.188	0.198
BP LM test	1.765	0.254

In Table 5, the [Pedroni \(1999\)](#) tests illustrate the investigation into long-term connections among all the entities studied. With the data's stability confirmed, exploring potential cointegration among the variables became feasible. The results of these tests confirm the presence of a meaningful cointegration relationship. This highlights the vital relevance of the link between the ecological footprint and its influencing factors, lending credibility to the findings.

Table 5. Cointegration test results for each model.

Pedroni Test	
	Statistic
Modified Phillips–Perron t	1.558 **
Phillips–Perron t	−9.768 ***
Augmented Dickey–Fuller t	−7.598 ***

Source: calculations made by the author. *** and ** demonstrate the levels of significance at 1% and 5%, respectively.

The test for Granger causality was run, and its results are presented in Table 6. In most cases, we found a two-way causal relationship between the variables, except in three instances with a one-way causality: EF to T, EF to G, EF to NE, and FR to EF.

Table 6. Models' Dumitrescu–Hurlin panel causality test results.

	W-Statistic (K1)	W-Statistic (K2)	W-Statistic (K2)	Hypothesis
EG → EF	6.988 *	5.618	5.592	Accepted
EF → EG	1.463	4.999	6.601 ***	Accepted
T → EF	4.303 *	5.532	6.143	Accepted
EF → T	1.557	2.864	4.817	Rejected
G → EF	4.947 *	4.863 *	6.885 *	Accepted
EF → G	0.638	1.506	2.356	Rejected
TNRR → EF	1.341	2.362	5.225 *	Accepted
EF → TNRR	1.667	2.802	6.774 *	Accepted
NE → EF	1.915	2.248	6.193 *	Accepted
EF → NE	1.771	3.746	5.009	Rejected
PD → EF	5.311 *	10.188 **	14.369 *	Accepted
EF → PD	9.745 *	10.421 *	6.333 **	Accepted
FR → EF	3.148	4.5799	5.305	Rejected
EF → FR	4.466 *	4.2146	4.776	Accepted

Note: ecological footprint is represented by EF, economic growth is represented by EG, tourism is represented by T, globalization is represented by G, nuclear energy use is represented by NE, total natural resource rent is represented by TNRR, population density is represented by PD, and fertility rate is represented by FR. ***, **, and * demonstrate the levels of significance at 1%, 5%, and 10%, respectively.

The environmental impact grows due to economic growth combined with visitor trends, alongside globalization activities, resource rent, and nuclear energy, together with rising population density and fertility rates. The ecological footprint generates cyclical effects on economic growth, together with resource rents, population density, and fertility rates. The study findings show that H2b, H3b, H5b, and H7a rejected the idea that ecological footprint does not impact tourism, globalization, or nuclear energy use, while other socio-economic processes continue operating normally in the face of environmental changes. Also, results are presented in Figure 2.

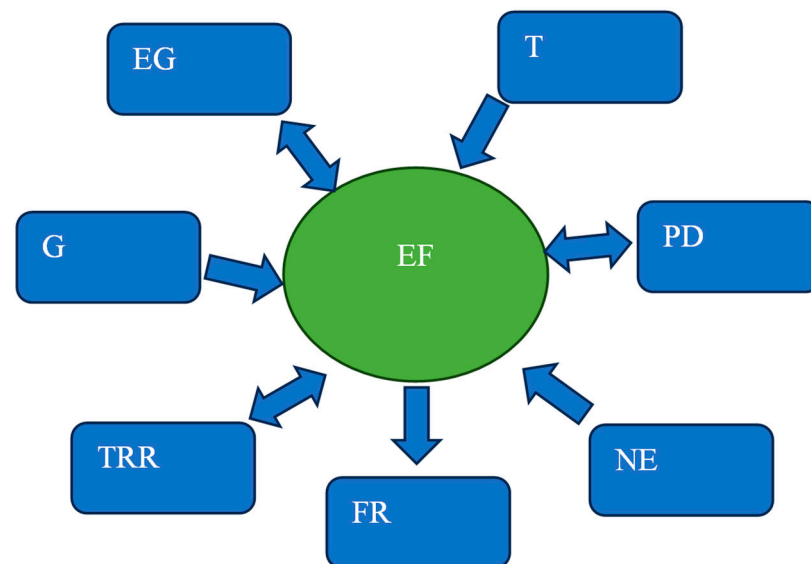


Figure 2. Model presentation of Granger causality results. Source: Authors own.

5. Discussions

This research explores the relationship dynamics between ecological footprint (EF) and its seven driving factors, including economic growth (EG), tourism (T), globalization (G), nuclear energy (NE), natural resource rent (TNRR), population density (PD), and fertility rates (FR) throughout the period from 1995 to 2023 in seven nations which utilize nuclear power (Russia, the US, China, France, the UK, Pakistan, and India). These factors show diverse patterns in their relationship with EF through economic systems, government strategies, and population changes in each nation. The following section details the core components responsible for important study outcomes and their resulting impacts.

5.1. Economic Growth and Environmental Quality

This study shows that environmental quality influences economic growth and vice versa to the Environmental Kuznets Curve hypothesis in both the US and China. Early in the United States, the economy's expansion elevated EF levels by industrializing and increasing consumption until environmental laws, such as the Clean Air Act and green technology implementations, began to lower pollution intensity. The EKC hypothesis demonstrates this negative relationship through which wealth enhances environmental protection. The rapid industrialization that has occurred since the 1990s brought about a significant increase in EF in China because of its dependence on coal energy and growing urban areas. After 2010, China implemented new energy programs to reduce E, suggesting that the country may be transitioning to the negative slope of EKC. France and the UK demonstrate weak connections between environmental degradation and economic growth. They operate advanced economies and enforce strict environmental policies that allow for innovation and proper governance to separate economic expansion from ecological damage.

5.2. Tourism's Unidirectional Impact on EF

According to the findings, the research establishes that T (tourism) causes EF (environmental pressure), while EF does not impact tourism. The French tourist industry expanded EF by developing energy-intensive facilities such as ski resorts alongside its waste-production systems. Since 2000, the United States has experienced a rise in international tourists, which has led to enhanced carbon pollution in the transportation and hospitality sectors. The weak T-EF connections between Pakistan and India reflect their underdeveloped tourism infrastructure and the small number of tourists in these developing countries. Implementing sustainable tourism policies incorporating eco-certification processes and low-carbon transport systems presents a mechanism to reduce EF effects in developing economies while supporting growth potential.

5.3. Globalization's Dual Role

The effects of globalization (G) on environmental friendliness (EF) are mutual because G uniquely influences environmental outcomes twice. China and India experienced increased ecological pollution because of their manufacturing outsourcing activities, including textile exports and their imports of coal resources, which supports the idea of a "pollution haven." France, together with the UK, exploits global opportunities to implement clean technologies through EU renewable subsidy programs that lead to diminished EF, according to [Zafar et al. \(2019\)](#). The weak EF–globalization connection in Russia stems from its resource-based economy, which mainly enhances petroleum exports instead of green innovation.

5.4. Nuclear Energy's Complex Role

The relationship between nuclear energy (NE) and EF functions equally in two directions. French NE operations substitute fossil fuel power-generation systems, which decrease carbon emissions at the expense of reactor installations and waste-management site requirements. Operating nuclear plants across the United Kingdom's aging power system leads to offsetting benefits against decommissioning expenses. Pakistan and India need specific NE policies because their developing nuclear programs create a higher environmental footprint through uranium mining and infrastructure growth. France and the UK must recognize that their priority should be reactor modernization. At the same time, India and Pakistan need to distribute NE investments between traditional reactor plants and renewable sources to prevent sudden EF increases.

5.5. Demographic Drivers: Population Density and Fertility

The connection between population density (PD), fertility rates (FR), and EF exists in India and Pakistan as a two-way effect. India's distinct population density pushes against land resources, thus increasing both agricultural expansion and urban environmental footprint, whereas Pakistan's elevated fertility rates intensify waste-generation and water-scarcity problems. The population density in Russia is minimal, while declining fertility rates within the country lead to a diminished environmental footprint and raise healthcare waste levels through population aging. The connection between EF and PD is weakest in France and the UK due to urban-planning efforts such as maintaining parks and family-planning approaches that reduce demographic stresses. Reproductive health strategies (SDG 3) and sustainable urban practices must be priorities for dense nuclear economies because they determine their overall success.

5.6. Natural Resource Rent's Limited Role

The researchers find it interesting that no causal relationships exist between total natural resource rent (TNRR) and EF. The Russian economy depends on TNRR generated from oil and gas production, which does not cause EF to increase or decrease, probably because the government controls exports and restricts domestic use. Currently, China has a low total natural resource rent compared to its environmental footprint, because manufacturing activities and imports generate the most ecological pressures. The study indicates that resource rents have less impact on environmental footprint than trade dynamics and domestic policies, making these results crucial for India and Pakistan as they attempt to move beyond fossil fuels.

6. Conclusions and Policy Suggestions

The research demonstrates that economic growth and tourism strongly affect ecological footprint numbers alongside processes of globalization, such as natural resource removal, lean energy usage, and population density and birth rates. The research proves that governments need to put sustainability at the forefront and dedicate funding to advanced clean solutions for controlling environmental consequences created by these variables. The discovered evidence demonstrates why specific national policies should be adapted to fulfill each country's individual economic and ecological requirements. This section presents detailed policy recommendations based on the study's environmental footprint (EF) driver analysis, which explicitly addresses Russia, the US, China, France, the UK, Pakistan, and India.

Economic growth in the United States should be separated from environmental destruction through targeted policy implementation. The Environmental Protection Agency needs increased authorization to regulate industrial emissions better, while government agencies must stop subsidizing fossil fuel industries. According to research showing a two-way relationship between economic growth and EF, the author promotes green technology tax breaks for renewable energy systems and electric vehicles. Implementing electric shuttle systems in Yellowstone National Park's high-impact regions reduces EF effects because tourism activities have been proven to increase EF unilaterally.

The Government of China needs to expedite the closure of coal-fired power plants while advancing renewable energy deployment throughout its manufacturing strongholds, specifically in Guangdong. The study reveals that industrial EF growth makes digitizing energy optimization with smart grids essential. Urban planners who implement mixed-use developments in Shanghai have an opportunity to decrease EF associated with land use produced by urban sprawl. Tourism emissions, including Hainan Island flight emissions, could create financing to restore forests because current tourism activities produce only one-way negative EF effects.

The aging French nuclear reactors should be modernized through increased Flamanville reactor lifespans while the country invests in small modular reactors (SMRs) to minimize construction emissions. The combination of nuclear power generation with offshore wind projects in Normandy operates according to the relationship between energy production and the environmental impact of nuclear resources and EF. According to the research results linking tourism with expanded EF, public tourism policies should specify hotel retrofits for energy efficiency and promote railway transportation instead of short-distance flights.

The United Kingdom can resolve nuclear energy's two environmental consequences by implementing small modular reactors at Hinkley Point C alongside tidal-power initiatives at Swansea Bay. After Brexit, the UK could use environmental standards on imported goods to control pollution, exploiting globalization's dual effects. Combining urban green

belts surrounding London with family-planning services integrated into NHS wellness programs would help reduce population density and fertility rate effects.

Pakistan must establish strong safety measures for Karachi's K-2/K-3 nuclear reactors because these safety protocols should integrate with solar/wind projects to lower environmental impact. Vertical farming systems installed in densely populated urban regions of Karachi would help control population growth, and sending mobile healthcare facilities to rural Sindh could increase access to family-planning services to manage the expansion of the total environmental footprint. The local communities of Gilgit–Baltistan can launch eco-tourism initiatives, which will help restrict infrastructure growth.

India must strengthen its “Beti Bachao Beti Padhao” family-planning initiative and the mixed-use developments specified in the Smart Cities Mission to tackle urban expansion. Integrating nuclear energy facilities such as Kudankulam with rooftop solar initiatives and a Nuclear Safety Regulatory Authority operates as a solution for managing nuclear EF trade-offs. The government should use tax revenue from fossil fuels to pay for renewable energy programs such as the Punjab solar-pump initiative, because this approach matches the study's results regarding economic growth dependency on environmental factors.

Russia needs to establish diversified renewable programs in Arctic regions, like implementing wind power facilities in Murmansk; it should dedicate natural resource revenues to developing green technology research while building mechanisms to reduce industrial waste's effects on environmental deterioration from extraction activities. Russia can improve the EF's role in globalization through green trade negotiations with EU member countries and additional regulations on environmental evaluation for international investments.

To effectively reduce environmental risks, countries must participate in international initiatives such as the Global Methane Pledge while implementing IAEA standards as models for nuclear safety in Pakistan and India. Implementing UN SDG reporting standards by EF and establishing Chinese-type national awareness programs for environmental responsibility would maximize their sustainable impact. This investigation establishes specific policy recommendations that assist countries in utilizing unique challenges for environmental benefits and the advancement of sustainable development goals.

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Abbreviations

The following abbreviations are used in this manuscript:

EF	Ecological Footprint
EG	Economic Growth
T	Tourism
G	Globalization
NE	Nuclear Energy Use

TNRR	Total Natural Resource Rent
PD	Population Density
FR	Fertility Rate

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