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How do nuclear energy consumption, environmental taxes, and trade globalization impact ecological footprints? Novel policy insight from nuclear power countries

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ABSTRACT

Energy systems should grab the opportunity to adopt clean energy sources and technologies to mitigate environmental impacts. This work explores the influence of nuclear energy consumption on reducing the ecological footprint, considering environmental taxes and trade globalization in five nuclear-powered economies from 1990 to 2021. This study employed several econometric models, including the preliminary analysis, the CS-ARDL test for long-run forecasting and the Dumitrescu-Hurlin causality test. The long-run findings revealed that nuclear energy usage and environmental taxes support reducing environmental costs by lowering the ecological footprint. However, trade globalization raises environmental costs by increasing the ecological footprint. Additionally, causality test outcomes show that a one-way causal link exists among nuclear energy and the ecological footprint. The results highlight government actions prioritizing investment in nuclear energy consumption projects and encouraging nuclear energy efficiency to mitigate ecological degradation and lead to a low-carbon future. This viewpoint also encourages policymakers to make well-informed decisions to uphold ecological sustainability.

Abbreviations

ECF	Ecological footprint	*TGLOB*	Trade globalization
CO_2	Carbon emissions	DHC	Dumitrescu and Hurlin panel causality
CSD	Cross-section dependence	CS-ARDL	Cross-sectional augmented distributed lag
EG	Economic growth	*PD*	Population density
AMG	Augmented mean group	*ENT*	Environmental Tax
NEC	Nuclear energy consumption	CCEMG	Common correlated effect mean group
SDGs	Sustainable development goals		

1. Introduction

The world currently faces significant environmental challenges, including resource depletion, air and water pollution and other forms of ecological degradation, largely driven by human activities [1]. The Global Footprint Network reports that human activities exceed Earth's carrying capacity by approximately 75 %.[1] This substantial environmental impact has broad implications, affecting economic activity, public health, and energy availability [2]. In response to these critical issues, many nations have implemented various measures aimed at conserving natural resources and reducing their ecological footprint [3]. Almost all nations have committed to reducing their carbon footprints by signing the Paris Climate Agreement. Moreover, the growth of human society and economies is tightly linked to energy consumption, which continues to drive global energy demand [4]. Currently, fossil fuels (FF) account for over 80 % of energy consumption, making a significant

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[1] https://www.footprintnetwork.org/our-work/ecological-footprint/.

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contribution to global pollution [5]. As a result, numerous countries are advancing energy transition policies to shift from fossil fuels to cleaner energy sources, aiming to balance energy needs with environmental considerations [6]. Recently, several nations have identified nuclear energy as a viable alternative to help address these environmental issues.

Nuclear energy plays an important part in transforming a more sustainable community due to its minimal ecological impact, high energy density, and capacity to provide electricity promptly, all while using less land than other energy sources [7]. Unlike traditional energy sources, nuclear power plants emit only a few greenhouse gases during operation, making them a pivotal solution for mitigating the ecological footprint associated with energy generation [8]. Nuclear energy enhances resource efficiency by safeguarding ecosystems from the harmful impacts of producing and consuming traditional energy sources, rapidly depleting natural resources [9]. In that sense, replacing conventional energy sources with nuclear power minimizes resource waste and establishes a foundation for a more efficient, less resource-intensive, and environmentally friendly growth model [10]. In that sense, nuclear energy represents an optimal choice for supporting environmental policies focused on achieving global ecological stability and ensuring energy security. Additionally, advancements in nuclear technology also contribute to improved waste management and enhanced safety protocols, ensuring better environmental protection [11]. However, despite the advantages of nuclear energy, nuclear power plants pose potential risks to the environment due to operating safety, radioactive waste disposal, the danger of nuclear proliferation, and public perception [12].

Although it is helpful to scrutinize the effects of *NEC* on ecological degradation, preventative measures through legislative rules also help decrease the impact of ecological degradation. In that sense, environmental taxes (*ENT*) are a proactive strategy to maintain ecological superiority by reducing pollutant emissions and ecological impact, particularly with energy usage [13]. These tax policies are implemented by governments to protect the environment, stress environmental effectiveness and economic efficiency, and encourage the efficient use of resources, especially energy [14]. Environmental taxes impose stricter constraints on resource-intensive processes in enterprises, increasing their financial burden through higher environmental costs [15]. At the same time, decision-makers offer special tax concessions to enterprises with low pollutant emissions and provide financial incentives for those making environmental investments. This dual approach encourages companies to develop green technologies, sustainable production, improve energy efficiency, and reduce waste, contributing to a reduced ecological footprint [16]. Furthermore, the government's revenue from environmental taxes can be reinvested into conservation projects, renewable energy infrastructure, and environmental restoration efforts to further reduce the ecological footprints [17]. Implementing taxes has long-term benefits, such as preventing climate change, limiting the overuse of natural resources, increasing awareness, and stimulating innovation in green technologies [18].

The relationship among trade globalization (*TGLOB*) and ecological footprint is a subject of discussion, as trade globalization is an emerging key predictor of environmental changes [19]. The expansion of international trade and investment has led to increased usage of natural resources, energy, and land, resulting in a contribution to ecological footprint [20]. This is due to several factors, including the growing demand for goods and services, the intensification of production processes, and the transporting of goods over long distances [21]. In addition. trade globalization is aggravated by the absence of environmental controls and standards in some countries, allowing for the extraction of resources and externalizing ecological costs. In that sense, expanding global supply chains has resulted in transferring environmental impacts from developed to poor countries, where environmental controls are frequently weaker [22]. Contrary, it is crucial to acknowledge that trade globalization significantly improves environmental sustainability through nuclear power generation technology transfer and effective international trade policy [23]. Moreover, trade globalization encourages innovation, raises living standards, and benefits the environment by manding trade.

The current work considers five countries that are major nuclear energy consumers, including China, India, Japan, Russia, and the USA. The rationale behind selecting the five major nuclear countries lies in their status as several important developing markets in the world. These nations have experienced remarkable economic growth, accounting for about 53 % of the world GDP in 2022, by playing pivotal roles in international trade and financial stability. These nations are the populated, industrialized, and highly energy-consuming nations, accounting for 57.5 % of global energy consumption in 2022. Moreover, these nations are the leading contributors to pollution in the environment with the highest ecological footprint, thereby putting a burden on biocapacity through increased ecological footprints, accounting for more than 51 % of the global total *ECF* in global hectares (See Fig. 1). Moreover, these countries are major consumers of nuclear energy. Nuclear energy demand has increased since 2012, with a significant increase of 3.8 % expected in 2021. These selected nations accounted for about 55.6 % of global nuclear consumption in 2021, with the United States (29.3 %) as the highest nuclear consumer, followed by China (14.6 %), (Russia 7.9 %), Japan (2.2 %), and India (1.6 %). Therefore, boosting the proportion of nuclear energy in these nations' energy diversification plans is essential to preserving and enhancing the environment.

Various existing literature has primarily focused on analyzing the influence of nuclear energy usage on CO^2 emissions and *ECF*. However, these studies have overlooked the impact of nuclear energy consumption on the *ECF* with the unified framework of environmental taxes, particularly in the chosen panel of countries. Additionally, findings from earlier research are often inconclusive and varied, largely due to the reliance on outdated and conventional estimation methods. None of these studies have comprehensively considered trade globalization within a unified framework. Thus, the limitations of earlier research motivate us to make novel contributions by examining the effects of nuclear energy usage on the ecological footprint within the framework of environmental taxes and trade globalization in five major nuclear power nations. This research seeks to answer the following unanswered questions: What unexpected effects could arise from the implementation of nuclear energy and environmental taxes on the *ECF*? How does trade globalization affect the *ECF*? Which policies are most effective in reducing the ecological footprint?

The key contributions of our work are outlined as follows: First, it probes the influence of nuclear energy consumption on the ecological footprint in the same framework of environmental taxes. While earlier works have concentrated on these variables individually, this research integrates them into a unified framework. This research provides valuable insights into nuclear energy's critical role in the transition to clean energy and its impact on reducing ecological footprints for sustainable development. This study offers a deeper recognizing of the dual role of environmental taxes as both incentives for sustainable practices and revenue-generating mechanisms for clean energy transition and ecological improvements. Second, our study incorporates trade globalization into the analysis. No research explicitly identifies trade globalization as a potential factor contributing to the *ENT*. The statistical evidence informs the possible role of trade globalization in developing effective strategies for reducing the ecological footprint while promoting economic growth. Third, this study employs an effective econometric model to evaluate the data and forecast the correlations between variables, especially the CS-ARDL, for long-run analysis. Other models, such as AMG and CCEMG, are also used to strengthen the dependability of the outcomes by ensuring the validity and robustness of findings. Unlike many traditional statistical approaches, they consider problems including endogeneity and CSD within the model, thereby capturing the true effects more accurately.

This research analyzed panel data from leading nuclear nations from

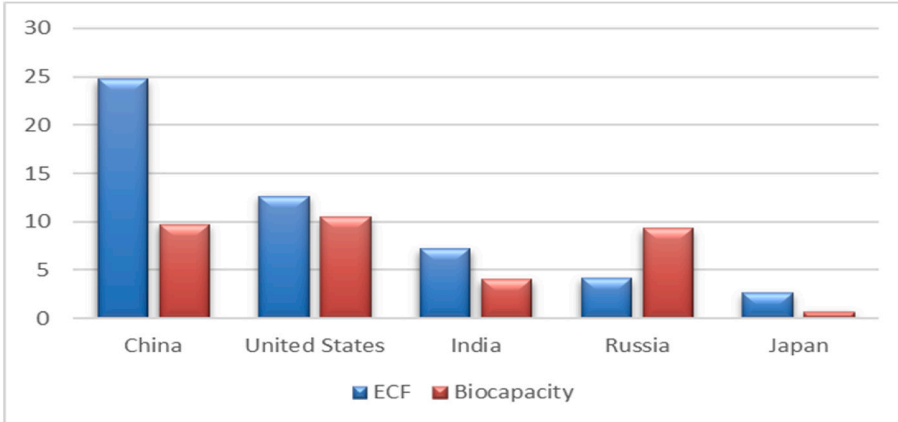

Fig. 1. Biocapacity and EFP in GHA of particular nations.

1990 to 2021 using the CS-ARDL model, providing valuable results that enrich the existing literature. The empirical outcomes suggested that nuclear energy consumption, environmental taxes, and population density contribute to the depletion of ecological footprints, while trade globalization and economic growth lead to increased ecological footprints across selected nations. This study provides policy recommendations to boost nuclear energy investments and environmental taxes while offering key insights for decision-makers addressing environmental challenges through trade globalization and promoting ecological sustainability.

This study has five parts: the 2nd part concentrates on an empirical literature evaluation.3rd part contains theoretical underpinnings· 4th part goes over the methodology and data that were used. 5th and 6th part contains the findings and discussions, and 7th part contains the conclusion, policy implications, and future directions. Fig. 2 shows the roadmap of this study.

2. Literature review

The study explores the influence of *NEC*, *ENT*, and *TGLOB* on ecological footprints. While nuclear energy garners significant attention from policymakers and scholars advocating for a low-carbon economy, its specific impacts on ecological footprints are not well-established in the literature. Developments in clean energy have a profound effect on economies, communities, and the environment [24]. Poinssot et al. [25] stated nuclear energy has been presented as a potential option for reducing *ECF* and minimizing the effects of climate change. Nuclear energy stands out as an environmentally beneficial and sustainable solution with low carbon qualities and the preservation of natural uranium resources in an ideal energy scenario. McCombie et al. [26] highlighted that nuclear energy is a land-efficient and high-energy density source for rapidly generating electricity compared to other renewables and fossil fuels.

The recent literature of Mehboob et al. [27] and Shen et al. [28] documented that nuclear energy is essential to global energy conservation efforts, enhancing efficiency and limiting negative environmental repercussions [29]. Studies like Sadiq et al. [5], Hassan et al. [30], and Kartal et al. [29] probed the impact of nuclear energy usage on *ENT* and argued that nuclear power could encourage a more sustainable community by providing low-carbon options to conventional fossil

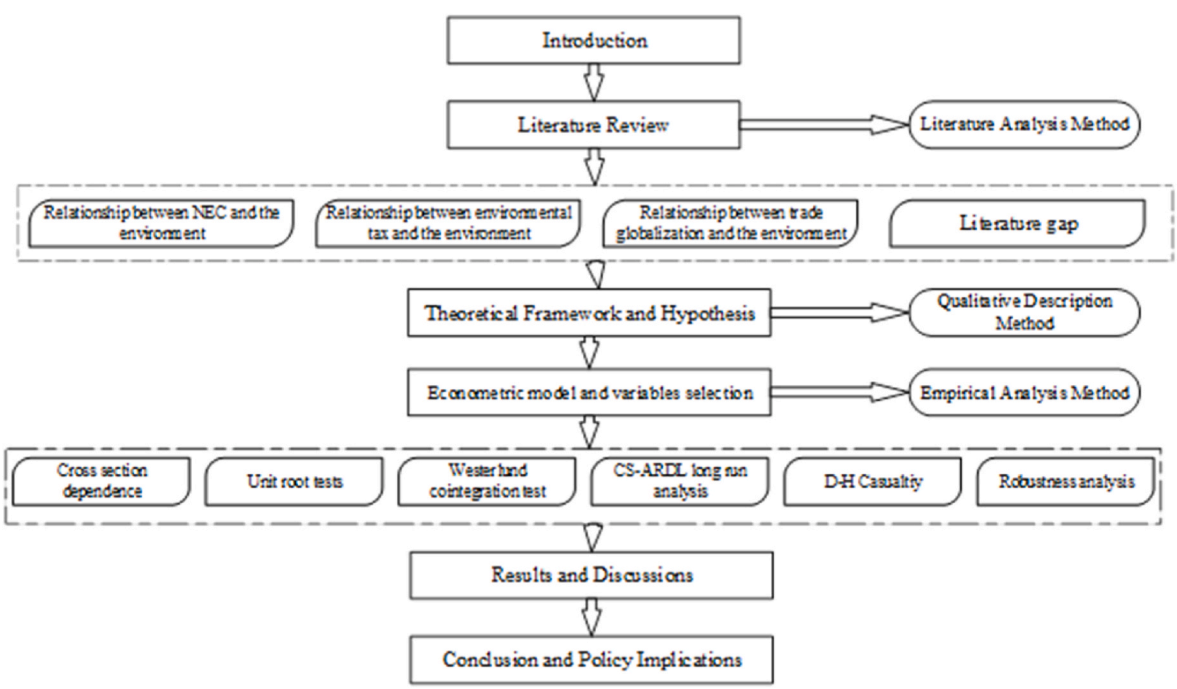

Fig. 2. Roadmap.

fuel-powered electricity generation. Similarly, Zhang et al. [31] the impact of *NEC* on the environmental footprints of nuclear power nations. They concluded that *NEC* is critical in promoting environmentally sustainable growth by reducing the *ECF*. A lot of other literature, including Cakar et al. [27], Azam et al. [32] and Caglar [33] support the idea that nuclear energy consumption has emerged as a highly successful tool for combating rising CO_2 emissions, shielding ecological quality, and slowing the rate of climate change. However, there exists contrasting research in this field, such as Sarkodie and Adams [34], Mahmood et al. [35], and Kim [36] highlighted the negative and nonpareil impression of *NEC* on environmental sustainability.

Previously, many studies have highlighted the significance of environmental tax in addressing ecological degradation. In that sense, Mehboob et al. [37] stated that environmental taxes are fiscal measures imposed by governments on activities that have a harmful impact on environmental degradation, seeking to encourage eco-friendly behaviour through the use of financial incentives. The goal is to make organizations and individuals more financially motivated to implement cleaner, more sustainable practices by internalizing the external costs connected with ecological degradation. *ENT* has become a valuable instrument for lowering ecological footprint and preventing environmental deterioration [30]. Such as Rafique et al. [14] and Javed et al. [38] analyzed the impact of *ENT* on mitigating the ecological degradation in OECD economies. They concluded that *ENT* considerably reduces long-term ecological footprint and boosts environmental quality [39]. Similarly, Ahmad and Satrovic [39] evaluated the influence of *ENT* on the ecological footprint; they concluded that environmental taxes have an important role in enhancing environmental sustainability by lowering the ecological footprint. Numerous works, such as Telatar et al. [40], Hao et al. [28], and Zhang et al. [41], have been undertaken to support the effectiveness of *ENT* in reducing CO_2 emissions. They concluded that solid environmental standards effectively reduce both the *ECF* and CO_2. On the other hand, several studies have found contrary expectations that environmental taxes negatively influence ecological quality, and some studies found that ENT does not impact environmental degradation. Such as Xie and Jamaani [42], Telatar and Birinci [18], and Wolde-Rufael and Mulat-Weldemeskel [43] argued that *ENT* is ineffective at reducing CO_2 emissions. Doğan et al. [44] concluded that *ENT* increases carbon emissions, which leads to ecological deterioration.

Globalization has expanded market access for firms by lowering trade barriers. Trade globalization increases the ecological footprint by promoting the spread of global trade, resulting in greater production and consumption patterns. Moreover, global trade frequently entails large-scale exploitation and transportation of natural resources. This may result in resource depletion, deforestation, and habitat damage, all contributing to environmental degradation. Many studies have investigated the environmental impact of globalization on the ecological footprint. For instance, Murshed et al. [19] inspected the impact of *TGLOB* on CO_2 emissions in Argentina, and they argued that *TGLOB* leads to increased pollution emissions. Awosusi et al. [22] probed the influence of *TGLOB* on environmental degradation. They found that trade contributed to the rise in CO_2 emissions. Sethi et al. [45] and Sadiq et al. [6] suggested that the rising trend of globalization has a damaging impact on the atmosphere to handle stress and directly leads to ecological deterioration through growing energy usage and economic expansion [7]. There are some contrary results of trade globalization on the environment, such as Ahmed and Le [40] evaluated the stimulus of *TGLOB* on environmental deterioration and established contrary results that *TGLOB* is a positive factor in attaining environmental sustainability in these countries since it efficiently cuts emissions. Similarly, Zaidi et al. [41] discovered that the expansion of *TGLOB* can improve ecological sustainability by promoting the distribution of advanced technologies. Due to the lack of a scholarly consensus on the subject, the results of these investigations remain unclear.

To summarize the literature, the influence of *NEC* on environmental economics has been the subject of extensive work. Still, documented evidence is scarce regarding the impact of nuclear energy consumption on ecological footprint, and previous studies have produced conflicting and inconsistent results. However, these studies overlooked the literature on environmental tax and trade globalization on ecological footprint under the same framework of nuclear energy consumption. This research proposes a novel contribution to earlier literature by evaluating the impacts of nuclear energy usage on mitigating the ecological footprint under the role of *ENT* and *TGLOB* in five nuclear power countries by utilizing solid approaches to provide reliable insight into this relationship.

3. Theoretical underpinnings and hypothesis

The analytical framework explores the interconnection of NEC, ENT, and TGLOB to alleviate the ecological footprint. The ecological footprint (EF) has become a vital tool in contemporary environmental management discussions. It comprehensively assesses resource demand across various sectors and highlights the ecological deficit that arises when resource consumption and waste generation surpass sustainable levels [4]. By integrating *ECF* into policy and decision-making processes, stakeholders can gain valuable insights into environmental challenges and work to mitigate ecological degradation. The *ECF* is recognized as a crucial metric for evaluating the sustainability and impact of human activities, guiding efforts toward more responsible resource use and environmental stewardship. In that sense, our study followed different the theories which suggest that environmental challenges arising from economic activities can be mitigated through improvements in energy efficiency, resource efficiency, and technological innovation. The given hypotheses are designed to be consistent with the theoretical framework and the knowledge gained from the discussed literature investigations. Fig. 3 outlines the major components of the theoretical framework.

Globally, energy consumption and environmental degradation are major challenges concerning human rights. Because of increased energy usage, balancing greenhouse gas reductions with economic growth is difficult. In this sense, ecological modernization theory highlights that nuclear energy can reduce the ecological footprint by offering a comparatively low-carbon substitute for fossil fuels [8]. Its consumption supports energy efficiency, enhances energy security, and facilitates the development of clean energy projects [5]. Nuclear energy has a high energy density, meaning it can produce large amounts of energy with relatively small amounts of fuel [46]. Moreover, the efficient consumption of nuclear energy can help boost energy sustainability, poverty alleviation, environmental protection, and human welfare by providing affordable and clean energy choices [31]. This evaluation is essential for developing effective climate policies considering nuclear energy's potential environmental effects.

H1. Implementing nuclear energy consumption reduces the ecological footprint

Environmental taxes are an important part of a larger regulatory framework that aims to boost environmental quality and long-term economic growth [47]. The Pigouvian taxation theory proposes that taxing activities that produce negative externalities, such as ecological footprint, encourages polluters to decrease emissions or embrace cleaner energy and technologies. Environmental taxes allow decision-makers to reduce the external costs of pollution and resource depletion inside the country. Businesses and individuals can be incentivized financially to adopt green technologies if governments impose taxes on activities with negative environmental effects, such as polluting emissions and natural resource extraction [48]. In addition, these taxes can encourage people to alter their behaviours, resulting in less pollution, less waste, and the expansion of cleaner technologies such as nuclear energy-based technologies [49]. Therefore, it is vital to investigate the ecological impacts of environmental tax.

H2. Encouraging environmental tax mitigates the ecological footprint

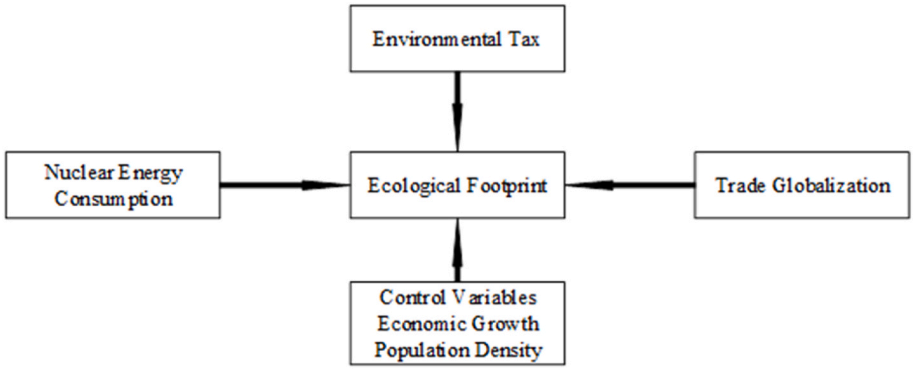

Fig. 3. Theoretical framework.

Trade globalization is an increase and integration of trade between countries, which leads to more global exchanges of goods, services, and investments. In that sense, more energy, infrastructure, and natural resources are required for this process, which can degrade the environment [19]. The Pollution Haven Hypothesis posits that companies relocate production to countries with lax environmental regulations, creating "pollution havens" where ecological footprints expand unchecked. Trade globalization allows industries to circumvent strict rules, increasing the global ecological footprint in regions with fewer environmental protections. Trade globalization can increase waste generation and production to meet consumer needs, leading to the overuse of resources and expanding ecological footprints [50]. Despite these issues, ecological moderation theory suggests that globalization can potentially increase the dissemination of new green technologies through relaxed trade rules and the elimination of borders [11]. This theory also suggests that trade globalization might facilitate the global spread of nuclear technology and expertise, streamlining the advancement of nuclear infrastructure while also necessitating the establishment of worldwide safety and security standards. Thus, the impressions of trade globalization on ecological contamination must be factored into any thorough investigation.

H3. Trade globalization boosts the ecological footprint

4. Methodology

4.1. Empirical model

To evaluate the dynamic connection between *ECF*, nuclear energy usage, trade globalization, environmental taxes, population density, and economic growth. In chosen panel data analysis, this study employs an initial functional form.

$$ECF = f(\text{NEC}, \text{ENT}, \text{TGLOB}, \text{EG}, \text{PD}) \tag{1}$$

where *ECF* and *NEC* denote ecological footprint and nuclear energy consumption, *TGLOB* denotes trade globalization, *ENT* signifies environmental tax, *EG* represents economic growth, and *PD* for population density, respectively. The data series is normalized by using natural logarithms for each variable in line with the approaches outlined by Shahbaz et al. [44]. This logarithmic transformation is very useful when dealing with data that has exponential growth or multiplicative relationships. The natural logarithm is used to scale the data, and the percentage changes become additive, allowing for more meaningful interpretations. This allows coefficients to be interpreted as elasticities, describing the responsiveness of one variable to changes in another. We use the econometric specification given by Eq. (2), which is the log transformation.

$$\ln ECF_{it} = \lambda_0 + \lambda_1 \ln\text{NEC} + \lambda_2 \ln\text{ENT} + \lambda_3 \ln\text{TGLOB} + \lambda_4 \ln\text{EG} + \lambda_5 \ln\text{PD} + \varepsilon_{it} \tag{2}$$

where "i" represents cross-sections and the "t" stands for the period (1990–2020). The anticipated residual represents deviations from long-run stability and long-run parameters pertain by λ_1 -λ_5.

4.2. Data sample and variables selection

The chosen of the ecological footprint as a dependent variable is justified by its widespread acceptance and comprehensive assessment of human impact on the environment, encompassing resource consumption and waste generation. The ecological footprint per capita was measured in global hectares (gha) per person, and the data were obtained from the Global Footprint Network. The primary independent variable under examination is nuclear energy utilization, which is recognized for its low-carbon characteristics as it produces power without emitting greenhouse gases. Nuclear energy statistics were taken from the British Petroleum Statistical Review of World Energy and are calculated in millions of tons of oil equivalent. This study selects environmental taxes as the second independent variable due to their dual role in addressing environmental issues and funding conservation efforts. Environmental taxes align with sustainability principles by internalizing pollution costs and promoting eco-friendly practices. The *ENT* data were taken from the World Bank and measured in percentage of GDP. The independent variable is trade globalization, representing global interconnectedness through exchanging goods, services, technology, and ideas, which influences the environment through heightened international trade and transportation. Trade globalization was measured by the KOF index, and statistics were obtained from the KOF Swiss Economic Institute website.

The economic growth data used in this study were obtained from the World Bank database and were calculated in terms of per capita GDP constant 2015 USD. Sadiq et al. [5] specified that human production and living activities majorly affect environmental degradation. Rapid economic growth can lead to overexploitation of natural resources, contributing to deforestation, habitat loss, and nonrenewable resource depletion. Population density is an important demographic characteristic that must be carefully considered in the selected panel. Data measuring population density as individuals per square kilometre were sourced from the World Bank`s database. Population density quantifies the number of individuals in a specific area and significantly impacts the environment. High population density has the potential to improve environmental quality. This density considerably impacts environmental quality by encouraging renewable energy, green building technologies, and efficient public transport [51][]. On the other hand, it is speculated that rapid population growth frequently leads to habitat degradation, air and water pollution, resource depletion, and climate change. Growing populations are also linked to problems with urbanization, food security, water scarcity, and increased waste production [52]. The studied data includes annual data based on data availability for five nuclear economies (China, India, Japan, Russia, and the US) from 1990 to 2021. The data is sourced from multiple databases and measures in different units, as indicated in Table 1.

4.3. Estimation techniques

CSD detection is the primary objective of the econometric analysis of panel data. The CSD test is essential for examining geographic impacts, unidentified joint shocks, and the existence of relationships inside a social network. This analysis is necessary to avoid biased stationarity and cointegration results, ensuring more accurate and effective information. The Pesaran CSD is calculated as follows:

$$CSD = \sqrt{\frac{2T}{N(N-1)}}\left(\sum\nolimits_{i-1}^{N-1}\sum\nolimits_{j=i+1}^{N}\rho_{ij}\right), N\left(0,1\right) \tag{3}$$

The pairwise correlation coefficients are shown by the notation ρ_{ij}, N and T = 1, 2,..,. The H_0 = no CSD and H_1 =CSD exists in the model.

Unit root analyses are frequently used to ensure the correctness of economic event assessments, decreasing reliance on untrustworthy datasets. Furthermore, these tests are critical in determining the stationarity of each series inside a panel model. Panel unit root tests have greater robustness and significance when compared to typical time-series unit root testing. This work applied a 2-s generation test, including CADF and CIPS tests coined by Pesaran [57] to check stationarity among variables. Second-generation stationarity tests are preferred over first-generation counterparts when dealing with CSD and heterogeneous panel data. The CIPS statistic is written as follows:

$$CIPS = \frac{1}{N}\sum\nolimits_{i-1}^{N} CDF_i(\mathrm{N}, \mathrm{T}) \tag{4}$$

when the CIPS statistic is combined, it lacks a normalized asymptotic limit, and critical values for various N values are established.

A panel cointegration model determines the selected variables have long-run interrelationships after confirming the unit root integration. This research utilized a panel cointegration test created by Westerlund [58] to determine whether cointegration exists in a panel dataset. This approach overcomes the issues of heterogeneity and CSD in panel data, making it a viable alternative to conventional cointegration approaches. This test provides panel-oriented error-correcting test statistics with distinct panel statistics (Pτ and Pα) and group statistics (Gτ and Gα). The cointegration statistic is expressed as follows:

$$ai(\mathrm{L})\Delta y_{i,t} = \gamma 1_{i,t} + \gamma 2_{i,t} + \beta_i\left(y_{i,t} - 1 - a_i x_{i,t} - 1\right) + \lambda_i(\mathrm{L})\nu_{i,t} + \eta_i \tag{5}$$

The parameters $\gamma 1i$ and $\gamma 2i$ represent the long-term dynamics of the series, while L indicates the lag operator. The term $\beta i' xit-1$ refers to the preceding period's vector of independent variables, while stands for error correction.

This work applied a cross-sectional augmented autoregressive distributed lag (CS-ARDL) technique, determining the variables' short and long-run outcomes [59]. The CS-ARDL approach has significant advantages over traditional econometric models regarding variable endogeneity, unobserved heterogeneity, and CSD. The key advantage of the CS-ARDL framework is its ability to address potential sources of latent variables using the correlated effects approach. This integration occurs in the context of the panel ARDL method, in which the lag of the dependent variable is characterized as a weakly exogenous variable inside the error correction structure. In addition, the CS-ARDL approach resolves problems with missing variables and small sample sizes and works with balanced and unbalanced panel data. The CS-ARDL is mathematically formulated as follows:

$$y_{i,t} = a_i + \sum_{j=1}^{x}\delta_{ij}p_{i,t-j} + \sum_{j=0}^{y}\xi_{ij}q_{i,t-j} + \sum_{j=0}^{N}\phi'_{ij}\overline{Z_{i,t-j}} + \varepsilon_t \tag{6}$$

In this model, Z = $(p_i, q_i)'$ stands for the cross-sectional units that each unit's independent variables (q_i) and endogenous variable (p_i). The residual term is indicated by ε_t , and N specifies the lag duration.

To ensure the CS-ARDL outcomes, AMG and CCEMG are used for robustness. These methods carry out long-run estimations by combining heterogeneity and CSD. Their findings give deeper insights into the associations among the selected variables and assure the resilience and reliability of the model's conclusions, regardless of the assumptions or data used.

CS-ARDL does not clearly show the precise directions of short-run causality among the variables. Nonetheless, long-term panel correlation and potential cointegration among the variables suggest that causal links exist in at least one direction. Therefore, the Dumitrescu and Hurlin causality (DHC) method was employed to check the causal direction between variables to see if any of the variables could be used to predict the status of the others [60]. The DHC model incorporates both CSD and heterogeneity. The DHC statistic can be written as follows:

$$P_{i,t} = \alpha_i + \sum_{i=1}^{q}\gamma_i^n P_{i,t-i} + \sum_{i=1}^{q}\lambda_i^n\beta_{i,t-i} + \varepsilon_t \tag{7}$$

In the D-H equation, the constant is denoted by αi, the regression parameter by γ_i^n, and the auto-regression coefficients by λ_i^n. H_0 argues that the selected panel has no causal relationship, while H_1 suggests that casual relationships exist between the variables.

5. Empirical results

Table 2 exhibits the descriptive analysis of variables measured in log form. The descriptive stats display that all variables have positive mean values; nevertheless, Ln*ECF* demonstrates greater volatility compared to the other parameters. On the other hand, Ln*TGLOB* is less volatile than the rest of the factors. Fig. 4 depicts a boxplot graph displaying a selected panel's data distribution and summary statistics.

The CSD outcomes are revealed in Table 3. Both Pesaran scaled LM CSD, and Pesaran CSD models disproved the cross-sectional independent

Table 1
Data sources and variables description.

Variables	Symbols	Measurements	Data Source
Dependent variable			
Ecological footprint	*ECF*	Global hectares per person	Carbon footprint network [53]
Independent variables			
Nuclear energy consumption	*NEC*	Millions of tons of oil equivalent	British Petroleum [54]
Environmental taxes	*ENT*	Percentage of GDP	World Bank [55]
Trade globalization	*TGLOB*	KOF Trade Globalization Index	KOF Index [56]
Control variables			
Economic growth	*EG*	GDP constant 2015 US$	World Bank [55]
Population density	*PD*	Individuals per square kilometre of land area	World Bank [55]

Table 2
Descriptive statistics.

	Ln*ECF*	Ln*NEC*	Ln*ENT*	Ln*TGLOB*	Ln*EG*	Ln*PD*
Mean	4.664	−0.092	1.313	1.633	12.400	2.387
Median	4.911	0.155	1.200	1.652	12.439	2.423
Std. Dev.	3.030	0.706	0.606	0.096	0.560	0.153
Skewness	0.398	−0.530	0.205	−1.078	−0.183	−0.529
Kurtosis	2.219	2.587	2.776	3.575	1.861	2.030
Jarque-Bera	8.034	8.359	1.409	32.21	9.251	13.32

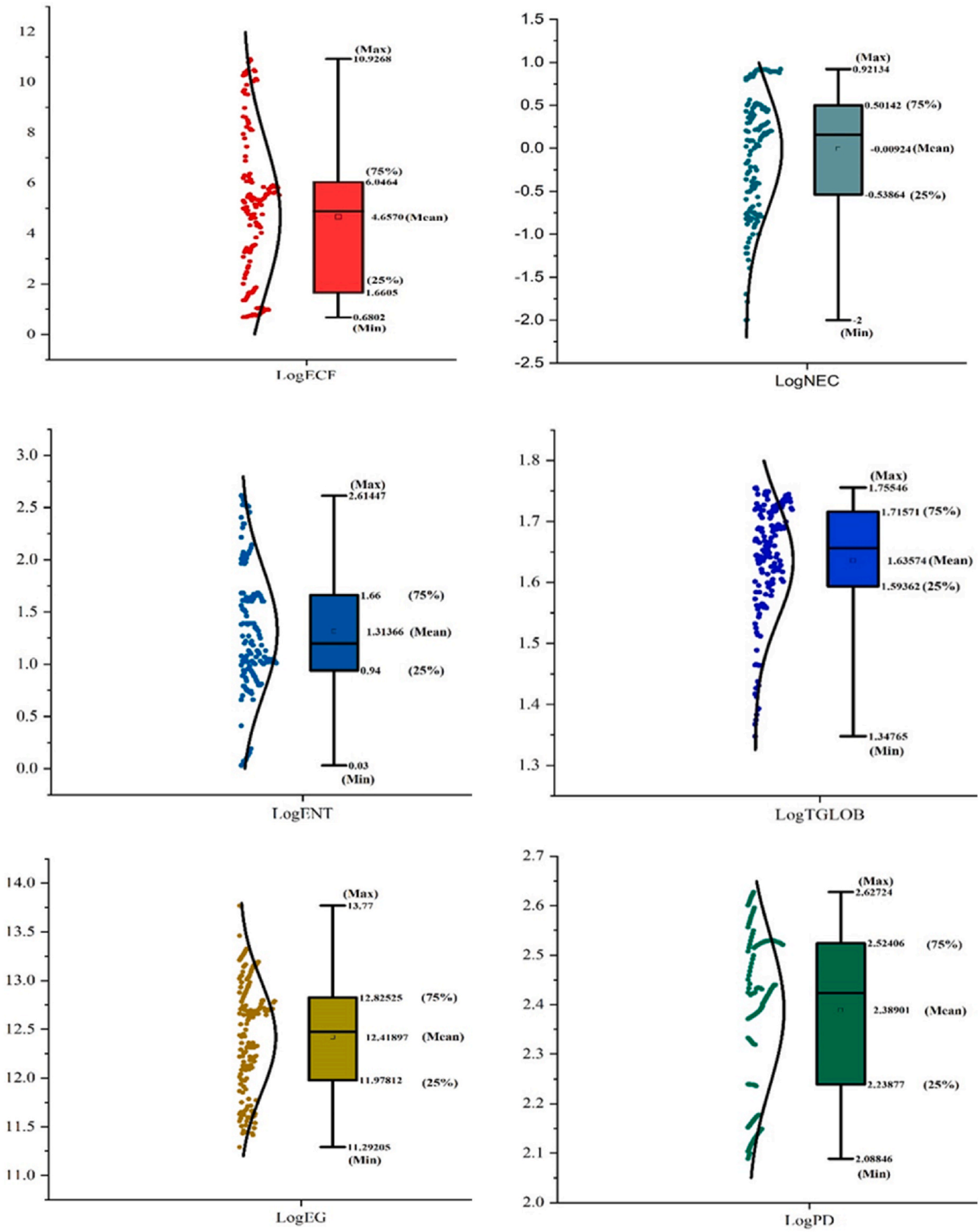

Fig. 4. Boxplot.

null hypothesis at a significance level of 1 %. This suggests that there is proof of CSD among the study's regressors. Simply indicated, the parameters used in the research are not independent of one another. Thus, shocks that occur in one nation within the sample could potentially impact additional countries.

The outcomes of the stationarity models (CADF and CIPS) are shown in Table 4, which evaluates the integration order of each variable. The CADF test results demonstrate that all variables prove stationarity after the first difference. The CIPS statistics support this finding by showing that all variables are stationary after the difference. So, we can perform a cointegration analysis to estimate the model after confirming stationarity for all variables. *, *p-value less than 0.5, and p-value less than 0.01.

Table 5 displays the findings of panel cointegration. The results signify sufficient evidence to reject the H_0 of no cointegration between the given variables, as shown by the significance level based on robust p-values of G_t, P_t, and P_a. Therefore, this research provides evidence supporting the presence of cointegration in at least one of the models'

Table 3
Findings of CSD.

Variables	Pesaran scaled LM		Pesaran CSD	
	Stats.	p-value	Stats.	p-value
Ln*ECF*	32.614*	0.000	−3.121 *	0.002
Ln*NEC*	33.102*	0.000	3.025*	0.002
Ln*ENT*	10.568*	0.000	−1.584*	0.001
Ln*TGLOB*	22.406*	0.000	13.011*	0.000
Ln*EG*	25.086*	0.000	1.759**	0.040
Ln*PD*	19.308*	0.000	1.189***	0.088

Note:***, **,* signify 0.1, 0.5, 0.01 significance.

Table 4
Stationary results.

Variable	CIPS	I (1)	CADF	I (1)
	I (0)		I (0)	
Ln*ECF*	−0.218	−4.232*	−0.452	−2.490**
Ln*NEC*	−0.060	−3.556*	−0.063	−4.465*
Ln*ENT*	−0.245	−3.414*	−1.200	−3.255*
Ln*TGLOB*	−1.752	−4.345*	−2.112	−2.671*
Ln*EG*	−1.875	−3.598*	−2.034	−3.598*
Ln*PD*	−1.620	−3.758*	−1.298	−3.758*

Note: **,* signify 0.5, 0.01 significance.

Table 5
Result of Westerlund cointegration.

Statistic	Value	z-value	Robust p-value
G_t	−3.080	−0.160	0.000*
G_a	−11.136	1.971	0.100
P_t	−8.971	−2.753	0.000*
P_a	−17.146	−0.363	0.000*

Note: * signify 0.01 significance.

cross-sectional units. The presence of cointegration in the models specifies a stable affiliation among the independent and response parameters, which suggests that they are connected in a long-term equilibrium. The conclusion drawn is that we can now proceed to analyze the long-term elasticity of the model.

This study utilized the CS-ARDL method to estimate the long-term and short-term relationship between variables. Table 6 presents that *LnNEC* and *LnECF* are negatively correlated at a p-value less than 0.01. The results concluded that a 1 % increase in nuclear energy usage reduced *LnECF* by 0.50 % and 0.33 % in short and long periods, provided all other factors remain the same. The outcomes suggest that nuclear energy can help reduce ecological issues in the countries considered in this research. These nations recognize nuclear energy potential as a long-term, eco-friendly option and have supported it.

Table 6
CS-ARDL findings.

Ln*ECF*	Coef.	Std. Err.	P-values
Short run			
Ln*NEC*	−0.498*	0.183	0.007
Ln*ENT*	−0.504**	0.709	0.037
Ln*TGLOB*	0.683**	0.914	0.033
Ln*EG*	0.885**	0.234	0.048
Ln*PD*	−0.443*	6.380	0.009
ECT (t-1)	−1.441*	0.070	0.000
Long run			
Ln*NEC*	−0.334*	0.115	0.004
Ln*ENT*	−0.107**	0.200	0.035
Ln*TGLOB*	0.331**	0.488	0.034
Ln*EG*	0.962***	0.162	0.091
Ln*PD*	−0.997**	2.013	0.049

***, **,* signify 0.1, 0.5, 0.01 significance.

The findings revealed that environmental taxes negatively correlate with *LnECF*. A coefficient of *LnENT* indicates that a 1 % increase in environmental taxes leads to a proportional decrease in the ecological footprint of about 0.107 % in the long run, keeping other variables constant. Environmental taxes efficiently reduce the ecological footprint by influencing behavior and promoting sustainable practices in selected panels. Furthermore, environmental taxes encourage the use of clean energy, by making them more economically appealing by increasing the fee for carbon-intensive fuels [61].

Moreover, CS-ARDL results represent the positive relationship between Ln*TGLOB* and ecological footprint at a 1 % significance level. Keeping all else the same, a 1 % increase in Ln*TGLOB* increases the amount of Ln*ECF* by 0.683 % in selected economies. This indicated that trade globalization integrates the global economy, promotes industrialization, and increases demand for goods and services.

The observed outcomes demonstrate a positive association among Ln*EG* and Ln*ECF* in the long run. The analysis discloses that a 1 % upsurge in Ln*EG* corresponds to a 0.88 % boost in Ln*ECF*, keeping other factors constant in selected nations. The positive conclusion shows that panel countries emphasize productivity growth through large-scale production and polluting industries over environmental quality[62].

Population density is negatively correlated with an ecological footprint in selected nations. The negative coefficients show that an increase of 1 percent in LnPD results in a drop of 0.99 % in LnECF in the long run, and all else is the same. These results suggested that these selected nations reduce the ecological footprint by increasing the denser population.

Table 7 displays a series of model diagnostic tests. The p-value of the F-statistic confirms the overall goodness of fit of the model at the 1 % level. Furthermore, Wooldridge for autocorrelation and Modified Wald for homoscedastic error term yielded insignificant p-values, indicating that the null hypotheses of no autocorrelation and homoscedasticity could not be rejected. Therefore, the model presented is considered robust, suitable and consistent for informing policy design in selected nations.

Table 8 displays the robustness results using the CCEMG and AMG estimators. AMG findings indicate that the coefficient values for Ln*NEC* and Ln*ENT* imply that a 1 % increase in these factors results in a 0.172 % and 0.846 % reduction in ecological footprint, while trade globalization increases the ecological footprint by 0.58 % in selected countries. The CCEMG analysis reveals similar findings. A 1 % increase in Ln*NEC* and Ln*ENT* reduces Ln*ECF* by 0.047 % and 0.210 %, respectively. The results of CS-ARDL are supported by additional robustness analyses, with comparable signs for the coefficients being consistently demonstrated throughout analyses but at varying levels of significance.

The DHC test was used to determine the direction of the causal relationship in this work. Table 9 reveals the outcomes of this analysis. The findings proposed that the two way association between Ln*EG* and Ln*PD* with Ln*ECF* imply these nations' economies and populations are growing at the expense of rising costs related to environmental harm. Our outcomes also suggest that there is only one direction of causality for the relationships between Ln*NEC*, Ln*ENT*, Ln*TGLOB,* and Ln*PD* to Ln*ECF*. This work generally ensures that these findings provide further confirmation and support for the conclusions drawn.

Table 7
Diagnostic test.

Test	Diagnostic	Test Stats.	P-values
F-statistics	Goodness of Fit	7.55*	0.000
Wooldridge	Autocorrelation	188.621	0.902
Modified Wald	Heteroskedasticity	862.01	0.564

Note: * signifies P value is less than 0.01.

Table 8
Robustness results.

CCEMG			
LNECF	Coef.	Std. Err.	P-value
LnNEC	−0.172*	0.040	0.000
LnENT	−0.846***	0.463	0.068
LnTGLOB	0.585*	0.491	0.001
LnEG	0.898**	0.830	0.028
LnPD	−0.531**	0.454	0.031
AMG			
LnNEC	−0.047*	0.014	0.001
LnENT	−0.210**	0.139	0.013
LnTGLOB	0.267***	0.015	0.072
LnEG	0.210**	0.154	0.019
LnPD	−0.934**	0.717	0.027

***, **,* denote 0.1, 0.5, 0.01 significance.

6. Discussion

Table 6 displays the CS-ARDL results to probe the long-term impact of *NEC* on the ecological footprint with the framework of *ENT* and *TGLOB* in the top five nuclear power nations from 1990 to 2021. Our results found that *NEC* significantly impacts ecological footprints, In contrast to the earlier conclusions of Soto et al. [63], who argued that nuclear energy generation itself does not produce carbon emissions but requires significant resources and land use, which can lead to ecological degradation. Our results demonstrate that while generating significant amounts of carbon-free power, nuclear energy is crucial in reducing ecological footprints. The implications of our findings are profound, particularly in the context of global climate change initiatives. A fundamental finding of our study is that nuclear energy may be a more effective way of decreasing pollution than renewable energy sources, even when considering the associated risks, such as health effects and potential accidents. Our results are in agreement with those of Danish et al. [64] and Hassan et al. [30], who emphasized the need for nuclear energy sources to mitigate environmental footprints. Nuclear energy's high energy density allows for rapid electricity production with less land usage than fossil fuels and renewables [65]. Moreover, nuclear waste still contains useable materials for further energy production, emphasizing the potential for recycling to enhance sustainability [21]. Nuclear energy has several benefits, such as energy independence, lowering current account deficits, and fostering job creation in the energy sector [66]. Therefore, incorporating *NEC* into the energy mix is essential for nations aiming to mitigate ecological footprint and boost sustainability.

The long-run findings indicate environmental taxes significantly reduce the *ECF* in selected nations. In earlier research work by Ullah et al. [67] and Sharif et al. [17] support these estimates, stating that environmental taxes can reduce harmful emissions and ecological footprints when properly established and administered. In the context of the selected panel, our study is consistent with theoretical assumptions and demonstrates the effectiveness of environmental taxes as a policy tool for managing ecological externalities and achieving environmental sustainability. Environmental taxes stimulate organizations and individuals to reduce their ecological footprint and embrace more environmentally friendly activities [61]. By increasing the price of fossil fuels, individuals and organizations are more likely to seek out energy-efficient appliances, nuclear and renewable energy sources, and alternative transportation methods. This can improve economic and environmental efficacy, reducing ecological footprints [68]. Moreover, the income produced from environmental taxes and government can be reinvested into green energy projects, public transportation, and energy efficiency programs. This can create a positive feedback loop in ecological improvement by reducing the ecological footprint further [69]. Our study contributes to global efforts to combat ecological footprint and boost sustainability by implementing environmental taxes that align with international sustainability goals.

Our study's findings show that trade globalization significantly increases the ecological footprint in the selected panel. Our findings corroborate those Azam et al. [70] and Pata [71], who stated that trade globalization encourages the cross-border flow of goods and services, but this expansion harms the environment. Moreover, our findings confirm the pollution haven hypothesis, highlighting that trade globalization contributes to the displacement of ecological impacts, where goods are produced in one country but consumed in another, leading to a transfer of environmental burdens [72]. In the context of the selected panel, trade globalization unifies the global economy, stimulates industrialization, and increases demand for various goods and services. This frequently leads to over-exploitation of environmental resources, resulting in considerable biodiversity loss and ecological deficiency [5]. Furthermore, trade globalization via international commerce and investment increases land use for production, transportation, and energy needs, resulting in an ecological footprint [64]. Some prior research work, such as those by Mehboob et al. [21] and Saud et al. [73], suggested that trade globalization can enhance economic activity with minimal ecological impact if domestic reforms are implemented, especially when the production sector commits to ecological improvements. Therefore, it is essential to incorporate the effects of trade globalization into the *ECF* when developing long-term environmental policies to achieve sustainable growth.

Our outcomes disclose that economic growth significantly impacts

Table 9
Results of DHC.

Variables	LnECF	LnNEC	LnENT	LnTGLOB	LnEG	LnPD
LnECF	–	7.077	2.363	0.625	7.599*	8.719*
		4.622	0.178	−1.459	5.114	6.170
		0.407	0.858	0.144	0.000	0.000
LnNEC	3.052*	–	3.303	0.829	12.794*	6.506*
	0.828		1.064	−1.267	10.011	4.084
	0.000		0.287	0.204	0.000	0.000
LnENT	6.531*	7.119*	–	1.222	6.196*	9.487*
	4.107	4.662		−0.896	3.791	6.894
	0.000	0.000		0.369	0.000	0.000
LnTGLOB	7.681*	3.826	4.135***	–	3.079	8.076*
	5.191	1.557	1.848		0.853	5.564
	0.000	0.119	0.064		0.393	0.000
LNECG	4.652**	3.255	4.148***	2.720	–	15.526
	2.336	1.019	1.861	0.515		12.588
	0.019	0.308	0.062	0.606		0.000
LnPD	4.986*	4.167***	3.824	5.451*	5.265*	–
	2.651	1.879	1.555	3.092	2.914	
	0.008	0.060	0.119	0.002	0.003	

Note: The values in the first, second, and third positions represent the w, z, and p-values, respectively; ***, **,* denote 0.1, 0.5, 0.01 significance.

increasing the *ECF*. The affiliation among economic growth and environmental degradation is often analyzed through the Environmental Kuznets Curve (EKC) theory [74], which posits that while ecological degradation may initially worsen, it eventually improves as societies adopt cleaner technologies and stricter standards. However, my findings challenge this optimistic perspective, indicating that the selected panel countries prioritize increasing productivity through heavily relying on polluting industries and brown production, which often comes at the expense of ecological integrity. This trend can be linked to the increase in economic activity, as does the demand for scarce natural resources and higher energy use for production [75]. Thus, enhanced economic growth comes with substantial ecological consequences, particularly resource depletion, habitat loss, and increased pollution. Moreover, my findings align with Adebayo et al. [76] and Numan et al. [2], who highlighted that economic growth in developing countries often leads to increased ecological footprints, as these economies tend to rely more heavily on resource extraction and energy-intensive industries. This work suggests vital implications for decision-makers balancing economic progress with environmental protection.

Our work's outcomes show that population density reduces ecological footprint and helps to provide deep information on the connection among population dynamics and environmental effects. Some research suggests that population density raises ecological challenges due to concentrated natural resource consumption and waste [77]. Contextually, the results correspond with the theoretical assumption that supports our premise that population density can improve the efficient extraction and use of existing natural resources to meet human needs while upholding ecological equilibrium [78]. It can promote sustainability through economies of scale, lower transportation emissions, and improved access to public services [79]. Our findings contribute to the important implications for urban planning and policy, suggesting that increasing population density through mixed-use developments and improved public transportation can effectually diminish ecological footprints and promote ecological sustainability [80,81].

7. Conclusion and policy suggestion

The world is grappling with global energy challenges, prompting decision-makers to address the adverse environmental effects of burning fossil fuels. Consequently, decision-makers increasingly embrace clean energy sources with minimal ecological impact to tackle these issues. Therefore, this work analyzed the ecological footprints mitigated by nuclear energy consumption in five nuclear nations with the role of environmental tax and trade globalization from 1990 to 2021. The work used several estimating techniques to evaluate the model after identifying CSD and stationarity. These techniques included the panel cointegration test, the CS-ARDL test, CCEMG, AMG models, and the DHC panel causality test. This work discovered exciting findings that nuclear energy usage, environmental tax, and population density boost ecological sustainability by decreasing *ECF* while trade globalization and economic growth upsurge *ECF* in these selected nations.

7.1. Policy implications

This work's results policymakers must consider the subsequent policy ramifications to effectively reduce environmental influence through ecological footprint mitigation and advancing a sustainable future.

Based on empirical evidence, this paper offers several policy recommendations for nuclear energy-consuming countries. First, these nations should include nuclear energy in their energy portfolios due to its lower environmental footprint. This requires prioritizing investments in nuclear technology and infrastructure, as well as integrating nuclear energy into long-term energy strategies. Second, policymakers should emphasize nuclear energy generation over other sources by encouraging financial institutions to make funds more accessible for nuclear investments. Governments should also support nuclear research and development, focusing on next-generation reactors to enhance efficiency, reduce waste, and improve safety. Finally, addressing public concerns, clarifying safety issues, and fostering dialogue through transparent communication and public forums are essential for building support and ensuring the successful implementation of nuclear projects.

The government should levy higher environmental taxes on enterprises using outmoded technologies contributing to environmental degradation. These taxes create a financial hardship for businesses and investors. To avoid these expenditures, firms are likely to adopt innovative eco-friendly technology, lowering their environmental footprint. These nations' governments should set aside a part of environmental tax income to support renewable energy projects, public transportation enhancements, and environmental conservation activities. Furthermore, policymakers should establish programs that help businesses understand and comply with environmental tax regulations while fostering collaboration between government and environmental organizations to develop comprehensive strategies for reducing emissions and waste through shared resources and common goals.

These selected nations should make the development and implementation of sustainable trade policies a top priority. These policies should encourage environmentally responsible manufacturing, promote environmentally friendly transportation, and ensure trade agreements with international environmental standards. These countries must establish robust environmental policies to manage energy-intensive trade practices and the transfer of polluting technologies in the sense of trade globalization. One effective strategy is to impose dumping duties on trading partners and foreign companies that use outdated technologies. These countries should align with global sustainable ecological standards when pursuing foreign capital projects, while actively promoting advancements in clean energy technologies. Additionally, enhancing ecological awareness through social media engagement can support this effort.

7.2. Limitation and further research

While the conclusions of this analysis are robust and persuasive, it's important to acknowledge its limitations and the potential for further study. One significant weakness of our study is its concentration on the top five nuclear countries, which limits the generalizability of our findings. While the results offer valuable insights into the affiliation among nuclear power, environmental policies, and sustainability in these nations, they cannot be applied to other nuclear nations. Additionally, data limitations may have influenced the robustness of the results. The reliance on country-level data over a specific time frame may overlook regional variations within these nations. The ecological footprint was used as the primary environmental indicator, which may overlook other important aspects of environmental quality. To highlight our limitations, we propose the following avenues for future investigation. Future research should broaden the study's geographic scope to include other nuclear-powered countries worldwide. This broader approach could provide a more comprehensive understanding of how nuclear energy interacts with environmental sustainability across different contexts. Future research should discover other measurements for assessing environmental quality. This is important because traditional ecological footprint metrics might not capture the full range of environmental impacts. Current indicators tend to focus on ecological footprint, but they often overlook other crucial dimensions of environmental degradation, such as biodiversity loss, soil quality, water pollution, and air quality. Additionally, applying other econometric methods that account for quantiles, asymmetries, and nonlinearities can provide more insights.

CRediT authorship contribution statement

Muhammad Yasir Mehboob: Writing – original draft, Software, Methodology, Formal analysis, Data curation, Conceptualization.

Benjiang Ma: Writing – review & editing, Supervision, Project administration, Conceptualization. **Muhammad Sadiq:** Visualization, Validation, Software, Data curation. **Muhammad Basit Mehboob:** Resources, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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