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Original Article

Environmental footprint impacts of nuclear energy consumption: The role of environmental technology and globalization in ten largest ecological footprint countries

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A B S T R A C T

This study investigates the environmental footprint impacts of nuclear energy consumption in the presence of environmental technology and globalization of the ten largest ecological footprint countries from 1990 up to 2017. By considering a set of methods that can help solve the issue of cross-sectional dependence, we employ the Lagrange multiplier bootstrap cointegration method, Driscoll-Kraay standard errors for long-run estimation and feasible generalized least squares (FGLS) and panel-corrected standard errors (PCSE) for robustness. The finding revealed significant negative effects of nuclear energy consumption, environmental-related technology, population density and significant positive effects of globalization and economic growth on ecological footprint. These results are also robust by assessing the long-run impacts of predictors on carbon footprint and CO_2 emissions as alternate ecological measures. These conclusions provide the profound significance of nuclear energy consumption for environmentally sustainable development in the top ten ecological footprint countries and serve as an important reference for ecological security for other countries globally.

1. Introduction

Both developed and emerging economies are confronted with balancing environmental and economic objectives. On the one hand, the rapid growth of world economies in recent decades has enabled them to create basic infrastructure, alleviate poverty, and raise citizens' living standards. On the other hand, global economies have compromised natural capital in pursuit of rapid economic expansion, resulting in serious environmental concerns such as energy resource exploitation, biodiversity loss, land degradation, and water and air pollution [1–3]. This concern, coupled with rising human energy consumption, increases society's vulnerability and the planet's ecological resource scarcity. According to some estimates, worldwide energy consumption and product production account for 25% of global pollution emissions [4]. For this reason, failure to achieve the sustainable societies and pollution reduction targets outlined by the United Nations Sustainable Development Goals (SDGs) would result in a colossal ecological deficit. Thus, the primary goal is to achieve economic development without jeopardizing environmental quality by balancing human demands with the planet's regenerative biological potential and exploring more sustainable ways to prevent socio-ecological disasters.

Along these lines, the growing concerns about environmental degradation have prompted countries to design and implement economic and environmental policies to reduce their total environmental footprint and manage environmental crises [5,6]. However, despite the attempts to reduce energy consumption and carbon pollution, several economies are still vulnerable to reducing their ecological and carbon footprint (EFP/CFP) [7]. The top ten countries with the largest EFP utilizing nuclear energy are also not immune to environmental concerns, as their rapid economic and energy expansion in the recent decades has caused considerable ecological difficulties. For example, India's fast-expanding population and China's rapidly developing economy are accompanied by increased energy consumption, natural resource exploitation, and therefore increased EFP,[1] CFP and emissions [8]. Recent growth in

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[1] The EFP assesses environmental quality by determining how much productive land is needed to meet human ecological needs. Any increase in EFP is regarded as an increase in environmental degradation and vice versa.

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the human ecological footprint shows a growing imbalance between humans and their environment. The majority of the world population lives in ecologically deficit countries, with about 80% dwelling on ecological scarcity and consuming more resources than the Earth can practically regenerate [9]. Fig. 1 shows that except in Russia and Brazil, the human demands in other countries have exceeded Earth's biocapacity, causing ecological overshoot and pressures on ecosystems in the form of land degradation and resources depletion (deforestation and overfishing), pollutant emissions and reducing biodiversity.

Energy is an inextricable component of production; therefore, it plays a fundamental role in economic development. Human and economic progress is directly linked to energy consumption, increasing global energy demands. The current energy portfolio that is almost 80% reliant on fossil fuel burning is largely accountable for pollution around the globe [10]. So, the world faces two global energy challenges: meeting increased energy demands and preserving the environment via energy transition. These challenges require altering the existing energy model to shift to low-carbon energies with a minimal environmental footprint (low land-use requirement) and preserve the scarce resources used to produce the energy for future generations through resource use efficiency [11]. Nuclear and renewable energies can process these difficulties that are increasing at an exceptional velocity recently due to enhanced energy mix efficiency, technological breakthroughs, and structural reforms. Against these backdrops, this research focuses on the ecological consequences of expanding nuclear energy consumption, environmental technology and globalization in nuclear-consuming nations with the highest ecological footprint.

Nuclear energy has generally been an important component in transitioning to a more sustainable society because of minimal carbon emissions, high power and energy density and quick electricity generation capacity with less land required [12]. It has been given priority development over renewable energy sources since its offers significant benefits in optimizing energy structure, ensuring ecological stability, and reducing air pollution [13,14]. Additionally, nuclear energy expansion affects industry-wide technology boosting production and energy efficiency, lowering power generation costs, and reducing energy dependence, all of which contribute to achieving the sustainable energy and green growth targets [15,16]. Hence, nuclear energy is the best option to assist environmental policies aimed at global ecological stability, energy security, and green growth in the long run. Regardless of the benefits of nuclear energy, nuclear power plants still risk the environment due to radioactive radiation and nuclear reactor accidents [17]. The underlying environmental damage of nuclear energy may arouse societal concerns and apprehensions. Moreover, the nuclear development process has been slowed by anti-nuclear public sentiment following the Fukushima disaster, especially in Europe and other developed countries, which has caused mistrust in nuclear reactor control under extreme conditions [18,19].

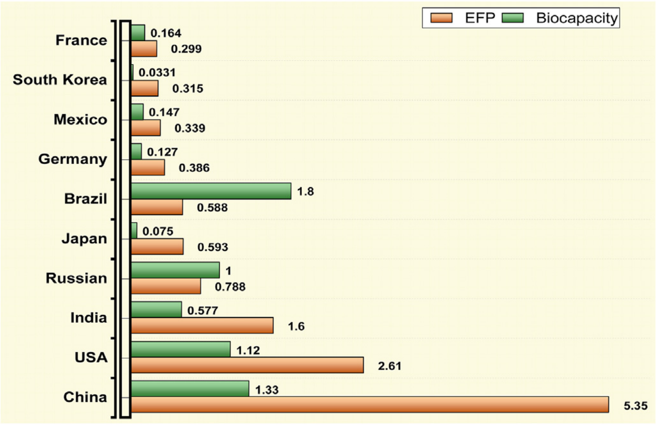

Fig. 1. **EFP and biocapacity in Billion GHA of selected countries** [9].

The increase in technical efficiency is critical for a long-term and significant decrease in ecological impact. Production and processing of products utilize environmental-related technologies (ERTs) to reduce environmental damage. ERT has the potential to both shorten the environmental degradation process and decrease it in the long run [20]. More resources should be put into ERT engaged in product manufacturing and processing to support nations with high ecological footprints to reduce their EFP and CFP levels [21]. The progress in new technology plays a major role in enhancing energy efficiency and improving the industrial sector's performance in reducing carbon emissions [22,23]. Similarly, the dissemination of economic, social, and political ideals is facilitated by globalization [24]. As a result, capital flows, technology exchanges, and associated pollution may directly influence people's lives, and ecological processes are inextricably linked to globalization. Because of the rapid increase in economic activity, globalization has the net impact of increasing everyone's EFP as it needs more infrastructure, energy, and natural capital for production. Global integration and economic inequities greatly increase the degree of ecological consequences, resulting in an excessive environmental footprint as human demands on our ecosystem expand [25]. However, literature has neglected the impacts of nuclear energy and environmental technology on the ecological footprint of the top ten EFP countries. This study expands the nexus of nuclear energy consumption, environmental technology, globalization and EFP by controlling for GDP and population density to fill in this research gap.

This work differs from prior research in a few ways. First, this is the first research, to our knowledge, that investigates the ecological footprint impacts of nuclear energy consumption in the world's top 10 EFP countries from 1990 to 2017. The study findings will better predict the criticality of nuclear energy in ecological pollution reduction and help the Government and the general public better understands the environmental consequences of nuclear energy usage for developing suitable energy policies. Second, this is the leading study to incorporate environmental technology and globalization in modeling the impacts of nuclear energy on EFP that have been overlooked in prior studies. Third, this study employs robust estimators such as Driscoll-Kraay standard errors, feasible generalized least squares (FGLS), and panel-corrected standard errors (PCSE) to address issues such as autocorrelation, heteroscedasticity, cross-countries dependence, endogeneity, and the presence of regressors with different integration levels, allowing us to evaluate accurate results.

The remainder of this study consists of four sections arranged as follows. Section 2 presents a literature review; Section 3 details the empirical model, data sources, and econometric technique utilized in this study; Section 4 explains statistical findings with detailed discussions. Section 5 sets out the conclusion and policy suggestions for the top ten ecological footprint countries.

2. Literature review

The present paper explores the impacts of nuclear energy, environmental technology, and globalization on EFP. Nuclear energy is already recognized as a low-cost clean energy resource with a low direct and hidden carbon footprint [14,26,27]. The recent investigations of Azam et al. [28], Danish et al. [16], and Sadiq et al. [29] corroborated that nuclear energy fosters environmental excellence, and increasing investment in nuclear energy is crucial to enhancing energy efficiency and realizing economic sustainability. Çakar et al. [30] observed that nuclear energy usage decreases CO_2 emissions more effectively after some degree of innovation and that new nuclear power plant technologies boost energy efficiency and contribute to environmental quality. Similarly, Kim [31] concluded that nuclear energy is the most economical and ultimate solution to carbon reduction in extreme clean energy scenarios than renewable energy. However, Mahmood et al. [17] and Sarkodie and Adams [13] observed the adverse impacts of nuclear energy on ecological quality resulting from operations inefficiency, technical incompetence, associated radioactive waste, and global infrastructural development restrictions obligatory for nuclear waste management.

Although nuclear energy is of considerable interest among scholars and policymakers in attaining a low carbon economy, the direct effects of nuclear energy on EFP are not documented in the scientific literature. In this context, McCombie and Jefferson [12] remarked that nuclear energy has a high energy density and is a land-efficient energy source to generate quick electricity than fossil fuels and other renewables. Poinssot et al. [18] demonstrated that nuclear energy has a lower environmental footprint and is more sustainable than other renewable energy sources due to preserving natural uranium resources necessary for energy generation in the current French twice-through fuel cycle. Similarly, Poinssot et al. [11] emphasized that nuclear energy is environmentally competitive in terms of pollution emission and land use and suggested that recycling nuclear wastes can boost nuclear energy's sustainability. Their findings indicated that nuclear waste recycling reduces the environmental footprint of the front-end activities, increases natural uranium usage efficiency, reduces reliance on fossil fuels and promotes energy independence in the participating nations by producing more electricity.

Meanwhile, the role of technological innovation has been a focus of several earlier studies on environmental pollution. Technology innovation helps explore new renewable energy technologies and maximize the existing energy efficiency that directly impacts the environment. Erdogan [32] observed that increased technological innovation improves the environment in BRICS countries by reducing carbon emissions. However, research on the impact of environmental technologies (ERTs) on EFP is relatively scarce. Ahmed et al. [33] concluded that considerable development in ERT can minimize emissions intensity while meeting economic growth objectives in BICS economies. Hussain et al. [34] probed the impacts of ERTs on consumption-based CO_2 in emerging economies and found that investment in ERTs is decreasing CO_2, offering a smooth path for sustainable growth. Similarly, Danish and Ulucak [20] and Mensah et al. [35] concluded that ERT promotes sustainable development in BRICS and OECD economies. Their results confirmed that environmental technologies increase production efficiency, promote new energy by replacing fossil energy, reduce energy intensity, and significantly decrease CO_2 emissions. The recent study of Hussain and Dogan [21] is the only attempt that reported that ERT facilitates EFP reduction in BRICS countries, and investment in production ERT is necessary for a sustainable environment.

Globalization is a commonly debated indicator of environmental contamination in academia since it accelerates consumption and production levels and aids in disseminating environmental technologies [16]. Several studies have considered the ecological footprint impacts of globalization. Pata [8] illustrated that globalization increases environmental pollution in China and Brazil due to lax environmental laws enticing foreign investment. Likewise, Langnel and Amegavi [2] and Pata and Caglar [36] argued that globalization intensifies environmental degradation by increasing EFP in Ghana and China. In contrast, Saud et al. [7] for one belt one road economies, Pata and Yilanci [37] for G7 countries, and Aluko et al. [38] for industrialized countries hypothesize that globalization reduces the environmental footprint and boosts the economy. However, Figge et al. [39] observed that globalization has diverse impacts on different dimensions of EFP, such as consumption, production, exports and imports. Their results confirmed that overall and social globalization raises the EFP of imports and imports, economic globalization expands the EFP of consumption, production, imports and exports, and political globalization has no impact on any dimension of EFP in a panel of 146 countries. Finally, the panel estimation of Pata et al. [40] indicated an insignificant impact of increasing globalization on the EFP in the ten largest ecological footprint countries.

To sum up, the importance of nuclear energy is evident in preceding studies of energy and environmental economics. However, none of the studies has documented the ecological footprint impacts of nuclear energy in the extant scientific literature. Similarly, in the reviewed literature, the nexus of ERT and EFP is uncommon and has offered varied opinions on the impacts of globalization on EFP that need further investigation. Therefore, this study aims to address the identified research gap by considering the ecological footprint impacts of nuclear energy consumption, counting the role of environmental technology and globalization in the ten largest EFP countries using robust econometric techniques.

3. Methodology

3.1. Data, model, and descriptive analysis

This research explores the environmental footprint impact of nuclear energy consumption, environmental technology, and globalization of the top ten countries ranked by total ecological footprint. The expanded commodities production and consumption result in increased usage of natural resources and energy, and extensive fossil fuel consumption increases a country's ecological footprint. The EFP is a comprehensive measure and important environmental proxy frequently used in recent years that better capture all direct and indirect environmental effects of energy and production activities in environmental pollution assessment [41]. Hence, this work follows the suggestion of Danish et al. [42] to consider the impact of nuclear energy consumption, environmental technology, and globalization on EFP as an alternative proxy for environmental degradation and utilizes the functional form for estimating the desired long-run model as follows:

$$EFP = f(NEC, ERT, GLOB) \tag{1}$$

Nuclear energy is acknowledged as one of the least expensive energies in terms of Levelized costs than coal, natural gas, and renewables to create more electricity. It can moderate the country's fiscal deficit by reducing foreign energy imports dependence and achieving sustainable economic growth by resolving energy supply and baseload problems. Further, nuclear energy is documented as the most land-efficient and energy-dense source of power that exploits the least amount of building supplies per unit of power produced each year. Hence, it can play a principal role in energy conservation, economic sustainability, and the reduction of energy-related environmental footprints. The goal of environmental technology is to preserve the environment. These technologies promote green growth by proposing innovative techniques for less polluting and more sustainable human consumption and production and avoiding natural resource depletion. Moreover, they can support the clean energy sector and nuclear energy participation in energy transition, thereby reducing environmental pollution and achieving sustainable development targets. Ecological processes are intertwined with globalization and economic movements due to capital and technological flows which have a net impact of increasing environmental footprints. Globalization can create extreme biodiversity loss triggered by excessive extraction of environmental resources due to increased economic activities and can improve the environment through eco-friendly technology transfer and supporting renewable and nuclear energy development.

Before estimating the model, all the variables are converted into natural logarithms to normalize the data and obtain reliable estimates by enabling regression coefficient elasticity interpretations. Additional variables, economic growth and population density, are incorporated to resolve the omitted variable bias and validate the model. Therefore, the panel log-linear econometric function of Equation (1) can be redrafted as:

$$LnEFP_{it} = \alpha_0 + \alpha_1 LnNEC_{it} + \alpha_2 LnERT_{it} + \alpha_3 LnGLOB_{it} + \alpha_4 EG_{it} + \alpha_5 LnPOPD_{it} + \varepsilon_{it} \tag{2}$$

The dependent variable EFP signifies ecological footprint, and the explanatory variables NEC, ERT, GLOB, EG and POPD represent nuclear energy consumption, environmental technology, globalization, economic growth and population density. α_0 is the intercept term, and the parameters α_1 to α_5 are the long-run elasticity coefficients of NEC, ERT, GLOB, EG and POPD. t is the study time (1990–2017), i is the number of countries (1-10), and ε is the normally distributed error term. Additionally, the study examines the impacts of independent factors on carbon footprint (CFP) and carbon emissions (CO_2) as additional proxies of environmental degradation for robustness checks in equations (3) and (4) below:

$$LnCFP_{it} = \beta_0 + \beta_1 LnNEC_{it} + \beta_2 LnERT_{it} + \beta_3 LnGLOB_{it} + \beta_4 LnEG_{it} + \beta_5 LnPOPD_{it} + \mu_{it} \tag{3}$$

$$LnCO_{2it} = \gamma_0 + \gamma_1 LnNEC_{it} + \gamma_2 LnERT_{it} + \gamma_3 LnGLOB_{it} + \gamma_4 LnEG_{it} + \gamma_5 LnPOPD_{it} + \eta_{it} \tag{4}$$

The current study covers available balance panel annual data from 1990 to 2017 for the ten countries with the largest EFP.[2] The top ten ecological footprint countries, in order, are China, the United States of America, India, Russia, Japan, Brazil, Germany, Mexico, South Korea, and France [9]. Table 1 provides information about the dataset and studied variables, and Table 2 depicts the descriptive statistics for the data series.

3.2. Econometrics strategy

This study employs panel data estimation considering cross-sectional dependence (CSD). The importance of econometric methods that account for CSD has grown since most econometric panel methods that ignore CSD influence the adopted methodological strategy and produce ambiguous test statistics in panel data analysis. Unobservable common factors like global shocks or national policies and the integration of socioeconomic and political systems causing interdependence effects among countries should be observed because variables and residual CSD may persist. Several CSD tests are used in the literature, the applicability of which depends on time and cross-section size. This paper applies the Breusch and Pagan [47] Lagrange Multiplier ($CDLM_{BP}$) and the Baltagi et al. [48] bias-corrected scaled LM ($CDSLM_{BC}$) tests to identify CSD in variable series, which are most suitable when the time dimension is larger than the cross-sectional component in the observed panel. The test statistics for these methods under the null hypothesis of cross-sectional independence are estimated as:

$$CDLM_{BP} = T \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \widehat{\rho}_{ij}^{2} \tag{5}$$

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

Where $\widehat{\rho}_{ij}^{2}$ signifies the cross-section correlation of residuals for i and j countries acquired from the panel's Ordinary Least Squares (OLS) regression. Moreover, the Pesaran [49], Frees [50], and Friedman [51] CSD tests are also used to inspect the existence of residuals CSD in the panel data models.

In the next step, we employed cross-sectional augmented Dickey-Fuller (CADF), and cross-sectional augmented Im, Pesaran, and Shin (CIPS) novel stationarity approaches insinuated by Pesaran [52] to inspect the integration of the variables under study. The CADF integrates the lagged cross-sectional average and first difference values of considered variables in ADF regression to deal with CSD across the dataset, producing more reliable results than conventional unit root tests. The CIPS test is estimated as an average of individual CADF statistics. The test statistics of CADF and CIPS regression under the null assumption of non-stationarity are calculated as:

$$\Delta y_{it} = \alpha_i + \beta_i y_{i,t-1} + \delta_i \overline{y}_{it-1} + \lambda_i \Delta \overline{y}_{it} + \varepsilon_{it} \tag{7}$$

$$CIPS = \frac{1}{N} \sum\nolimits_{i=1}^{N} t_i\,(N,T) \tag{8}$$

Where $\overline{y}_{it-1}$ and $\Delta\overline{y}_{it}$ are the cross-sectional mean approximates of the lagged variable and first difference, respectively. $t_i(N,T) = CADF$ denotes the test statistic of OLS regression for i_{th} cross-section.

After accessing variables' unit root properties, a cointegration connection among variables is tested using the LM bootstrap panel cointegration test established by Westerlund and Edgerton [53]. The key benefits of this technique are that it takes into account cross-sectional dependency and slope heterogeneity, allows for autocorrelation and heteroscedasticity in the cointegration equation and gives efficient outputs in small samples. Under the null hypothesis of cointegration, the bootstrap LM panel cointegration test statistic can be computed as:

$$LM_N^{+} = \frac{1}{NT^2} \sum_{i=1}^{N} \sum_{t=1}^{T} \widehat{\omega}_i^{\,-2} S_{it}^{2} \tag{9}$$

where S_{it}^{2} and $\widehat{\omega}_i^{\,-2}$ represents the partial sum process and the estimated long-run variance of the error term, respectively.

In estimating long-run coefficients, the Driscoll-Kraay robust standard errors estimator developed by Driscoll and Kraay [54] is estimated by the general form of pooled ordinary least squares (OLS) regression. The Driscoll-Kraay estimator adjusted the standard errors of the pooled OLS models to address cross-sectional or temporal dependency by applying the Newey–West correction to the series of cross-sectional averages of the moment condition. This estimate is a dynamic non-parametric technique for examining the linear relationship among the panel data that is not constrained by the number of panel cross-sections and is more effective as the time dimension increases. The advantages of using the Driscoll-Kraay covariance matrix algorithm are that it accounts for heteroscedasticity, autocorrelation, and cross-country dependence problems. Moreover, this approach is equally applicable for balanced

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[2] The data for NEC is readily available from 1990 onwards for these countries, and data for EFP and the CFP were available only up to 2017, constraining analysis period to 1990 to 2017 with 280 observations (n = 10, t = 28).

Table 1
Description of variables and sources of data.

Variable	Symbol	Definition	Measurement	Source
Ecological Footprint	EFP	EFP measures human demand from agriculture, construction, grazing, fishing and forest land, and CO_2 absorption from fossil fuel combustion.	Global hectares Per person	Global Footprint Network [9]
Carbon Footprint	CFP	CFP comprises the total area of forest land necessary to absorb CO_2 from fossil fuel usage, land use, chemical processes, and the ocean.	Global hectares Per person	Global Footprint Network
Carbon Emissions	CO_2	CO_2 is the energy-related emissions primarily caused by the burning of fossil energies such as oil, gas and coal	Million tones CO_2	British Petroleum [43]
Nuclear Energy Consumption	NEC	NEC accounts for the gross energy produced from nuclear fission by divorcing the atoms of selected elements (uranium and plutonium).	Million tons of oil Equivalent	British Petroleum
Environmental Technology	ERT	ERT is the creation of technologies to conserve, regulate, or reduce the environmental effects of production technology and resource consumption.	No. of Patent applications filed under the PCT	OECD [44]
Globalization	GLOB	GLOB encompasses the economic, social, and political aspects of integrating global economies, cultures, and populations.	Index	KOF Index [45]
Economic Growth	EG	EG is the total of the country's gross value added to commodities during manufacturing, adding all commodities taxes and deducting any subsidies not involved in the manufacturing.	GDP per capita (constant 2010 US$)	World Bank [46]
Population Density	POPD	POPD is the concentration of individuals or the number of people per unit geographic area.	People per sq. km of land area	World Bank

Table 2
Summary of descriptive statistics.

	LnEFP	LnCFP	$LnCO_2$	LnNEC	LnERT	LnGLOB	LnEG	LnPOPD
Mean	0.585128	0.331272	0.757406	1.188160	2.133984	1.814567	4.094425	1.986993
Maximum	1.020431	0.883828	1.387360	2.287529	3.783923	1.947887	4.728780	2.721592
Minimum	−0.106180	−0.631497	−0.149353	−1.881520	−0.602060	1.507056	2.760046	0.940322
Std. Dev.	0.271198	0.379161	0.372050	0.772859	1.014342	0.095081	0.551466	0.561142
Observations	280	280	280	280	280	280	280	280

and unbalanced panel data series and can process missing values effectively. Therefore, the linear model of Driscoll-Kraay standard errors for pooled OLS is expressed as follows:

$$y_{it} = x'_{it}\beta + \varepsilon_{it} \quad i = 1, \ldots., N, \; t = 1, \ldots., T \tag{10}$$

Where *yit* symbolizes the dependent variables (EFP) and *xit* specifies explanatory variables (NEC, ERT, GLOB, EG and POPD). In addition to robustness by using different proxies for environmental degradation, the estimation of feasible generalized least squares (FGLS) by Parks [55] and panel-corrected standard errors (PCSE) by Beck and Katz [56] have also been applied in this study to validate the result of the Driscoll-Kraay standard error approach. The PCSE provides OLS estimates with panel corrected standard errors, whereas the FGLS generates an OLS heteroskedasticity structure. Both FGLS and PCSE control cross-section dependency, heteroskedasticity, and serial correlation within panels, providing robust long-term estimates.

Lastly, this empirical study employed the Dumitrescu and Hurlin [57] panel causality test to determine the causal affiliation among observable variables, giving policymakers extended knowledge to design suitable policies. When the time (T) is greater than the cross-sections (N) in a cross-sectionally dependent, heterogeneous, and balanced panel, the D-H panel causality test based on Granger's individual Wald statistic is widely accepted. The linear model of DH causality test under the null hypothesis of homogenous non-causality is stated as follows:

$$y_{i,t} = \alpha_i + \sum_{k=1}^{k} \lambda_i^{(k)} y_{i,t-k} + \sum_{k=1}^{k} \beta_i^{(k)} x_{i,t-k} + \varepsilon_{i,t} \tag{11}$$

Where $\beta_i^{(k)}$ and $\lambda_i^{(k)}$ represents the coefficient estimates of lag independent and dependent variable, k describes the lag length anticipated to be unaffected for panel units.

4. Empirical results analysis and discussions

Table 3 shows the outcomes of the Breusch Pagan LM test and the bias-corrected scaled LM test to model variables CSD investigation and the Pesaran, Frees, and Friedman CSD approaches to model residual CSD investigation. The significance of results from all the tests presents robust evidence against the null hypothesis (H_0) of cross-sectional independence for all variables and residuals of the models. These results support the incidence of spillover and regional effects across the panel of ten nations with the highest EFP.

Table 4 summarizes the conclusions of the CADF and CIPS panel unit root testing. These results recommend that the null hypothesis (H_0) of unit root cannot be rejected in level series. However, after taking the first difference, all variables pose stationarity at the 1% significance level. The predicted results allow us to proceed with cointegration analysis, suggesting that all the study variables follow the I(1) process integrated with order one.

The LM bootstrap panel cointegration results for all three models presented in Table 5 demonstrate that the null hypothesis (H_0) of cointegration among the specified variables cannot be rejected since the p-value is larger than the significance level. This cointegration provides strong evidence to conclude the existence of a long-run equilibrium connection between the response variables (EFP, CFP, CO_2) and the analyzed independent variables.

After the basic panel data analysis, the Driscoll-Kraay standard errors technique is used in the next stage as a long-run predictor of the model's underlying variables. The results from the Driscoll-Kraay estimate for EFP, as presented in Table 6, indicate that the long-run coefficients of all the studied variables are statistically significant at a 1% significance level.

The results show that the long-run coefficient of nuclear energy consumption (NEC) is significant negative, claiming that a 1% incremental change in NEC is expected to alleviate EFP by around 0.10% in these top ten ecological footprint countries ceteris paribus. Nuclear

Table 3
Results of CSD tests.

Results of CSD tests in panel time-series data (Variables)

Tests	LnEFP	LnCFP	LnCO_2	LnNEC	LnERT	LnGLOB	LnEG	LnPOPD
CDLMBP	385.929*	413.887*	503.081*	547.002*	1122.979*	1202.451*	1041.697*	924.80*
CDSLMBC	35.751*	38.698*	48.101*	52.731*	113.443*	121.821*	104.875*	92.553*

Results of CSD tests in panel data models (Residuals)

Tests	Model 1	Model 2	Model 3
Pesaran	2.182**	1.827***	−1.701***
Frees	2.063*	1.654*	2.311*
Friedman	47.373*	42.647*	17.619**

Note: H_0 is cross-sectional independence; * *, **, &*** indicate $P < 0.01$, 0.05, 0.1, respectively.

Table 4
Results of Unit Root tests.

Variables	CIPS		CADF	
	Level	Difference	Level	Difference
LnEFP	−2.341	−4.691*	−2.427	−3.316*
LnCFP	−2.325	−4.656*	−2.337	−3.122*
LnCO_2	−2.169	−4.521*	−2.321	−3.667*
LnNEC	−2.202	−5.095*	−1.986	−3.503*
LnERT	−2.566	−4.759*	−2.292	−3.535*
LnGLOB	−2.162	−5.323*	−2.032	−3.638*
LnEG	−2.263	−4.622*	−2.577	−3.645*
LnPOPD	−1.432	−3.930*	−2.004	−3.326*

Note: H_0 is unit root; The 1%, 5% and 10% critical values are −3.10, −2.86 and −2.73, respectively; * indicate $P < 0.01$.

Table 5
Results of LM bootstrap panel cointegration test.

	Constant		Constant & trend	
	LM-statistic	Bootstrap p-value	LM-statistic	Bootstrap p-value
Model 1	3.465	1.000	6.233	1.000
Model 2	5.436	1.000	4.270	1.000
Model 3	4.181	1.000	8.479	1.000

Note: H_0 is cointegration; the bootstrap test statistic is computed with 1000 replications.

power is already identified as a clean energy source with a low carbon footprint capable of delivering baseload electricity at competitive costs due to low reliance on uranium prices, which is abundant and is less vulnerable to global crises in the extraction process [26,28,31]. Despite producing a heavy volume of carbon-free power, nuclear energy has beneficial impacts on EFP reduction, endorsing that it preserves the environment with minimal environmental footprint. Nuclear energy is substantially more concentrated, has a high power and energy density, and can generate electricity more quickly with less land required than fossil fuels and other renewables [12]. Moreover, the energy-dense nuclear energy results in minimal technical waste that can be reprocessed and recycled, reducing the environmental footprint by preserving the scarce natural resources (uranium) used to generate energy. Poinssot et al. [11] have demonstrated that nuclear waste used to generate electricity still contains potentially beneficial substances for additional power generation and is worth recycling to boost nuclear energy's sustainability. Hence, diversifying the energy supply to include nuclear energy is critical for the selected nations to minimize pollution and dependency on fossil fuels while simultaneously promoting energy independence and achieving sustainable development.

The long-run impact of environment-related technology (ERT) on ecological footprint is negative and statistically significant, meaning growth in ERT will improve environmental quality in the top ten EFP countries. Its coefficient value indicates that a 1% increase in ERT decreases EFP by 0.02%, keeping all else constant. The supportive role of ERT in these countries shows that environmental innovations promote cleaner manufacturing, effectively tackling environmental issues and promoting green growth. It is also projected that environmental pressure resulting from high economic progress, industrial growth and increased goods production would further force these economies to adopt technological innovation and pursue alternative energy sources by increasing ERT investments. Overall, improving innovation and technology is expected to be the most promising path to green economies and enhancing ERT investment will help the region reach its environmental sustainability target. Our findings have been supported by studies such as Hussain et al. [34], Danish and Ulucak [20], Ahmed et al. [33] and Mensah et al. [35].

The results for globalization (GLOB) showed a significant positive impact on the ecological footprint in the long run. It indicated that GLOB degrades the environmental quality, provoking the EFP for the sampled countries. A 1% increase in GLOB is linked to increased EFP by 0.65%. Globalization combines the global market, fosters industrialization, and increases demand for products and services, resulting in excessive extraction of environmental resources, creating extreme biodiversity loss and an ecological deficit. Similarly, globalization through foreign trade and investment leads to increased transportation, production and energy consumption resulting in the land, water, and air pollution. The adverse influence of globalization due to trade openness and foreign investment in industrial and manufacturing units also undermines environmental

Table 6
Results of Regression with Driscoll-Kraay standard errors.

Variables	Model 1 (Dependent: EFP)			Model 2 (Dependent: CFP)			Model 3 (Dependent: CO_2)		
	Coefficient	St. error	p-value	Coefficient	St. error	p-value	Coefficient	St. error	p-value
LnNEC	-.1098*	.0098	0.000	-.2145*	.0325	0.000	-.2076*	.0371	0.000
LnERT	-.0244*	.0123	0.005	-.0310***	.0224	0.078	-.0742*	.0232	0.004
LnGLOB	.6533*	.1652	0.001	.1350***	.2669	0.061	.6292**	.2753	0.030
LnEG	.3943*	.0146	0.000	.3443*	.0279	0.000	.3122*	.0276	0.000
LnPOPD	-.1181*	.0112	0.000	-.0649*	.0162	0.000	-.1140*	.0126	0.000

Note: *, **, &*** indicate $P < 0.01$, 0.05, 0.1, respectively.

and economic reforms. That is why globalization is claimed to promote pollution-intensive industries and increase human ecological demand in countries with lax environmental and land regulations [8]. Some previous research, such as Saud et al. [7] and Pata and Yilanci [37], hypothesizes that globalization with a minimum ecological effect can boost economic activity with domestic reforms, provided that the manufacturing sector is committed to environmental reforms. Hence, it is critical to consider globalization in the EFP function while creating long-term environmental policies to achieve sustainable growth. Our evidence is in harmony with the results of Langnel and Amegavi [2] and Pata and Caglar [36].

The long-run Driscoll-Kraay coefficient of economic growth (EG) appeared positively significant, indicating that augmenting it impacts the environment adversely. A 1% increase in EG corresponds to a 0.39% increase in EFP for ten ecological footprint countries; all things kept the same. This positive conclusion implies that the selected panel countries are primarily focused on increasing their productivity through enormous brown production and polluting industries at the expense of environmental quality. This trend may be explained because as economic activity expands, the demand for scarce natural resources to fuel manufacturing enterprises also expands. Hence, accelerated economic growth degrades ecological reserves resulting from increased industrialization and production activities that wreak havoc on the environment by devoting agricultural land to manufacturing uses, depleting and destroying wildlife habitats, exploiting natural resources, and deforestation. These results are similar to Yilanci and Pata [10] Langnel and Amegavi [2], and Saud et al. [7].

Finally, the long run Driscoll-Kraay regression results show that population density (POPD) decreases EFP in countries with the largest ecological footprint. The negative coefficients show that the EFP decreases by 0.11% with every 1% increase in POPD, ceteris paribus. This negative coefficient contradicts the assumption that higher population density raises demand for natural resource-related products and increases waste generation that degrades environmental quality, as Sarkodie [58] reported. This is because population density facilitates the efficient extraction and usage of available natural capital to meet living requirements while maintaining ecological balance. Moreover, population density decreases EFP through economies of scale, technological innovation, resource efficiency, and public services provision [59]. This conclusion is consistent with Kongbuamai et al. [60] and Ahmed et al. [61].

Models 2 and 3 assess the long-run impacts of predictors on CFP and CO_2 emissions to perform a robustness check. The significant negative effects of NEC, ERT, POPD and significant positive effects of GLOB and EG on CFP and CO_2 emissions are consistent across Models 1, 2, and 3, confirming the primary model's robust findings.

This study also applies FGLS and PCSE estimation to check the robustness of the Driscoll-Kraay test findings. The long-run estimation coefficients of FGLS and PCSE for all exogenous variables confirm the finding of the Driscoll-Kraay regression in Models 1, 2 and 3, as illustrated in Table 7. The empirical findings indicate the same directional associations of all regressors with the dependent variable at various significance levels, confirming the consistency and robustness of Driscoll-Kraay estimates. The common correlated effect mean group (CCEMG) and the augmented mean group (AMG) estimation are also performed as additional robustness tests showing the same results for all three models (see Table A1 in Appendix).

Table 8 represents the outcome of pairwise Dumitrescu-Hurlin panel causality analysis to identify the variables' causal interrelationships. The results explain that bidirectional feedback causality exists between EPF to NEC, ERT, EG, and POPD. A feedback causal association is also found between CFP to NEC, ERT, EG, POPD and CO_2 to NEC, ERT, EG and POPD. There are, however, one-way causalities, running from GLOB to EFP, CFP and CO_2. Moreover, a casual bond among the exogenous variables revealed two-way causality of NEC with ERT and POPD and ERT with EG. Overall, these findings demonstrate that policies aiming at these variables might influence each other. These causality results support the claims and directions of the long run estimation of Driscoll-Kraay standard errors, FGLS and PCSC presented in Tables 6 and 7.

5. Conclusion and policy recommendations

The world faces global energy challenges of increased energy demands and preserving the environment from the adverse impacts of fossil fuels combustion via energy transition. In pursuit of these challenges, countries are shifting towards using nuclear and other renewable energy with minimal carbon and ecological footprint. This paper examines the impacts of nuclear energy, environmental technology, and globalization on the ecological footprint of a panel of ten largest ecological footprint countries from 1990 to 2017 utilizing the Driscoll-Kraay standard errors, FGLS and PCSE regression approach. The results infer that nuclear energy and ERT sustain the environment by reducing the ecological footprint, whereas globalization expands the ecological footprint. Nuclear energy is confirmed as less impacting energy that can be beneficial in reducing the energy-related environmental footprint. Moreover, the ecological footprint has a bidirectional feedback causality with nuclear energy and environmental technology and a unidirectional causal association with globalization.

These findings provide potential implications for Government and policymakers. First, the policymakers of these countries need to deploy nuclear energy in the energy portfolio that has a lower

Table 7
Robustness results of FGLS and PCSE estimation.

	Model 1 (Dependent: EFP)			Model 2 (Dependent: CFP)			Model 3 (Dependent: CO_2)		
Variables	Coefficient	St. error	p-value	Coefficient	St. error	p-value	Coefficient	St. error	p-value
Cross-sectional time-series FGLS regression									
LnNEC	-.0191*	.0069	0.006	-.0081***	.0075	0.082	-.0089**	.0057	0.022
LnERT	-.0131***	.0071	0.066	-.0059**	.0089	0.050	-.0127**	.0062	0.042
LnGLOB	.4832*	.1146	0.000	.2027**	.1537	0.018	.1512***	.1124	0.079
LnEG	.4715*	.0203	0.000	.5764*	.0314	0.000	.5727*	.0282	0.000
LnPOPD	-.1577*	.0155	0.000	-.1539*	.0289	0.000	-.0943*	.0280	0.001
Correlated panels corrected standard errors (PCSEs)									
LnNEC	-.0271*	.0089	0.002	-.0310**	.0143	0.030	-.0195*	.0115	0.009
LnERT	-.0242*	.0088	0.006	-.0257***	.0141	0.069	-.0148***	.0086	0.085
LnGLOB	.5467*	.1294	0.000	.0991***	.2271	0.062	.1159***	.1806	0.052
LnEG	.4592*	.0218	0.000	.5253*	.0418	0.000	.5067*	.0412	0.000
LnPOPD	-.1150*	.0089	0.000	-.0410**	.0202	0.043	-.0959*	.0305	0.002

Note: *, **, &*** indicate $P < 0.01, 0.05, 0.1$, respectively.

Table 8
Results of Pairwise Dumitrescu-Hurlin (DH) panel causality.

	LnEFP	LnCFP	$LnCO_2$	LnNEC	LnERT	LnGLOB	LnEG	LnPOPD
LnEFP	–	3.0993 1.1440 0.2526	3.5429 1.7150 0.0863***	3.5065 1.6681 0.0953***	4.2600 2.6379 0.0083*	2.7325 0.6718 0.5017	5.0436 3.6466 0.0003*	4.1058 2.4395 0.0147**
LnCFP	5.3027 3.9801 0.0000*	–	6.1779 5.1065 0.0000*	3.6187 1.8125 0.0699***	4.4609 2.8965 0.0038*	2.3327 0.1572 0.8750	4.8245 3.3645 0.0008*	6.0822 4.9833 0.0000*
$LnCO_2$	4.7073 3.2137 0.0013*	4.8154 3.3529 0.0008*	–	3.9596 2.2513 0.0244**	4.5494 3.0104 0.0026*	1.8629 −0.4473 0.6546	4.2786 2.6619 0.0078*	6.8555 5.9787 0.0000*
LnNEC	3.9279 2.2105 0.0271**	3.1861 1.2558 0.2092	6.2818 5.2403 0.0000*	–	6.4586 5.4677 0.0000*	1.6622 −0.7057 0.4804	2.5890 0.4872 0.6261	4.6523 3.1429 0.0017*
LnERT	6.2475 5.1961 0.0000*	5.4730 4.1992 0.0000*	7.0360 6.2110 0.0000*	4.7011 3.2057 0.0013*	–	2.8774 0.8584 0.3907	5.0892 3.7052 0.0002*	7.8264 7.2283 0.0000*
LnGLOB	4.4720 2.9108 0.0036*	4.6674 3.1623 0.0016*	6.9074 6.0455 0.0000*	3.8029 2.0496 0.0404**	3.3630 1.4834 0.1380	–	4.3091 2.7011 0.0069*	4.0576 2.3774 0.0174**
LnEG	7.1584 6.3685 0.0000*	4.5418 3.0006 0.0027*	9.5847 9.4915 0.0000*	3.6769 1.8875 0.0591***	3.4888 1.6453 0.0099*	4.1425 2.4866 0.0129*	–	6.2723 5.2280 0.0000*
LnPOPD	6.5580 5.5957 0.0000*	6.7478 5.8400 0.0000*	9.9673 9.9840 0.0000*	5.4422 4.1596 0.0000*	7.0115 6.1794 0.0000*	5.3294 4.0144 0.0000*	7.6237 6.9674 0.0000*	–

Note: H_0 is no causality; 1st, 2nd and 3rd value indicates W-stat, Z-stat and P-value, respectively; *, **, &*** indicate $P < 0.01$, 0.05, 0.1, respectively.

ecological and carbon footprint. In doing so, the governments of these countries must prioritize investment in nuclear energy technology and infrastructure and stimulate nuclear energy development by integrating it into their long-term energy policies. It is recommended that these countries' governments set up international collaboration, encourage public-private partnerships in nuclear power plants and technology development, encourage license renewals, promote nuclear energy research, pilot programs, and educational endeavors accenting nuclear energy's benefits to promoting nuclear energy supply. Policymakers, however, should be cognizant of the negative public sentiment caused by the possible nuclear reactor accidents and the related radioactive waste disposal. To this end, the policy analysts of these countries should consider the environmental footprint impact of nuclear energy alongside atmospheric pollution that may assist in building objective criteria for future decision making and guiding the public and the Government in nuclear energy cognizance. The Government, through intuitional reforms, must raise public awareness of recent sustainable breakthroughs in nuclear power usage and waste disposal technology and frequently disseminate radiation and health information to communities of nuclear power plants. We suggest the Government ensure nuclear waste recycling by deploying modern nuclear technology such as small modular reactors technologies and twice-through fuel cycle to increase the energy supply, minimize waste storage, and preserve the natural uranium for future generations. Second, this study argued that establishing supporting policies for ERT development in the selected countries may facilitate EFP reduction. Therefore, policymakers should promote investment in ERT to support the clean energy sector and participate in the energy transition. It is suggested that the governments should incentivize the private investors to benefit from ERT and set up an international technological collaboration to minimize global and regional environmental concerns.

Third, these countries should enforce stringent environmental policies restricting energy-consuming trade activities and pollutive technology transfer in the globalization process. As a policy tool, these countries might impose dumping duties on trade partners and foreign companies using outmoded technologies, particularly those in the resource extraction sector. These nations must follow global sustainable ecological protocols in hunting overseas capital projects, strengthening nuclear and renewable energy technology development, and enabling sustainable production via ecological awareness with the help of domestic media and enhanced social interaction globally. Fourth, the Government needs to change economic policies to economic decarbonization policies by systematic economic changes to promote sustainable energy production. In doing so, the Government should provide a favorable political climate and supportive behavior to public and private investors in utilizing modernized resources for promoting and using eco-friendly energy sources, thereby promoting the environment's quality. Finally, these economies should accelerate urbanization to raise population density since it contributes significantly to environmental improvement. Policymakers should develop a prudent population strategy that enables the advantages of scaling effects to be realized by enhancing service affordability and resource utilization efficiency with the increase in natural capital stocks. These policies must be properly linked with land reforms to avoid jeopardizing arable land available for agricultural output.

Despite providing some novel findings, this study also poses some limitations which could bring future research opportunities. The environmental footprint impacts of nuclear energy are a controversial subject affected by certain social, cultural, and institutional factors and are open to debate. This study examined the nuclear energy impacts on EFP for a panel of 10 largest ecological footprint countries, directing future studies for other emerging and developed nuclear energy-consuming countries for both panel data and country-specific investigation to bring more specific facts. Finally, extending this study with additional contributing factors, such as political risk and institutional quality, for different case studies may result in fascinating literature contributions.

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.

Appendix

Table A1
Robustness results of CCEMG and AMG estimation

	Model 1 (Dependent: EFP)			Model 2 (Dependent: CFP)			Model 3 (Dependent: CO$_2$)		
Variables	Coefficient	St. error	p-value	Coefficient	St. error	p-value	Coefficient	St. error	p-value
CCEMG									
LnNEC	−0.049**	0.039	0.016	−0.061*	0.031	0.007	−0.040***	0.054	0.066
LnERT	−0.015**	0.014	0.045	−0.017***	0.009	0.074	−0.032***	0.019	0.098
LnGLOB	0.460***	0.276	0.091	0.392**	0.484	0.018	0.013*	0.330	0.009
LnEG	0.569*	0.199	0.000	0.399*	0.274	0.000	1.039*	0.193	0.000
LnPOPD	−0.455*	1.848	0.006	−0.414**	0.844	0.033	−0.237**	0.909	0.021
AMG									
LnNEC	−0.017***	0.054	0.057	−0.023***	0.040	0.070	−0.030**	0.062	0.030
LnERT	−0.010**	0.012	0.036	−0.029**	0.013	0.021	−0.023***	0.020	0.057
LnGLOB	0.332***	0.196	0.083	0.190**	0.381	0.012	0.035***	0.268	0.093
LnEG	1.064*	0.166	0.000	0.763*	0.278	0.000	0.907*	0.167	0.000
LnPOPD	−0.452**	1.244	0.016	−0.331*	2.029	0.007	−1.201*	2.065	0.009

Note: *, **, &*** indicate $P < 0.01$, 0.05, 0.1, respectively.

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