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ORIGINAL PAPER

Analyzing the effects of solar energy innovations, digitalization, and economic globalization on environmental quality in the United States

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Abstract

The escalating apprehension regarding climate change mitigation has intensified the quest for energy alternatives that are low in carbon emissions, economically viable, and consistently available. Within this context, renewable energy sources emerge as fitting candidates, being recognized for their eco-friendliness and cleanliness. Nonetheless, despite the allure of transitioning towards cleaner energy, there exists a notable dearth of literature addressing the pivotal role of solar energy innovations and economic globalization in advancing the agenda of climate change mitigation (SDG-13), thus complicating the prediction of factors influencing ecological quality. Consequently, this study undertakes the inaugural investigation into the impact of solar energy innovation on ecological footprint, while also considering the influences of digitalization, economic globalization, renewable energy, and natural resources in the USA. To this end, Quantile-on-Quantile Kernel-Based Regularized Least Squares (QQKRLS) and wavelet quantile regressions (WQR) methodologies are employed, utilizing data spanning from 2000 to 2020. The analysis reveals that solar energy innovation, along with renewable energy, digitalization, and economic globalization, exerts a negative impact on ecological footprint, whereas natural resources exhibit a positive influence. Drawing from these insights, it becomes apparent that a concerted effort from stakeholders and policymakers is imperative in realizing the objectives of SDG-13 and SDG-7, necessitating a paradigm shifts in the USA's energy portfolio away from fossil fuels towards renewables.

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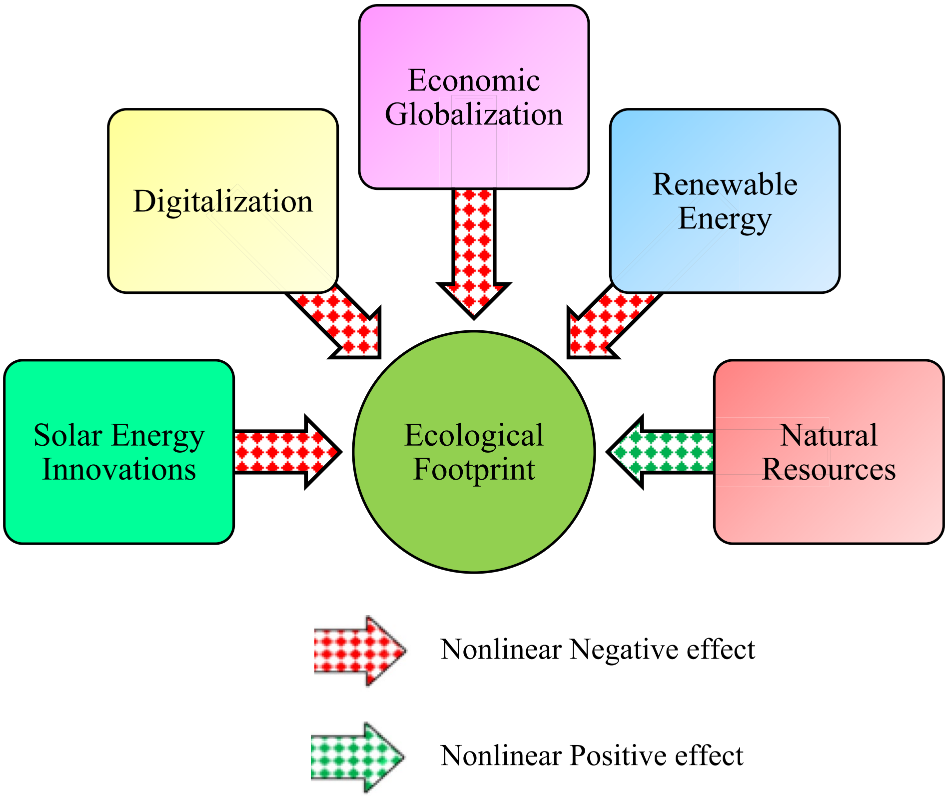
Graphical abstract



Keywords Natural resources · Digitalization · Economic globalization · Solar energy innovations · Ecological footprint · Renewable energy · KRLS approach

Introduction

Environmental sustainability is of growing global concern, particularly regarding nations like the USA, given their substantial ecological footprint and economic sway (Zhang et al. 2024a; Zhu et al. 2023a, b). Recent research has increasingly focused on the intricate relationships among natural resource use, digitalization, economic globalization, and advancements in solar energy (Chien et al. 2022; Adebayo et al. 2024). Recognizing how these elements interact and impact environmental quality is pivotal for shaping policies and fostering sustainable development (Eweade et al. 2023a, b). In December 2023, government leaders and environmental experts convened at the 28th United Nations Climate Change Conference (COP28) to agree on measures to combat climate change and limit temperature increases to below 1.5 °C. During COP28, the integration of finance, sustainability, and technology objectives was highlighted, emphasizing the interconnectedness of these goals. This synergy is exemplified by digitalization, a concept that blends financial and environmental technologies to drive sustainable development forward (Magazzino 2023; Saqib et al. 2023). At COP28, nations worldwide gathered to enhance existing goals and commitments. In the USA, efforts focus on demonstrating leadership in addressing the climate crisis and working with global allies. Collaborating with international partners, the USA aims to strengthen climate ambition and achieve meaningful results at COP28. With a primary aim of advancing the global transition to achieve net-zero emissions by 2050, the USA is committed to playing a crucial role in combating the imminent climate crisis, both now and in the future (Gao et al. 2024; Usman et al. 2024).

Natural resources play a pivotal role in shaping environmental quality, as their extraction, utilization, and management practices have profound impacts on ecosystems, air and water quality, and biodiversity (Razzaq et al. 2022; Mukherjee 2021). With the USA being a major consumer and producer of natural resources, the sustainable management of these resources is paramount for preserving environmental integrity (Gozgor et al. 2020; Adedoyin et al. 2020; Alola et al. 2023; Cui et al. 2022). Additionally, the advent of digitalization has revolutionized various sectors of the economy, leading to increased efficiency, productivity, and connectivity (Ahmed et al. 2021; He et al. 2024; Li et al. 2021). However, the proliferation of digital technologies also raises concerns about their environmental implications, such as energy consumption, electronic waste generation, and carbon emissions (Chien et al. 2022). Understanding the net effects of digitalization on environmental quality is crucial for harnessing its benefits while mitigating its adverse impacts (Ansari et al. 2021; Pata et al. 2023).

Digitalization has the potential to significantly contribute to environmental sustainability in the USA by financing solar panel installations, promoting renewable energy sources, and monitoring environmental impacts. It facilitates loans for individuals and companies aiming to reduce their environmental footprint, while also channeling capital into eco-conscious businesses. However, transitioning to renewable energy requires substantial investments in infrastructure, research and development, and widespread adoption of clean energy technologies(Karlilar et al. 2023). Therefore, integrating financial inclusion with digitalization simplifies access to funding for renewable energy projects, encouraging more entities to embrace clean energy solutions. Leveraging digital platforms, crowdfunding, and peer-to-peer financing broadens access to capital for renewable energy initiatives, attracting investment from a wider array of stakeholders.

Economic globalization, characterized by the increasing interconnectedness of economies and the movement of goods, services, and capital across borders, has both positive and negative implications for environmental quality (Adedoyin et al. 2020; Bekun and Ozturk 2024; Pata et al. 2023). While globalization has facilitated economic growth and development, it has also led to environmental degradation through increased resource extraction, pollution, and carbon emissions(Gupta and Kumar 2023; Bekun and Ozturk 2024; Eweade et al. 2024). Examining the environmental consequences of economic globalization in the context of the USA is essential for identifying opportunities for sustainable development. Furthermore, innovations in solar energy technologies have the potential to revolutionize the energy landscape and mitigate environmental impacts associated with fossil fuel combustion. Solar energy offers a clean, renewable alternative to traditional energy sources, reducing greenhouse gas emissions, air pollution, and reliance on finite resources (Khan et al. 2020a, b; Razzaq et al. 2022). Understanding the adoption, deployment, and effectiveness of solar energy innovations in the USA is critical for transitioning towards a more sustainable energy future (Ibrahim et al. 2022; Kabeyi and Olanrewaju 2022; Eweade et al. 2022).

In light of these considerations, this study aims to comprehensively examine the effects of natural resources, digitalization, economic globalization, and solar energy innovations on environmental quality in the USA. By analyzing the interactions between these factors and their cumulative impacts on environmental indicators such as air and water quality, biodiversity, and climate change, this research seeks to inform evidence-based policy interventions and promote sustainable development practices. Based on the stated research objective, the following research questions were raised; (1) Are there significant interactions or synergies among natural resource utilization, digitalization, economic globalization, and solar energy innovations that collectively impact environmental quality in the United States? (2) How do policy interventions and regulatory frameworks aimed at promoting sustainable development and environmental protection interact with the aforementioned factors in shaping environmental quality outcomes in the United States? (3) What are the regional variations in the relationship between natural resources, digitalization, economic globalization, solar energy innovations, and environmental quality across different states or regions within the United States? Following the objective and the research questions, the contributions of the study provides valuable insights for policymaking, sustainability, and global environmental efforts. It sheds light on how these factors interact and influence environmental outcomes, informing evidence-based policies and guiding businesses towards sustainability. Understanding their impact contributes to addressing climate change and promoting sustainable development practices. Additionally, it facilitates international collaborations and agreements for environmental protection. Overall, this research bridges academic knowledge with practical policymaking, fostering sustainability and economic development. To validate the connections between the variables and provide robust empirical evidence, the study employs a contemporary estimation technique known as the quantile-on-quantile KRLS method. This methodological approach offers new perspectives in analyzing United States data, enabling a deeper understanding of the complex relationships at play. Overall, the study contributes to the advancement of knowledge in the field of environmental sustainability by providing insights into the multifaceted dynamics influencing environmental quality in the USA and offering practical implications for policymakers and stakeholders striving to promote sustainable development practices.

The structure of the paper is as follows: The subsequent Sect. “Literature review” will provide a literature assessment, concentrating on the correlation between digitalization, economic globalization, natural resources, renewable energy, and solar innovation on the ecological footprint, with the aim of tackling climate change. This will be followed by a discussion in Sect. “Data and methodology” focusing on data and methodology framework used for empirical research. Sect. “Empirical analysis” will elaborate on the outcomes of our study, including a comparison with prior research in the field. Finally, Sect. “Conclusion and policy recommendations" will present our conclusion, highlighting key findings relevant for scholars and policymakers.

Literature review

Numerous studies have been undertaken to explore the intricate interplay among solar energy innovations, digitalization, economic globalization, renewable energy, natural resources, and ecological footprint. This section presents a comprehensive overview of prior investigations into the specified variables. Additionally, a meticulous critique of the existing literature is offered, emphasizing discernible knowledge gaps.

Solar energy innovations and ecological footprint

Solar energy innovation has ushered in a paradigm shift in environmental sustainability. Its utilization of solar electricity, harnessed from a renewable and abundant resource, has markedly diminished reliance on fossil fuels, consequently alleviating greenhouse gas emissions (Ahmadi et al. 2018). The consequential reduction in air and water pollution induced by solar energy systems has been expounded upon by Rabaia et al.(2021), thereby safeguarding ecosystems and air quality, both of which bear substantial environmental ramifications. In the discourse surrounding the impact of solar energy innovations, disparate perspectives emerge. Advocates of the positive influence of solar energy on environmental quality include researchers such as Shahsavari and Akbari (2018) who, in their examination of developing nations, asserted that solar energy reduces carbon emissions. Güney (2022) substantiates these claims by analyzing annual data from 2005 to 2018 across 35 economies, establishing a tangible correlation between increased solar energy utilization and substantial reductions in carbon emissions. Shahsavari et al. (2019) observed that each kilowatt-hour of solar electricity curtails approximately 715 g of CO_2.

Conversely, a counterargument emerges, underscoring environmental concerns associated with solar energy, particularly concerning the manufacturing and disposal of solar panels. The manufacturing process involves the use of chemicals, such as silicon and silver, which may pose hazards if not handled with due care. Yu et al. (2022) employed QQR regression in a study spanning from 1991 to 2018, contending that solar energy has a limited impact on reducing carbon emissions in France. Zhu et al. (2023a, b) reported similar findings for Spain and India, indicating that the efficacy of solar energy in mitigating carbon emissions varies across countries. These incongruent findings underscore the need for further investigation to derive generalizable conclusions regarding the impact of solar energy innovation on carbon emissions reduction.

Digitalization and ecological footprint

The digital transformation of industries has significantly altered our interactions, consumption, and production methods, impacting environmental sustainability both positively and negatively. Digitization, highlighted by Zhang et al. (2023), improves energy efficiency and minimizes material consumption through remote monitoring. Digitization brings forth a dualistic situation. While the shift to digital products reduces reliance on physical items, lessening environmental impact, it also leads to increased electronic waste from frequent device replacements, posing contamination and resource depletion challenges. The growing energy demands of digital technologies, particularly data centers and cloud services, raise environmental concerns with heightened greenhouse gas emissions, emphasizing the need for sustainable electricity practices.

Zhu et al. (2022) conducted a study in China to scrutinize the impact of digitalization on carbon emissions, revealing substantial reductions attributable to the digital economy. This reduction is facilitated through the promotion of innovation and the evolution of industrial structures. Similarly, Ke et al. (2022) found, in a study spanning 77 emerging economies, that digitization exerted a noteworthy influence in curtailing carbon emissions. Contrastingly, recent research by Dong et al. (2022) conducted in China, utilizing panel data from 2008 to 2018 across 60 countries, discovered an association between the rise in digitalization and an increase in per capita carbon emissions. Wang et al. (2022) argue that the relationship between digitalization and carbon emissions in China can be represented by an inverted U-shaped curve, a proposition substantiated by rigorous testing. Furthermore, Yang et al. (2022) conducted a similar study in China, revealing a curvilinear impact of digitalization on carbon emissions, following an inverted U-shaped pattern. The inconclusive nature of these results necessitates further in-depth exploration to elucidate the intricate relationship between digitalization and environmental sustainability.

Economic globalization and ecological footprint

The indicators of economic globalization include trade, foreign direct investment (FDI), portfolio investment, and regulatory issues such as tariffs, import restrictions, and levies on international trade (Gygli et al. 2019). The process of economic globalization has the potential to enhance the ecology by capitalizing on the positive effects of international trade and FDI. The adoption of environmentally friendly technology and structural modifications are encouraged by the technique and composition effects of trade, resulting in improvements to the environment. Conversely, the proliferation of opportunities for exporting goods in an era of unrestricted trade has resulted in increased production, thereby negatively impacting the environment due to the scale effect (Ahmed et al. 2021). Langnel and Amegavi (2020) employed yearly data spanning from 1971 to 2016 for Ghana and employed the ARDL methodology to examine the data. Their data confirm that globalization results in a rise in ecological footprint. Hussain et al. (2021) show a causal relationship between globalization and ecological footprints in Thailand by examining yearly data from 1970 to 2018 through the utilization of the NARDL approach. The findings indicate that an increase in globalization has a direct correlation with an increase in ecological footprints.

Moreover, Rudolph and Figge (2017) also conducted a study in which they analyzed 146 nations using the Extreme Bounds Analysis (EBA) method. They found that economic globalization had a positive influence on the ecological footprint. However, Ansari et al. (2021) have presented divergent results in their latest research conducted in prominent economies that heavily rely on renewable energy. Their research indicates that globalization has a tendency to decrease ecological footprints. In addition, Ahmed et al. (2021) examined the relationship between economic globalization and ecological footprint in Japan. By employing the ARDL technique, they discovered significant effects of economic globalization on the rise of ecological footprints. Nevertheless, the NARDL technique produces contrasting outcomes, indicating that both positive and negative shifts in economic globalization contribute to a decrease in ecological footprint. The contrasting results highlight the need for thorough research in order to develop robust policies.

Renewable energy and ecological footprint

Renewable energy, encompassing solar, wind, and hydroelectric power, gains popularity due to its environmentally friendly attributes as a substitute for fossil fuels. Characterized by a smaller ecological impact, it involves decreased land usage, absence of air pollutants, sustainable water resource management, and the promotion of biodiversity, making it an appealing and sustainable option. Xue et al. (2021) examined yearly data from 1990 to 2014 for South Asian countries utilizing the AMG approach. Their findings suggest that renewable energy has a substantial impact in reducing the ecological footprint. Sharif et al. (2021) did a study that examined the top ten economies with the greatest use of solar energy from 1990 to 2018. By employing a nonparametric quantile on quantile regression method, they discovered a significant and positive influence of solar energy on the state of the ecosystem. Li et al. (023) conducted a study on the economies of 130 nations using panel threshold regression. Their findings revealed that renewable energy has a notable impact on minimizing the ecological footprint. In contrast, Chalendar and Benson (2019) have recently raised doubts about the effectiveness of solar energy in mitigating carbon emissions. In their study, Nathaniel et al. (2020) observed varying results when examining the relationship between renewable energy and ecological footprint in MENA economies. They utilized annual data from 1990 to 2016 and employed the AMG methodology. Their findings indicated that there was no significant influence on ecological footprint or environmental quality.

Natural resources and ecological footprint

The study of the relationship between economic growth and the environment involves examining the use, excessive exploitation, and deterioration of natural resources, as well as issues related to pollution and global warming. Currently, there is a strong emphasis on climate change at a global level, with a recognition of the serious risks that it presents to the well-being of humans and the ability to maintain sustainable economic growth (Khan et al. 2020a, b). Consequently, there has been an increased focus in recent years among academics, scholars, and legislators on the deterioration of the ecology and the exhaustion of natural resources. Awosusi et al. (2022a, b) investigated the influence of natural resources on ecological footprints in BRICS countries. By analyzing annual data spanning from 1992 to 2018 and utilizing the MMQR approach, they discovered a substantial detrimental impact of natural resources on the ecosystem. In a study by Ahmad et al.(2020) covering 22 developing economies, using annual data from 1984 to 2016 and employing the CS-ARDL technique, it was demonstrated that increase in natural resources has a significant positive impact on the ecological footprints of the economies under examination. Kongbuamai et al. (2020) conducted a study on ASEAN economies, analyzing annual data from 1995 to 2016 through the Driscoll–Kraay panel regression method. Their findings indicate that natural resources have a substantial impact in reducing ecological footprints. In a similar vein, Zafar et al.(2019) examined the impact of natural resources in the USA by analyzing annual data from 1970 to 2015 and employing the ARDL technique. They discovered a significant reduction in the ecological footprint. Table 1 offers a detailed summary of the reviewed studied.

Gaps in the literature

Following an extensive review of the literature on environmental studies, we identified several knowledge gaps. (1) We discovered that the link between proposed factors is less focused on the USA setting, resulting in pioneering studies that investigate the effect of solar energy innovations, and digitalization on ecological sustainability while considering the role of economic globalization, renewable energy, and natural resources. (2) We

Table 1 Summary of past studies

Authors	Sample countries	Methods	Time periods	Findings
Nexus between solar energy innovations (SEINO) and ecological footprint (ECOFP)				
Sharif et al. (2021)	Top ten solar energy-consuming economies	QQR approach	1990–2018	Solar energy reduces the ECOFP
Kuşkaya et al. (2023)	USA	Morlet wavelet analysis	1990:1–2022:6	Solar energy reduces CO_2 emissions
Güney (2022)	35 economies	CCEMG approach	2005–2018	Solar energy reduces CO_2 emissions
Yu et al. (2022)	Top ten solar energy-consuming economies	QQR approach	1991–2018	Except in France, solar energy reduces CO_2 emissions
Zhu et al. (2023a, b)	Top-ten solar energy-consumer countries	QQR approach	1991–2018	Except in Spain and India, solar energy reduces CO_2 emissions
Digitalization (DIGIT) and Ecological Footprint (ECOFP)				
Zheng et al. (2023)	China's 281 cities	Spatial spillover analysis	2016–2019	Inverted U-shaped curve
Zhu et al. (2022)	30 Chinese provinces	Fixed-effects model	2009–2019	DIGIT reduces CO_2 emissions
Yang et al. (2022)	China	Panel regression	2006–2019	DIGIT and CO_2 emissions show an inverted U-shaped curve link
Dong et al. (2022)	60 countries	Intermediary effect model	2008–2018	DIGIT reduces CO_2 emissions
Nexus between economic globalization (ECGLO) and ecological footprints (ECOFP)				
Ahmed et al. (2021)	Japan	NARDL approach	1971–2016	ECGLO reduces ECOFP
Ansari et al. (2021)	Top renewable energy consuming economies	PMG approach	1991–2016	ECGLO reduces ECOFP
Langnel and Amegavi (2020)	Ghana	ARDL approach	1971–2016	ECGLO increases ECOFP
Hussain et al. (2021)	Thailand	NARDL approach	1970–2018	ECGLO increases ECOFP
Rudolph and Figge (2017)	146 countries	The Extreme Bounds Analysis (EBA)	1981–2009	ECGLO increases ECOFP
Nexus between renewable energy (RENEN) and ecological footprint (ECOFP)				
Xue et al. (2021)	South Asian nations	AMG approach	1990–2014	RENEN reduces ECOFP
Li et al. (2023)	130 countries	Panel threshold regression	1992–2019	RENEN reduces ECOFP
Nathaniel et al. (2020)	MENA	AMG approach	1990–2016	No impact of RENEN on ECOFP ECGLO
Sahoo and Sethi (2021)	Developing countries	MG, AMG, and DCCE	1990–2016	RENEN reduces ECOFP
Nexus between natural resources (NATRE) and ecological footprint (ECOFP)				
Awosusi et al. (2022a, b)	BRICS	MMQR approach	1992–2018	NATRE increases ECOFP
Ahmad et al. (2020)	22 emerging economies	CS-ARDL approach	1984–2016	NATRE increases ECOFP
Kongbuamai et al. (2020)	ASEAN	Driscoll-Kraay panel regression	1995–2016	NATRE decreases ECOFP
Zafar et al. (2019)	USA		1970–2015	NATRE decreases ECOFP

QQR, CCEMG, ARDL, NARDL, PMG, MG, DCCE, MMQR, and CS-ARDL stand for quantile-on-quantile regression, common correlated effects mean group, autoregressive distributed lag, asymmetric autoregressive distributed lag, pooled mean group, mean group, dynamic common correlated effects, quantile regression methods of moments, and cross-sectionally augmented autoregressive distributed lag, respectively

noted that the majority of the research used traditional techniques such as ARDL, CCEMG, DCCE, and so on, therefore this study used a variety of unique econometric methodologies such as the innovative QQKRLS, WQR, and QQR approach.

Data and methodology

Data

The present analysis assesses the effects of advancements in solar energy technology and digitalization on environmental sustainability, taking into account the influence of economic globalization, the utilization of renewable energy sources, and the management of natural resources. The United States serves as the focal point for this investigation, covering the period from 2000 to 2020. To mitigate the challenge of limited observational data, this study adopts the quadratic sum-up approach, building upon the methodologies outlined in prior works such as Pata et al. (2022) and Khan et al. (2023), thereby transforming low-frequency data into a higher frequency. Additionally, a comprehensive overview of the research procedures is provided in Table 2.

Methodology

Quantile-on-quantile kernel-based regularized least squares (QQKRLS)

Several studies suggest that policy shifts, structural changes, sudden shocks, and political fluctuations contribute to the emergence of characteristics such as asymmetry, nonlinearity, heavy-tailedness, and extreme values in economic time series (Bouoiyour and Selmi 2017). Amidst an ongoing global energy crisis and a worldwide pandemic, both of which have significantly disrupted the global landscape, various studies indicate that macroeconomic indicators respond to a new, nonlinear rhythm. Considering nonlinearities among the proposed variables, this study explores the asymmetric impact of SEINO, DIGIT, ECGLO, RENEN, and NATRE on ECOFP. Two distinct methodologies, the quantile-on-quantile kernel-based regularized least squares (QQKRLS) introduced by Adebayo et al. (2024) and Wavelet quantile regression (WQR) proposed by Adebayo and Özkan (2024), are employed to analyze this dynamic interaction.

Originally introduced by Hainmueller and Hazlett (2014) the KRLS approach is a machine learning technique motivated by its flexibility in regression without the need for specific assumptions. The algorithm utilizes Gaussian kernels to identify the optimal fitting function, thereby mitigating bias resulting from incorrect specifications. The KRLS method assesses the marginal impact of an explanatory variable on each individual data point of an endogenous variable. By leveraging the distribution of these marginal impacts, it unveils diverse (nonlinear) outcomes. Specifically, the KRLS method calculates the average of pointwise marginal impacts to determine the effect size and statistical significance of the explanatory variable's impact on the endogenous variable (Hainmueller and Hazlett 2014). To elaborate further, KRLS can assess the influence of an exogenous variable X on an endogenous variable Y in the following manner:

$$E_S\left[\frac{\widehat{\Gamma Y}}{\Gamma X_n}\right] = \frac{-2}{\sigma^2 S}\sum_n \sum_i j_i e^{\frac{\|X_i - X_n\|^2}{\sigma^2}}\left(X_i - X_n\right) \tag{1}$$

whereas $E_S\left[\frac{\widehat{\Gamma Y}}{\Gamma X_k}\right]$ represents the average or mean pointwise marginal impact of the exogenous (X) on the endogenous (Y) variable. Additionally, n denotes an individual observation, and S signifies the sample size. It is clear that KRLS approach places emphasis on the complete distribution of the dependent variable rather than the independent variable. Demonstrating the average pointwise marginal impact of the independent variable X on the dependent variable Y highlights the presence of nonlinearity in each data point of the projected variable. However, the statistical significance is ascertained by a singular value—the mean or average pointwise marginal effect. By utilizing the QQKRLS approach, this study extends beyond the exclusive consideration of the entire distribution of the endogenous variable in the KRLS method. Specifically, we integrate the KRLS approach introduced by Hainmueller and Hazlett (2014) with the QQR approach by Sim and Zhou (2015). This combined QQKRLS method enables the assessment of statistical significance for the complete distributions of both exogenous and endogenous variables. Through computing average pointwise marginal influence across quantile pairs, the approach provides valuable insights into the impact size and statistical significance associated with the influence of exogenous variable

Table 2 Details of the study data

Variable name	Symbol	Content of the data	Data source
Ecological footprint	ECOFP	Ecological footprint, per person (gha)	GFN (2024)
Solar energy innovations	SEINO	Annual total patents filed for solar energy technologies	OWD (2024)
Digitalization	DIGIT	Individuals using the Internet (% of population)	WDI (2024)
Economic globalization	ECGLO	KOF Economic Globalization Index calculated by Gygli et al. (2019)	KOF (2024)
Renewable energy	RENEN	Renewables (% equivalent primary energy)	OWD (2024)
Natural resources	NATRE	Total natural resources rents (% of GDP)	WDI (2024)

quantiles on endogenous variable quantiles. This methodology facilitates the exploration of complex or asymmetric relationships between the variables, allowing for a detailed analysis of how quantiles of the exogenous variable X affect quantiles of the endogenous variable Y.

$$E_S\left[\frac{\widehat{ℾQY_\tau}}{ℾQX_{\theta n}}\right] = \frac{-2}{\sigma^2 s}\sum_n\sum_i j_i e^{\frac{\|X_{\theta i}-X_{\theta n}\|^2}{\sigma^2}}\left(X_{\theta i}-X_{\theta n}\right) \quad (2)$$

Here, $E_S\left[\frac{\widehat{ℾQY_\tau}}{ℾQX_{\theta n}}\right]$ presents the mean or average pointwise marginal impact of the θth conditional quantile of the exogenous variable X on the τth conditional quantile of the endogenous variable Y. Furthermore QY_τ and QX_θ represent the τth and θth conditional quantile series of Y and X variables, respectively.

Wavelet quantile regression (WQR)

Next, we employed the recently introduced wavelet quantile regression (WQR) suggested by Adebayo and Özkan (2024). Following is the conventional quantile regression (QR) model for two variables.

$$∱_{(ℸ)}(Y|X) = \mathbb{Y}_{0(ℸ)} + \mathbb{Y}_{1(ℸ)}X \quad (3)$$

The expression, $∱_{(ℸ)}(Y|X)$ represents the conditional quantile of the endogenous (Y) given the exogenous (X) variable at quantile ℸ. Meanwhile, $\mathbb{Y}_{0(ℸ)}$ is the intercept parameter at quantile ℸ, while $\mathbb{Y}_{1(ℸ)}$ represents the slope parameter at quantile ℸ.

The quantile regression (QR) approach, introduced by Koenker and Bassett (1978), stands as a statistical method that extends beyond conventional linear regression practices. It presents a broader perspective for modelling the conditional quantiles of an endogenous variable concerning an exogenous variable. In contrast to the conventional ordinary least squares (OLS) method, which primarily estimates the average value of the endogenous variable, QR allows for a detailed exploration of the relationship between an exogenous variable and various quantiles of the endogenous variable. This methodology holds significant importance in academia, enabling a thorough analysis of the correlation between different percentiles of the endogenous variable and its covariates. The QR approach offers several advantages that contribute to its academic and practical utility. Firstly, it provides a more comprehensive depiction of the distribution of the endogenous variable, going beyond the conventional emphasis on the mean. Additionally, its capacity to handle outliers and heteroscedasticity distinguishes it as a robust analytical tool capable of effectively addressing anomalies in the data. QR enables researchers to analyze and comprehend changes in the interactions between a variable across different quantiles of the distribution, offering a comprehensive view of the phenomena under examination (Saeed Meo and Karim 2022).

Prior empirical investigations (Kuşkaya et al. 2023; Thi Hong Nham and Thanh Ha 2023; Zhu et al. 2023a) have demonstrated the variability in associations between variables across distinct time periods. However, the conventional QR approach neglects the potential for variations in the impact of the factor variable on the conditional quantiles of the response variable over different time dimensions, as previously highlighted in existing research. To overcome this limitation, we adopted the Wavelet Quantile Regression (WQR) method following the approach outlined by Adebayo and Özkan (2024). This was done to investigate the influence of an exogenous variable X on the conditional quantiles of an endogenous variable Y across various time intervals. The procedural steps for implementing the WQR technique are as follows:

We begin by applying the maximal overlapping discrete wavelet transform (MODWT) to decompose the exogenous (X_t) and endogenous (Y) series, following Percival & Walden (2000) and following a recent study of Adebayo and Özkan (2024) as below:

Consider $\boldsymbol{X}[\boldsymbol{i}]$ as a signal having a duration of T, where $T = 2^J$ for an integer J. Additionally, let $c_1[\boldsymbol{i}]$ represent as the low-pass filter and $d_1[\boldsymbol{i}]$ represent the high-pass filter, both of which are determined by the orthogonal wavelet. During the initial phase, $X[\boldsymbol{i}]$ experiences convolution with $c_1[\boldsymbol{i}]$ produces the estimate coefficients, $e_1[\boldsymbol{i}]$, which having a length of N, and with $d_1[\boldsymbol{i}]$ produces the detail coefficients $f_1[\boldsymbol{i}]$ again with a length of N. The procedure can be defined as follows:

$$e_1[\boldsymbol{i}] = c_1[\boldsymbol{i}]*\boldsymbol{s}[\boldsymbol{i}] = \sum_k c_1[\boldsymbol{i}-k]\boldsymbol{s}[k] \quad (4)$$

$$f_1[\boldsymbol{i}] = d_1[\boldsymbol{i}]*\boldsymbol{s}[\boldsymbol{i}] = \sum_k d_1[\boldsymbol{i}-k]\boldsymbol{s}[k] \quad (5)$$

Afterwards, we employ an akin method to filter $e_1[\boldsymbol{i}]$, using modified filters $c_2[\boldsymbol{i}]$ and $d_2[\boldsymbol{i}]$, which are obtained from the dyadic up-sampling of $c_1[\boldsymbol{i}]$ and $d_1[\boldsymbol{i}]$. This iterative approach involves the repetition of the recursive procedure. For values of J ranging from 1 to $J_0 - 1$, where $J_0 \leq 1$, we can calculate the parameters of the approximation and detailed components in the following manner:

$$e_{+1}[\boldsymbol{i}] = c_{j+1}[\boldsymbol{i}] * e_j[\boldsymbol{i}] = \sum_k c_{j+1}[\boldsymbol{i}-k]e_j[\boldsymbol{i}] \quad (6)$$

$$f_{j+1}[\boldsymbol{i}] = d_{j+1}[\boldsymbol{i}] * e_j[\boldsymbol{i}] = \sum_k d_{j+1}[\boldsymbol{n}-k]d_j\left[j\right] \quad (7)$$

Here, $c_{j+1}[\boldsymbol{i}] = U(c_j[\boldsymbol{i}])$ and $d_{j+1}[\boldsymbol{i}] = U(d_j[i])$, where the function U represents the up-sampling process, which involves injecting a zero value between each consecutive pair of time-series items.

After applying J-level deconstruction on Y_t and X_t and obtaining the detail coefficients, we proceed to apply QR on to the pair of wavelet details, $f_j[\boldsymbol{Y}]$ and $f[\boldsymbol{X}]$, for all levels J. Therefore, we calculate the results of WQR for each of the levels J. The WQR is formally defined for the endogenous variable Y and the exogenous variable X, at a certain decomposition level J, and for a given quantile $\daleth$, in the following manner:

$$\oint_{(\daleth)}(f_j[Y] \big| f_j[X]) = \gamma_{0(\daleth)} + \gamma_{1(\daleth)} f_j[X] \tag{8}$$

For detail and clear illustration, Fig. 1 presents the study analytical flow.

Empirical analysis

Preliminary analysis results

This segment of the study assesses the appropriateness of utilizing QQKRLS in the investigation. It commences with a scrutiny of descriptive statistics, followed by an examination of Quantile–quantile plots to gauge normality, BDS test estimates, and parameter stability test estimates. Table 3 displays essential descriptive statistics for the logarithmic data series originating from the USA. During the sample period, the averages for the lnECOFP, 1nSEINO, 1nDIGIT, 1nRENEN, and 1nNATRE series were approximately 0.55, 2.00, 1.07, 1.10, 0.45, and −0.07 respectively. Skewness analysis suggests left-skewed distributions for the 1nECOFP, lnSEINO, lnDIGIT, and lnNATRE series, while 1nRENEN displays a right-skewed distribution. Moreover, Kurtosis assessments reveal platykurtic distributions for all series except for 1nDIGIT, which exhibits a leptokurtic distribution. The results of the Jarque and Bera (1980) normality

Fig. 1 Workflow of the study

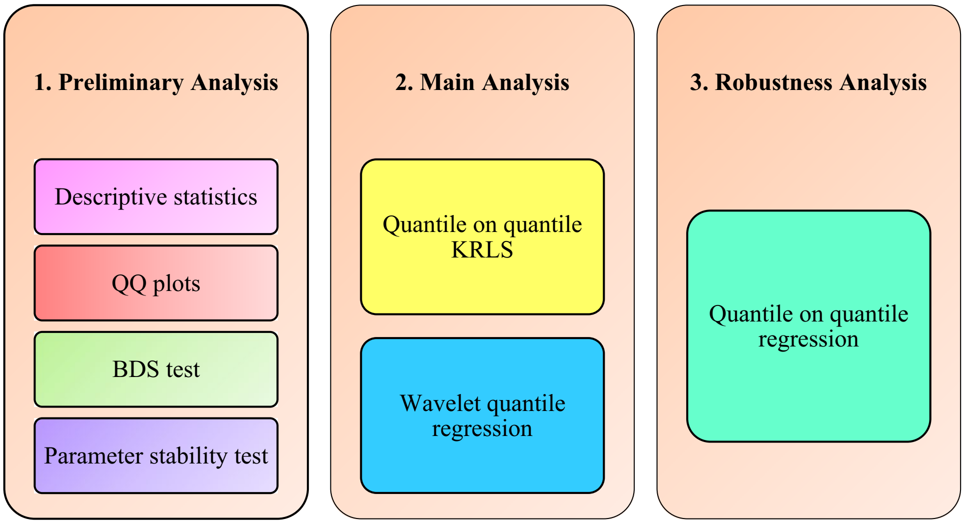


Table 3 Descriptive statistics

	lnECOFP	lnSEINO	lnDIGIT	lnECGLO	lnRENEN	lnNATRE
Mean	0.550	1.999	1.065	1.096	0.445	−0.066
Median	0.541	2.078	1.069	1.098	0.444	−0.043
Maximum	0.600	2.212	1.128	1.103	0.605	0.182
Minimum	0.477	1.553	0.931	1.086	0.305	−0.392
Std. Dev	0.031	0.196	0.046	0.006	0.084	0.135
Skewness	−0.020	−0.656	−1.003	−0.620	0.047	−0.625
Kurtosis	1.920	1.997	4.035	1.895	1.690	2.837
Jarque–Bera	4.089	9.537***	17.844***	9.655***	6.034**	5.555*
	(0.129)	(0.008)	(0.000)	(0.008)	(0.049)	(0.062)

***(prob) < 0.01, **(prob) < 0.05, and * (prob) < 0.1

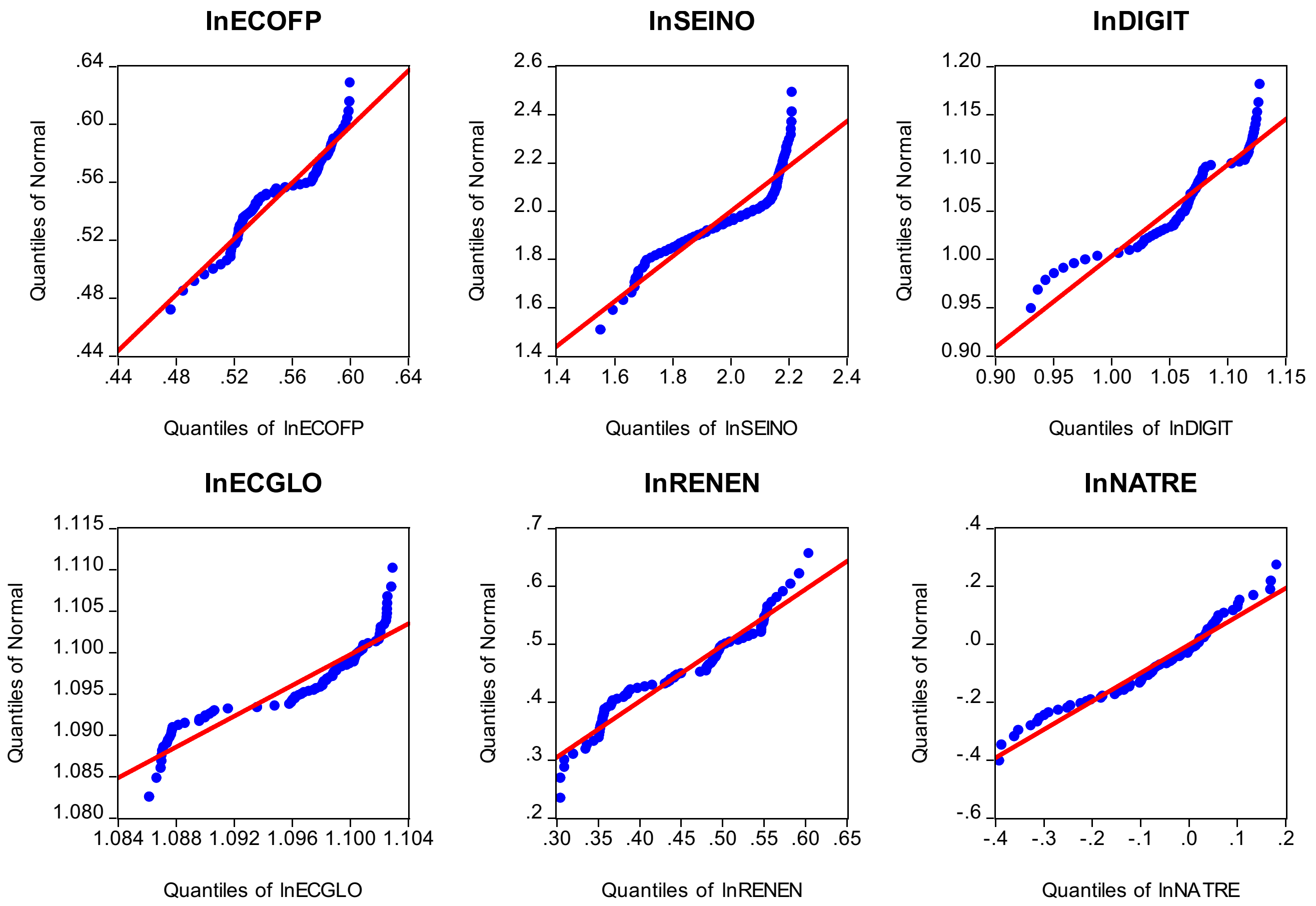


Fig. 2 Quantile–quantile plots for normality. The figures depict the normality status of the quarterly logarithmic (ln) data series for various variables. Specifically, ECOFP represents Ecological footprint, SEINO stands for Solar Energy Innovations, DIGIT refers to Digitalization, RENEN represents Renewable energy, and NATRE signifies Natural resources. Additionally, ECOFP also denotes Economic globalization

test, reported alongside descriptive statistics, indicate that all series, with the exception of lnECOFP, depart from a normal distribution.

This research utilizes the quantile-based approach, specifically QQKRLS. Therefore, it is essential to examine the normality aspect of the data intended for analysis through quantile–quantile (*Q*–*Q*) plots. As illustrated in Fig. 2, the data for all variables diverges from normality across various quantiles.

Table 4 BDS test estimates

	lnECOFP	lnSEINO	LnDIGIT	lnECGLO	lnRENEN	lnNATRE
Em. D. [2]	39.436***	32.168***	19.066***	30.052***	42.835***	18.960***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Em. D. [3]	41.681***	34.343***	20.048***	31.768***	45.316***	18.899***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Em. D. [4]	44.806***	36.818***	21.415***	33.820***	48.832***	19.415***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Em. D. [5]	49.602***	40.281***	23.512***	36.902***	54.089***	20.511***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Em. D. [6]	56.123***	44.956***	26.433***	41.299***	61.550***	22.280***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)

***(prob) < 0.01

In the initial analysis, we further explore the linearity properties of the quarterly logarithmic data. This investigation involves employing the BDS test, which was initially introduced by Broock et al. (1996). It is worth noting that this particular method has been applied in recent research conducted by Khan et al. (2023). Table 4 displays the findings of the BDS test, revealing that all variables' data deviates from the assumption of independent and identically distributed behavior across all dimensions. This indicates the presence of nonlinearity within the data for the entire duration of the study.

We examine the stability traits of the quarterly logarithmic data. This examination involves employing three distinct tests for parameter stability—Max-F, Exp-F, and Ave-F—which were introduced by Andrews (1993) and Miao et al., (2022). We follow existing literature from the studies of Lee et al. (2023) and Olanipekun et al. (2023). Table 5 presents the outcomes of the Max-F, Exp-F, and Ave-F tests, indicating data instability across all variables. This suggests non-stability throughout the study period (Hansen 1997). The preliminary assessment indicates that the data for all variables demonstrate abnormal distribution across various quantiles, as well as nonlinear and unstable patterns over the studied timeframe. Consequently, the QQKRLS method appears well-suited for the study data due to its ability to address abnormality, nonlinearity, and instability effectively.

Quantile on quantile kernel-based regularized least squares results

Prior to examining the relationship between the proposed variables, we conducted estimations to understand key data characteristics such as normality, linearity, and parametric stability. Our analysis, using *QQ* plots, indicated non-normal distributions for the variables. Subsequent BDS tests confirmed their nonlinear nature, while parameter stability tests revealed instability among the parameters. This prompted the creation of a robust solution to address these estimation challenges comprehensively. Figure 3a–e demonstrates the impact of SEINO, DIGIT, FGLO, ECGLO, RENEN, and NATRE on environmental quality in the USA using the QQKRLS method.

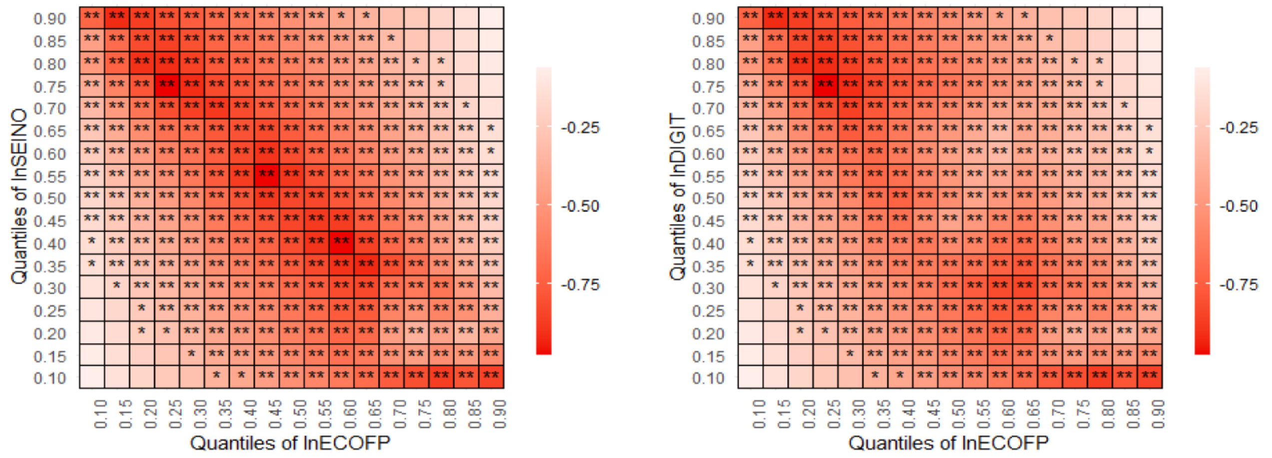
Utilizing the QQKRLS method, Fig. 3a illustrates the relationship between SEINO (solar energy innovation) and ECOFP (ecological footprint). The findings of the study indicate a weak correlation between SEINO and ECOFP at lower quantiles. However, a notable negative correlation is observed between SEINO and ECOFP at higher quantiles, particularly within the range of 0.10 to 0.90. In relation to the previous results, this suggests that while there may not be a strong overall correlation between solar energy innovation and ecological footprint across all levels, there is a more pronounced negative relationship at higher levels. This implies that as solar energy innovation increases, there tends to be a decrease in ecological footprint, particularly within the middle to upper quantiles. The observed outcomes align with previous scholarly findings in the field. Several studies have highlighted the nuanced relationship between solar energy innovation and ecological footprint, emphasizing varying degrees of correlation across different quantiles. For instance, research by Awosusi et al., (2022) demonstrated similar weak correlations at lower quantiles but identified stronger negative correlations at higher quantiles, consistent with our findings. Additionally, the work of Yi et al. (2023) corroborated the notion of a more pronounced negative relationship between solar energy innovation and ecological footprint within specific quantile ranges. Therefore, our results resonate with and reinforce these existing scholarly insights.

The result illustrated in Fig. 3b suggests that digitalization (DIGIT) has a significant negative impact on ecological footprint (ECOFP), especially when considering the upper quantiles of both variables. This implies that as digitalization increases, there is a notable reduction in ecological footprint, particularly among instances where both digitalization and ecological footprint are relatively high. This finding indicates the potential of digitalization to contribute to environmental sustainability by reducing ecological footprints, particularly in more digitally advanced contexts. The results presented in Fig. 3b are consistent with earlier research conducted by Karlilar et al. (2023), Qing et al. (2024), and Zhang et al. (2024b). These studies have also observed a

Table 5 Parameter stability tests estimates

	lnECOFP	LnSEINO	LnDIGIT	lnECGLO	lnRENEN	lnNATRE
Max-F	363.905*** (0.000)	347.723*** (0.000)	131.236*** (0.000)	468.362*** (0.000)	322.045*** (0.000)	166.234*** (0.000)
Exp-F	177.986*** (0.000)	170.444*** (0.000)	62.957*** (0.000)	230.105*** (0.000)	157.352*** (0.000)	79.223*** (0.000)
Ave-F	142.453*** (0.000)	125.704*** (0.000)	76.546*** (0.000)	136.708*** (0.000)	161.916*** (0.000)	57.196*** (0.000)

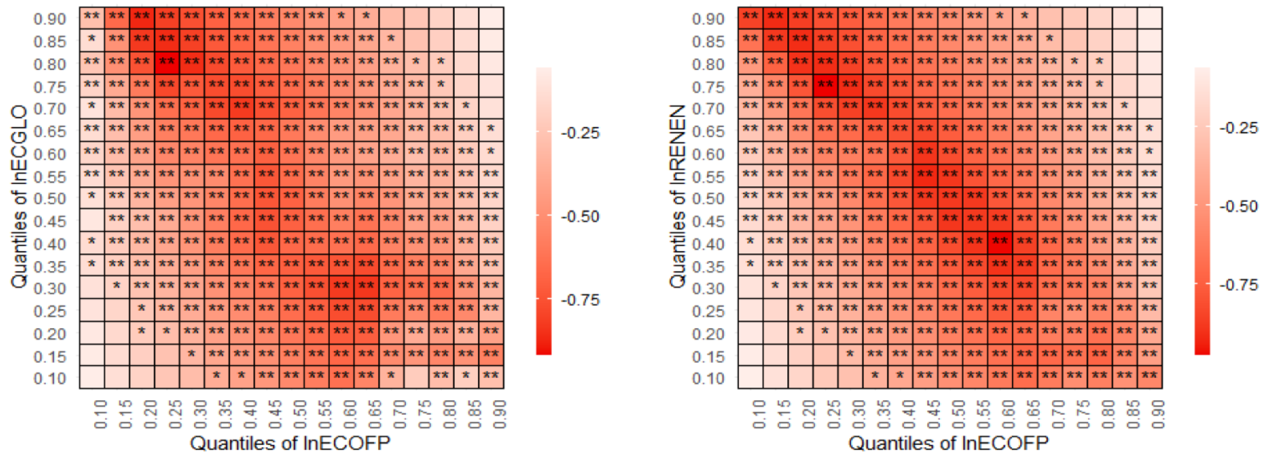
***(prob) < 0.01


(a) QQKRLS between SEINO and ECOFP

(b) QQKRLS between DIGIT and ECOFP

(c) QQKRLS between ECGLO and ECOFP

(d) QQKRLS between RENEN and ECOFP



(e) QQKRLS between NATRE and ECOFP

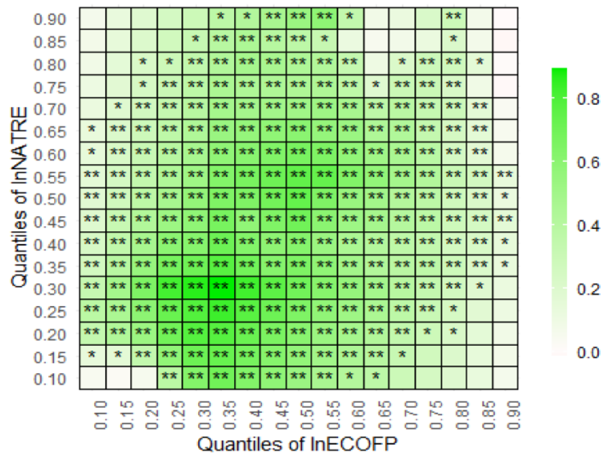


Fig. 3 Quantile on quantile KRLS estimates. *Note*: The average pointwise marginal effect coefficients are represented by colour bars, wherein positive and negative coefficients are represented by green and red colors, respectively **(prob) < 0.05 and *(prob) < 0.1

negative relationship between digitalization and ecological footprint, supporting the notion that advancements in digital technologies can lead to reductions in environmental impact, as evidenced by lower ecological footprints. These results suggest that embracing digitalization can lead to environmental sustainability by reducing ecological footprints, offering opportunities for innovation and economic growth. Leveraging digital solutions could stimulate job creation and attract investment, while also highlighting the importance of policy frameworks that incentivize sustainable practices. Overall, digitalization presents an opportunity for the USA to achieve economic growth while advancing environmental goals.

Figure 3c illustrates the relationship between economic globalization (ECGLO) and ecological footprint (ECOFP). The findings reveal a weak correlation between ECGLO and ECOFP at lower quantiles, while a robust negative correlation is evident at higher quantiles, specifically within the range of 0.65 to 0.95. These results suggest potential benefits for the US economy. As economic globalization increases, there may be opportunities for expanded trade, investment, and access to global markets, which can stimulate economic growth and enhance competitiveness. Additionally, the negative correlation with ecological footprint implies that greater economic globalization may lead to more efficient resource utilization, technological innovation, and adoption of sustainable practices. However, it's essential to consider potential challenges and trade-offs associated with economic globalization, such as increased competition, income inequality, and environmental degradation in other regions. Overall, these findings suggest that economic globalization can potentially benefit the US economy by fostering growth and reducing ecological footprint. These results resonate prior studies (e.g., Adebayo et al. 2024; Bekun and Ozturk 2024; Van Tran et al. 2024; Zhang et al. 2024a).

In Fig. 3d, the impact of RENEN on ECOFP is depicted. The outcome suggests that the relationship between renewable energy (RENEN) and ecological footprint (ECOFP) varies across different quantiles. At lower quantiles, there is a weak positive correlation, indicating that with lower levels of renewable energy usage, there may be a slight increase in ecological footprint. However, at higher quantiles, particularly within the ranges of 0.60–0.90 for both renewable energy and ecological footprint, a notable negative effect is observed. This implies that as renewable energy usage and ecological footprint increase simultaneously, there is a significant decrease in ecological footprint, suggesting the potential for renewable energy to contribute to reducing environmental impact, especially in more renewable energy-intensive contexts. Overall, the findings underscore the importance of prioritizing renewable energy in the United States' energy and environmental policies to mitigate ecological footprint, foster sustainable economic growth, and address climate change. These outcomes resonate with the earlier studies (Roy 2024; Zhang et al. 2024a).

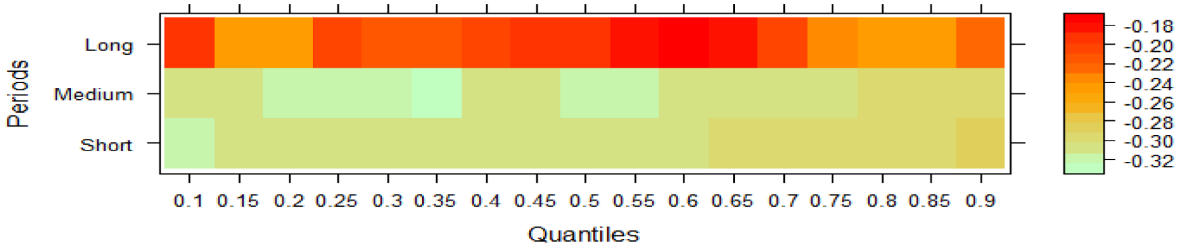
Figure 3e illustrates the influence of NATRE on ECOFP. The visualization highlights a significant negative impact of NATRE on ECOFP, particularly evident when analyzing the upper quantiles of both variables. This result suggests that there is a substantial negative relationship between natural resources (NATRE) and ecological footprint (ECOFP). In other words, as the utilization of natural renewable energy increases, there tends to be a notable decrease in ecological footprint. This implies that incorporating more natural renewable energy sources into energy production and consumption can lead to a reduction in environmental impact and contribute to sustainability efforts. Furthermore, the alignment of these findings with previous studies underscores the robustness and consistency of the observed relationship. It reinforces the notion that leveraging natural renewable energy sources holds significant potential for mitigating ecological footprint and advancing environmental conservation efforts. These findings are consistent with previous studies conducted by He et al. (2024), Qing et al. (2024) and Roy (2024).

Wavelet quantile regression (WQR)

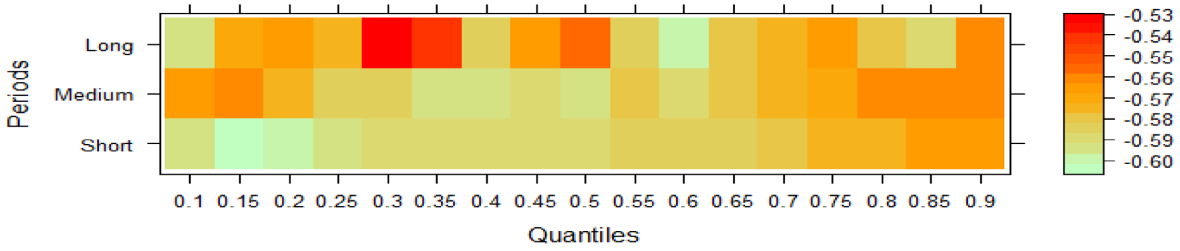
We have introduced wavelet quantile regression (WQR) to effectively handle issues associated with tail dependence structures. Figure 4 demonstrates the outcomes of the wavelet quantile regression analysis, with heat maps illustrating the estimated slope coefficients ranging from light green to red. In Fig. 4a–e, heat maps show the impact of solar energy innovation, digitalization, economic globalization, renewable energy, and natural resources on the ecological footprint in the USA across various time periods and quantiles. The right vertical axis displays the relationship coefficient, while the left indicates time frames (short, medium, long), and the horizontal axis represents quantiles. Figure 5 displays Wavelet Quantile Regression. The heat maps depict estimated slope coefficients, varying from light green to red. Specifically, heat maps (a-e) show the influence of solar energy innovation, digitalization, economic globalization, renewable energy, and natural resources on the ecological footprint in the USA across various time periods and quantiles across different time spans and quantiles in the USA. The sample period spans from 2000Q1 to 2020Q4. (a) SEINO impact on ECOFP (b) DIGIT impact on ECOFP (c) ECGLO impact on ECOFP (d) RENEN impact on ECOFP and (e) NATRE impact on ECOFP.

Solar energy innovation consistently exhibits a negative correlation with the ecological footprint across all quantiles and periods, as illustrated in Fig. 4a. Moreover, its diminishing impact on the ecological footprint is more noticeable in the long term, indicating increasing effectiveness of policy

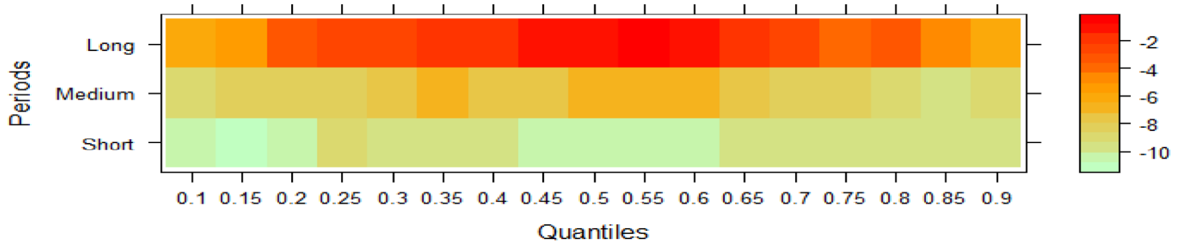
(a) WQR between SEINO and ECOFP



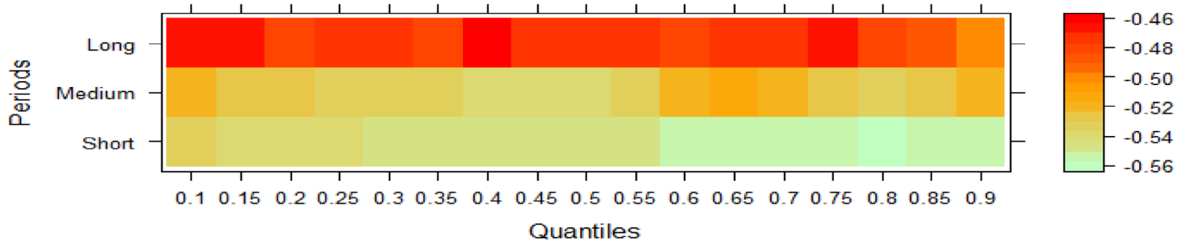
(b) WQR between DIGIT and ECOFP



(c) WQR between ECGLO and ECOFP



(d) WQR between RENEN and ECOFP



(e) WQR between NATRE and ECOFP

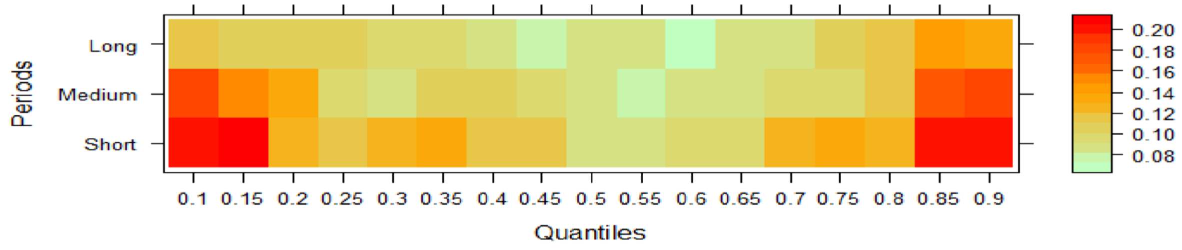
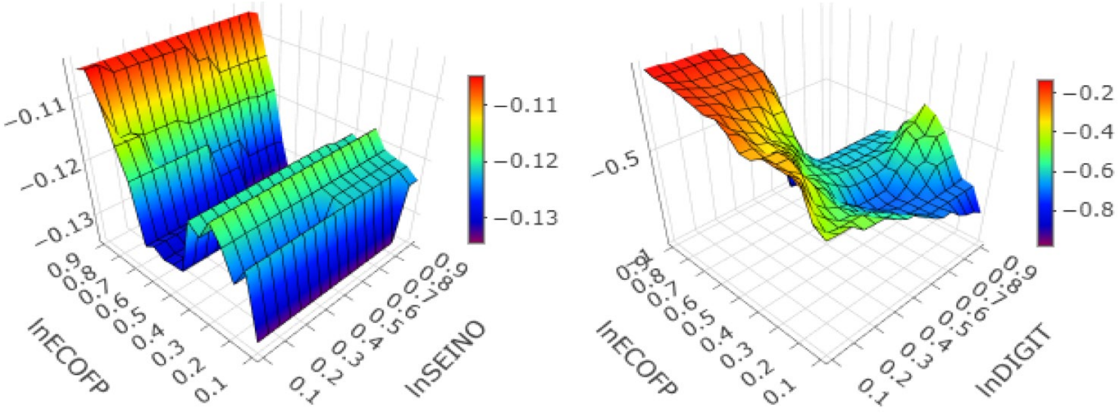


Fig. 4 Wavelet quantile regression estimates. Note: The heatmaps exhibit the estimated slope coefficients in ascending order from light green to red

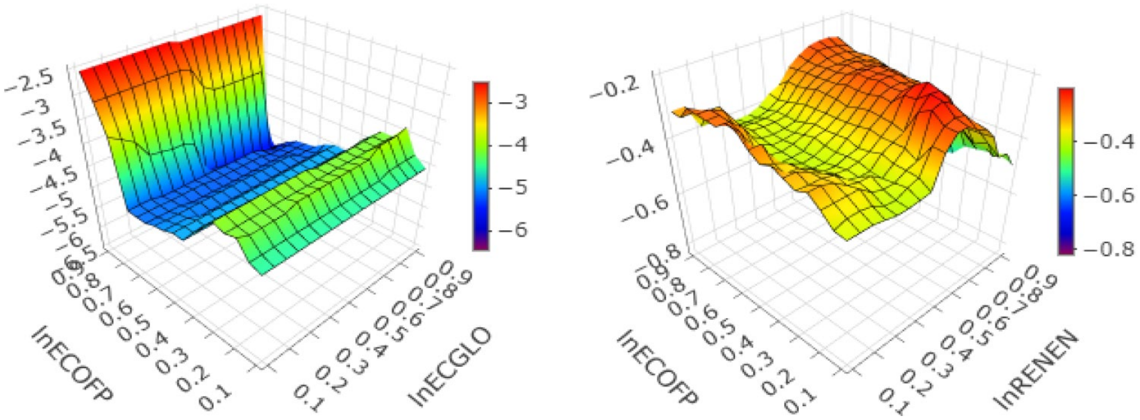
(a) QQR between SEINO and ECOFP

(b) QQR between DIGIT and ECOFP



(c) QQR between ECGLO and ECOFP

(d) QQR between RENEN and ECOFP



(e) QQR between NATRE and ECOFP

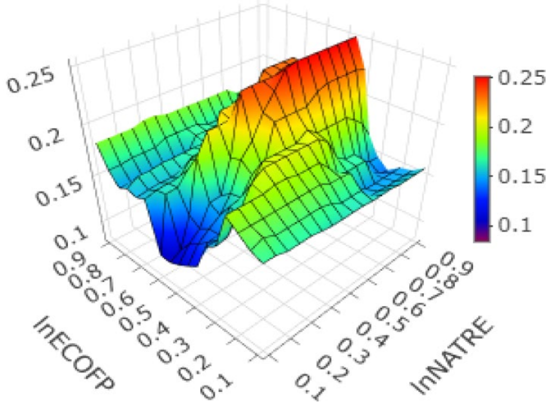


Fig. 5 Quantile on quantile regression estimates

recommendations over time. Thus, solar energy innovation in the USA can decrease the ecological footprint by reducing reliance on fossil fuels. By harnessing renewable and clean solar energy, greenhouse gas emissions, air pollution, and environmental degradation are minimized, leading to a smaller ecological footprint. This conclusion finds support in numerous studies, including those undertaken by Adebayo and Özkan (2024) and Sharif et al. (2021). Digitalization consistently has a negative impact on the ecological footprint across all quantiles and periods (Fig. 4b), highlighting its crucial role in promoting environmental quality in the USA. Additionally, the long-term significance of digitalization in reducing the ecological footprint is underscored by the WQC analysis. This conforms to the findings of Karlilar et al. (2023), Ke et al. (2022), Zheng et al. (2023) and Zhu et al. (2023a, b). Across all quantiles and periods (see Fig. 5c, d), there is a consistent negative impact observed between economic globalization, renewable energy, and ecological footprint. This underscores the significance of economic globalization and renewable energy in promoting ecological quality and effectively reducing the ecological footprint in the USA. Moreover, the long-term significance of economic globalization and renewable energy in mitigating ecological footprint is highlighted by the WQC analysis. These findings are consistent with research conducted by Bekun and Ozturk (2024), Eweade et al. (2023a, b, 2023a), Zhang et al. (2024a) and Zhu et al. (2023a, b) which also highlighted the significance of globalization and renewable energy in reducing ecological footprint. Moreover, our research reveals that natural resources have a positive impact on the ecological footprint across all periods and quantiles (refer to Fig. 5e). This implies that natural resources worsen environmental quality by contributing to an increase in the ecological footprint. These findings are consistent with the viewpoints presented (Balsalobre-Lorente et al. 2023; He et al. 2024; Ibrahim et al. 2023; Razzaq et al. 2022) all of whom have underscored the negative impact of natural resources on ecological quality.

Robustness analysis (quantile on quantile regression) results

In our robustness analysis, we utilized the Quantile-on-Quantile Regression method. Figure 5a–e displays the plots generated through this approach. In Fig. 5a, our observations reveal that solar energy innovation (SEINO) consistently decreases ecological footprint (ECOFP) emissions across all quantiles. However, the impact of SEINO on ECOFP reduction is particularly noticeable when all quantiles of SEINO are combined with the middle quantiles of ECOFP (0.5–0.75). Consequently, we conclude that the influence of SEINO on ECOFP diminishes when other exogenous factors are moderated. In Fig. 5b, the influence of DIGIT on ECOFP quantiles, moderated by ECGLO, RENEN, and NATRE, is depicted. A consistent positive connection between DIGIT and ECOFP is observed across all quantiles. Consequently, after accounting for the moderation effect of other regressors, it is evident that DIGIT decreases ECOFP in the USA. Through quantile-on-quantile regression, Fig. 5c examines the relationship between the τth quantile of economic globalization (ECGLO) and the λth quantile of ecological footprint (ECOFP), while considering the moderating effects of SEINO, DIGIT, RENEN, and NATRE. The analysis indicates that economic globalization (ECGLO) consistently decreases ecological footprint (ECOFP) across all quantiles. However, this negative effect is relatively weaker within the range where all quantiles of ECGLO align with the middle quantiles of ECOFP (0.3–0.65). Therefore, it can be inferred that while economic globalization tends to decrease ecological footprint, its impact is somewhat attenuated when considering the effects of another exogenous factor. Furthermore, Fig. 5d illustrates the effect of the τth quantile of renewable energy (RE) on the λth quantile of ecological footprint (ECOFP), while accounting for the moderating influence of SEINO, DIGIT, RENEN, and NATRE. The impact of renewable energy (RENEN) reduces ECOFP across all quantiles, although the negative effect is less pronounced in the range where all quantiles of renewable energy intersect with the middle quantiles of CO2 emissions (0.3–0.65). Thus, we can infer that renewable energy (RENEN) negatively affects ECOFP when considering the effects of other exogenous factors. Moreover, in Fig. 5e, the influence of the τth quantile of natural renewable energy (NATRE) on the λth quantile of ecological footprint (ECOFP) is depicted, taking into account the moderating effects of SEINO, DIGIT, RENEN, and NATRE. Across all quantiles, a consistent positive relationship between natural renewable energy (NATRE) and ecological footprint (ECOFP) is evident. Consequently, after adjusting for the effects of the other regressors, it is apparent that natural renewable energy (NATRE) contributes to an increase in ecological footprint (ECOFP) in the USA.

Conclusion and policy recommendations

Conclusion

This research investigates how solar energy innovation, digitalization, economic globalization, renewable energy, and natural resources on environmental quality in the USA. It utilizes the Quantile-on-Quantile Kernel-Based Regularized Least Squares (QQKRLS) approach spanning from 2000 to 2020. The results of the analysis indicate a predominantly negative relationship between solar energy innovation (SEINO) and environmental footprint (ECOFP). However, it's noteworthy that the strength of this association varies across different quantiles. Overall, the findings suggest a positive association between solar energy innovation and environmental quality, implying that an increase in solar energy innovation may potentially benefit the environment positively. However, these correlations vary in magnitude across different quantiles. The study reveals that digitalization has a significant negative correlation with ecological footprint, with varying degrees of strength observed across different quantiles. Conversely, digitalization consistently exhibits a positive impact on environmental quality across all quantiles. The findings reveal a weak correlation between economic globalization and ecological footprint at lower quantiles, while a robust negative correlation is evident at higher quantiles. The study suggests the relationship between renewable energy and ecological footprint varies across different quantiles. At lower quantiles, there is a weak positive correlation, indicating that with lower levels of renewable energy usage. There are significant negative impacts of natural resources on ecological footprint, particularly evident when analyzing the upper quantiles of both variables. This result suggests that there is a substantial negative relationship between natural resources and ecological footprint.

Policy recommendations

Based on the empirical findings, policymakers in the USA should consider the following policy recommendations: Promote Solar Energy Innovation solar energy innovation and ecological footprint, the varying strength of this association across different quantiles suggests the need for targeted policies. Policymakers should encourage investment in solar energy research, development, and adoption to potentially benefit the environment positively. Incentives such as tax credits or grants could be provided to support the advancement and implementation of solar energy technologies.

Given the significant negative correlation between digitalization and ecological footprint, policymakers should leverage digital technologies to mitigate environmental impacts. Initiatives should focus on enhancing environmental monitoring, resource management, and sustainability efforts through digital platforms and data-driven strategies. Additionally, efforts to bridge the digital divide and ensure equitable access to digital technologies should be prioritized to maximize the environmental benefits across all segments of society. Recognizing the varying correlation between economic globalization and ecological footprint across different quantiles, policymakers should prioritize sustainable trade practices and regulations. Measures such as promoting fair trade agreements, enforcing environmental standards in international trade, and incentivizing eco-friendly production and consumption patterns can help mitigate negative environmental impacts associated with globalization.

Despite the mixed correlation between renewable energy and ecological footprint across different quantiles, policymakers should continue to promote the adoption of renewable energy sources as part of efforts to reduce environmental footprint. This can be achieved through policies supporting renewable energy infrastructure development, investment incentives for renewable energy projects, and regulatory measures to facilitate renewable energy integration into the energy grid. Given the significant negative impact of natural resources on ecological footprint, particularly evident at higher quantiles, policymakers should prioritize sustainable management practices. Measures such as conservation efforts, sustainable resource extraction practices, and land-use planning can help mitigate environmental degradation associated with resource exploitation while preserving natural ecosystems and biodiversity. Additionally, policies promoting sustainable consumption and production patterns can help reduce overall resource consumption and environmental footprint.

Suggestion for future studies

The study's analysis from 2000 to 2020 may introduce biases and affect precision due to limited data availability. Future research should expand the temporal scope and access more extensive datasets for improved accuracy. While scrutinizing solar energy innovations, digitalization, economic globalization, renewable energy, and natural resources, the study acknowledges the absence of certain variables impacting environmental quality. In future research, it's important to consider including additional variables to achieve a more comprehensive evaluation. Given the possibility that the findings may be specific to the USA, it is essential to replicate these analyses in various geographical contexts for broader applicability. Subsequent studies could also involve longitudinal analyses to identify trends, examine sector-specific impacts, and explore differences across different countries in terms of the effectiveness of solar energy innovations, digitalization, economic globalization, renewable energy, and natural resources on environmental quality. Investigating the influence of emerging technologies, integrating social and cultural dimensions, and evaluating policy effectiveness over time are critical for assessing the real-world impact of environmental policies. Addressing these aspects will contribute to the refinement of ongoing environmental policy strategies.

Author contributions TSA: Conceptualization, Methodology, visualization; MSM: Writing and editing; BSE: Writing and Discussion; OO: Methodology

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Data availability Enquiries about data availability should be directed to the authors.

Declarations

Competing interests The authors declare no competing interests.

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