Environmental Science and Pollution Research (2023) 30:123412–123426
https://doi.org/10.1007/s11356-023-31007-4

RESEARCH ARTICLE

Do the asymmetric effects of eco-digitalization amidst energy transition make or mar the strides toward environmental sustainability in the USA?

Fangbin Han[1] · Ridwan Lanre Ibrahim[2] · Jun Tang[1] · Usama Al-Mulali[3]

Received: 6 June 2023 / Accepted: 7 November 2023 / Published online: 20 November 2023

Abstract
The present era faces adverse effects of the strides recorded in economic advancements of the prior generations thus leading the present generation to growth dilemma. Consequently, there is a conscientious consideration for the ecological effects of economic growth. To resolve the preceding issue, due consideration must be given to harmless growth of which eco-digitalization, green financing, green technology, energy transition, and regularity quality are key determinants. Despite the aforesaid importance, empirical studies advancing this nexus are scarce. Hence, this study contributes to environment empirics by providing empirical evidence for the impacts of the highlighted indicators on sustainable environment in the USA. The study explores quarterly data from 1996Q1 to 2019Q4 based on the novel non-linear autoregressive distributed lag (ARDL) model. The pretests' outcomes show that long-run nexus exists among the variables, whereas the Zivot-Andrew uncovers breakpoint years in the observations. The main findings show that eco-digitalization, green financing, green technology, and renewable energy promote sustainable environment. On the flip side, non-renewable energy and regulatory quality hinder the pathways to sustaining the environment in the USA. Robustness analyses conducted based on FMOL, DOLS, and CCR provide substantial support and validity for the main results. Furthermore, the causality nexus lends empirical support for the existence of bidirectional and unidirectional causalities in the empirical model. Policy insights that drive the paths to sustainability in the US are suggested based on the findings.

Keywords Eco-digitalization · Green financing · Green technology · Energy transition · Regulatory quality · Sustainable environment

Introduction

The last few decades have witnessed extensive debates on issues surrounding the sustainability of the ecosystem to the extent that substantial strands of empirical outcomes submit that environmental degradation within the framework of climate change and global warming is the most discussed issue of the present era (Rehman et al. 2022). Several treaties, policies, and regulations cutting across national, regional, and international boundaries have been reached with a common and ambitious goal of achieving an atmospheric system that is safe for people, planets, and plants (Ibrahim and Ajide 2022; Oke et al. 2021). Among the various international organization and global gatherings championing the cause of sustainable environment, the United Nations stands out through the Conference of the Parties (COP) which provide annual declaration and directions on policies and measures that can reshape the environment and resolve the pervasive

Responsible Editor: Ilhan Ozturk

✉ Usama Al-Mulali
UMulali@su.edu.om

Fangbin Han
liu2020934@163.com

Ridwan Lanre Ibrahim
lanrid23@gmail.com

Jun Tang
tj2001766@sina.com

[1] School of Science, Mongolia University of Science and Technology, Baotou 014010, China

[2] Department of Economics, University of Lagos, Akoka, Lagos, Lagos State, Nigeria

[3] Faculty of Business, Sohar University, Sohar, Oman

ecological challenges facing the global economy (Ibrahim 2022). Precisely, COP26 advocates the inexplicable need to phase out coal consumption and significantly reduce fossil fuel subsidies. It emphasizes surpassing the emission level of 1.5-degree temperature limit is a danger to the ecosystem and the people that live in it (Ibrahim 2022; Ibrahim et al. 2022c). Similarly, the need to achieve increased growth at a decreasing rate of carbon emission is further accentuated by COP26 (Murshed et al. 2022).

The emphasis on maintaining global warming within 1.5° further accentuates the urgency of taking action in addressing the devastating consequences of climate change. This concern prompts the advocacy for Sustainable Development Goal 13 which posits the inevitability of taking urgent action in addressing the unrelenting adverse effects of climate change (Ahmed et al. 2022). Empirical studies such as Anwar et al. (2022) and Zhao et al. (2022) provide robust evidence to advance the pertinence of taking sturdy policies that enhance the practicality of pursuing SDG-13 as a viable tool for achieving environmental sustainability. As the global economy is pursuing these ambitious goals jointly, governments at their various states must complement the global strides at the national level especially the key contributors to the pervasive surge in global warming like the USA.

The need for the USA to pursue sustainability targets can never be overemphasized. Available statistics indicate that the USA is the second largest contributor of carbon emissions behind China among the global economies (International Energy Agency 2020). Besides, the USA equally ranks third globally behind China and India regarding coal production and consumption. Despite the leading contributions of the USA to global climate change, the flows of carbon emissions in the country have been at decreasing rates in the last two decades (Fig. 1). The achievements of declining carbon emissions in the USA do not come as a surprise on the ground that the country is a key member of the leading international organizations such as the United Nations, G7, and G20 countries that have contributed significantly to global decisions on environmental sustainability. In accordance with this advocacy, the USA is among the countries that are practically pursuing the transition to renewable energy with efforts geared towards reducing non-renewable energy (Fig. 2) and at the same time increasing the stock of renewable energy (Fig. 3).

The consideration of investment in eco-digitalization which suggests the level of the US economy with huge concentration in the service sector is notable strides that are helping in reducing the stock of carbon emissions (Adha et al. 2022). The trend in eco-digitalization suggests the prospects of the country in neutralizing the adverse environmental effects of carbon emissions in the near future

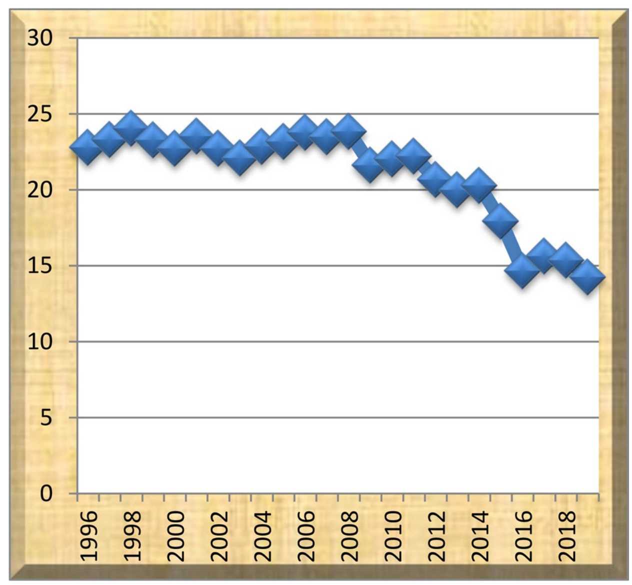
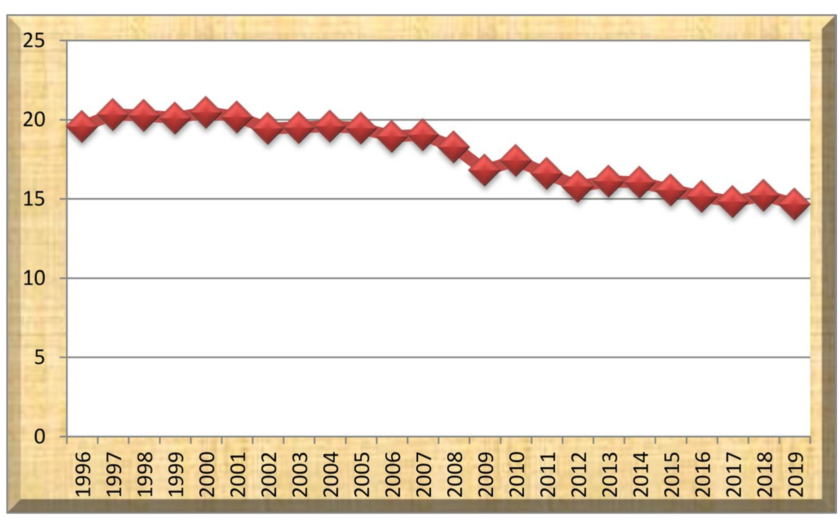


Fig. 2 Trend in non-renewable energy

Fig. 1 Trend in carbon emissions per capita



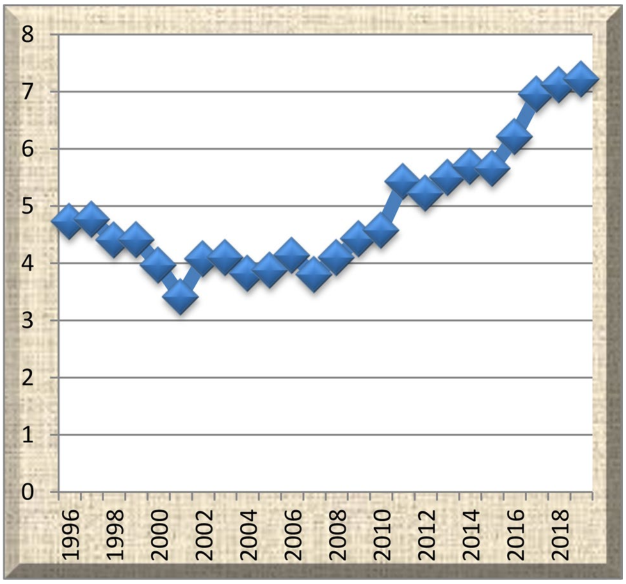


Fig. 3 Trend in renewable energy

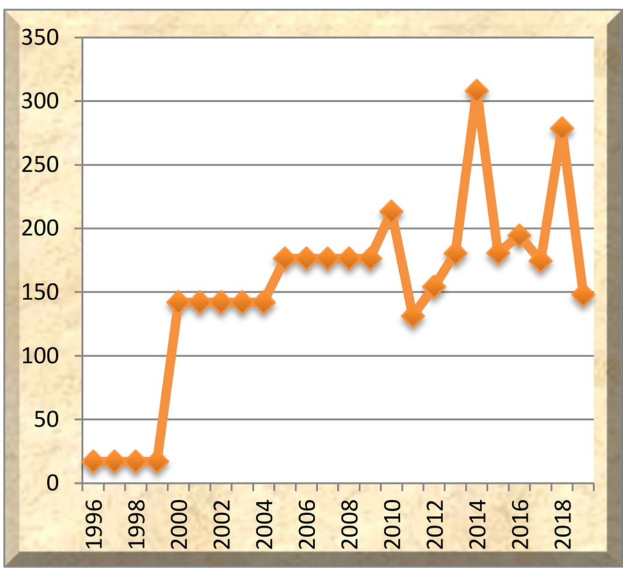


Fig. 4 Trend in eco-digitalization

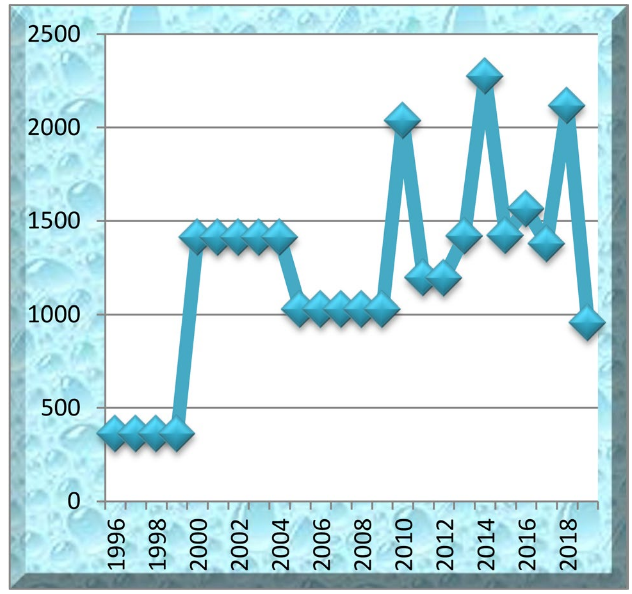


Fig. 5 Trend in green finance

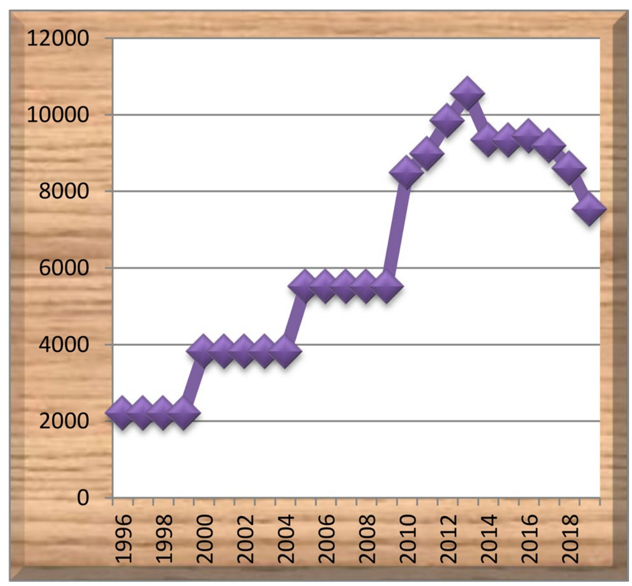


Fig. 6 Trend in green technology

(Fig. 4). Similarly, green finance is another notable factor believed to be efficient in driving sustainable environment (Shen et al. 2023). An assessment of this indicator shows the US economy is making significant progress even though such strides are unstable (Fig. 5). Within this prospective framework of performing indicators of environmental sustainability, green technology is keeping the hope high for the country with significant improvements in the last two decades (Fig. 6). Specifically, empirical outcomes have alluded that green technology is efficient in driving economic growth without degrading the environment thereby enhancing pathways toward sustainable development (Gao et al. 2022; Ibrahim et al. 2022a, b, c, d). That notwithstanding the regulatory quality in the USA seems to stress little on factors escalating fossil fuel consumption. This is evident in the fact despite pursuing the transition to sustainable environment, the country still relies more on fossil energy in the production of goods and services. Precisely, regulatory quality has experienced a downward slope in the fight against environmental pollution (Fig. 7).

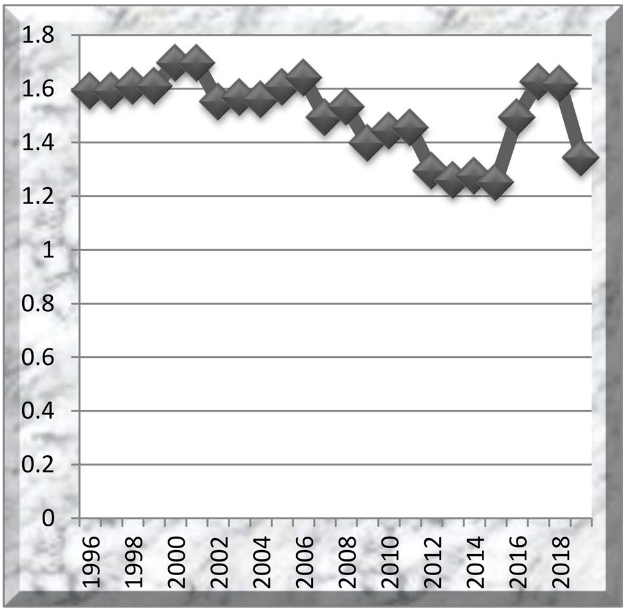


Fig. 7 Trend in regulatory quality

It is instructive to clarify that notwithstanding the prospective drivers of environmental sustainability, the USA remains among the leading contributors of greenhouse gas (GHG) emissions. The curiosity to resolve this environmental puzzle confronting the USA motivates the research interest of the current study. Consequently, this research primarily aims to examine the asymmetric effects of eco-digitalization on environmental sustainability in the USA. The intervening roles of green finance, green technology, energy transition, and regulatory quality are carefully assessed. Eco-digitalization differs from the usual digitalization on the grounds that it provides mitigation measure for carbon emissions (Shen et al. 2023). Consequently, the robustness of eco-digitalization to effectively drive growth rates without deteriorating the environment makes it a better measure of driving the digital economy.

Following the research objectives, the contributions of the present inquiry are four-fold. First, the chunk of extant studies has often considered the nexus between digitalization and environment with conflicting results. For instance, studies such as those of Huang and Zhang (2023), Tang et al. (2023), and Zheng et al. (2023) provide empirical evidence positing that digitalization has both militating and inducing effects on carbon emissions. To resolve this issue, this study employs eco-digitalization believed to be eco-friendly without any possibility of degrading the environment as observed in the usual digitalization indicators. Hence, this research constitutes the first strand of empirical research examining the nexus between eco-digitalization indicators and carbon emissions in the USA. Second, the asymmetric impacts of eco-digitalization are worth lauding on the ground that both the positive and negative shocks of eco-digitalization are evaluated on carbon emissions. Examining these two diverging effects will enhance the realization of robust policy implications that will be channeled toward maximizing the full potential of the indicator while at the same time minimizing the inherent adverse environmental complications. Third, the engagements of energy transition, green finance, green technology, and regulatory quality in a single research is rare among prior studies. Exploring these indicators in a multiple regression model will open the floor for critical assessment of how environmental sustainability can be attained through these crucial factors especially for the USA. Besides, policy implications in this analysis can be extrapolated to other developed economies. Fourth, the study considers non-linear autoregressive distributed lag (NARDL) model. Aside from computing the positive and negative shocks, the estimator is robust for estimating the long-run and short-run effects of eco-digitalization on carbon emissions. Moreover, the consideration of advanced estimators such as non-linear ARDL, fully modified OLS, dynamic OLS, and canonical cointegration regression coupled with the wide acceptance of Granger causality. Fifth, the policy implications that will emanate from this study will be useful in providing empirically backed evidence on the best practices to be adopted in pursuing SDG 13.

The outline of this empirical study delineates thus; besides "Introduction" presented above, "Literature review" focuses on the appraisal of the existing studies and positions its contributions within the areas of lacunas identified. "Method" provides details on the methods that guide the verification of the empirical outcomes. Section "Results" presents the empirical results and discusses them. "Conclusion, policy implications, and limitations" summarizes, concludes, recommends, and provides areas of limitation that can be explored by future studies.

Literature review

The pervasive challenges of global warming causing a series of irreparable losses to the ecosystem have constituted the center of attraction to scholars in the last few decades. Feedback from the empirical studies reviews certain macroeconomic indicators such as renewable and nonrenewable energy, technological innovation, green finance, digitalization, regulatory quality, and others. This section reviews the extant literature in accordance with the objective of the current study.

Starting with the environmental impacts of digitalization, Shen et al. (2023) assess digitalization, green hydrogen, energy efficiency, green finance, and environmental technologies in a panel of the seven most consuming nations in hydrogen from 1995 to 2019. The study employs advanced estimators comprising CCEMG, AMG, and MG to estimate the empirical model. Findings show that digitalization significantly drives environmental sustainability by reducing carbon emissions. Besides, the fundamental roles of the covariates are well supported empirically. Yang et al. (2022) investigate the impacts of heterogeneous digital systems comprising digital economy, infrastructure, application, and industry on carbon emissions in China. Feedback from the analyses reveals divergent effects of the various components of the digital system employed. Besides, the study finds empirical support for rising and declining environmental effects of digitalization suggesting the validity of the inverted "U" curve relationship. Dong et al. (2022a, b) carried out a global analysis of the environmental effects of digital economy from 2008 to 2018 in a panel of sixty selected economies. Findings indicate that advancement in digital economy significantly moderates carbon emissions. Besides, financial development and economic growth escalate the emissions.

The environmental effects of energy transition are empirically documented from both country-specific and panel angles. For instance, Bashir et al. (2023) extend the frontier of knowledge on the environment by exploring how energy transition in the presence of environmental innovation drives significant decline in ecological footprint for a panel of top ten manufacturing economies from 1995 to 2019. Feedback from a battery of estimators reveals that transitioning to renewable energy is a viable means for mitigating the surge in ecological footprint. The moderating impacts on ecological footprint are evident for environmental innovation whereas financial development and urbanization escalate the footprint towards a deteriorating state of the environment. Balcilar et al. (2023) probe the role of energy transition in the pursuance of environmental sustainability targets in 34 African economies from 1990 to 2017. The empirical evidence which relies on System GMM and quantile regression considers the interplay of natural resource rents, multinational corporations, and foreign direct investment. The findings show that energy transition through the conduit of renewable energy significantly reduces the surge in environmental pollutants. Besides, natural resource rents reduce the pollutants, foreign direct investment escalates the pollutants. Ibrahim et al. (2023) examine the roles of energy transition in G7 in the presence of technological innovation and demographic mobility from 2000 to 2019 on environmental sustainability. The empirical model endogenizes the intervening effects of structural change and natural resources. Findings show that energy transition, structural change, and technological innovation reduce carbon emissions. Conversely, demographic mobility from both rural and urban areas exacerbates the emissions. The inducing effects on carbon emissions are equally evident in natural resources.

The empirical effects of structural change on environmental sustainability are well documented in recent times. For example, Zou et al. (2023) examine the ecological consequences of population growth and structural change within the framework of technological advancements, foreign direct investments, and renewable energy. The research represents the first empirical analysis of these factors by employing second-generation techniques to analyze data from the five largest emitters in Africa between 1990 and 2019. Additionally, the study employs the MMQR regression technique. The impact of demography on both rural and urban populations is assessed, while structural changes are measured by examining value added in the industry, services, and agriculture sectors. The findings indicate that carbon dioxide emissions are increased by the manufacturing and agricultural sectors, as well as by the rural and urban populations. Conversely, technological advancements and structural change have mitigating effects on emissions. Ibrahim et al. (2022c) investigate the impact of natural resources on carbon dioxide emissions in the ten most resource-dependent countries between 1995 and 2019. Additionally, the study explores the relative significance of renewable energy, green finance, energy technological advancement, and structural change. To account for cross-sectional dependence difficulties in panel models, initial tests include cross-sectional interdependence tests, homogeneity tests, stationarity tests, and cointegration tests. These tests follow the general principle. The findings indicate that natural resources contribute to an increase in carbon emissions whereas structural change, technological innovation, renewable energy, and green finance reduce the emissions. Lanre Ibrahim et al. (2022) evaluate how structural change, dependence on natural resources, environmental technology, and renewable energy of the five African countries with the highest carbon dioxide emissions moderate the strides toward environmental sustainability based on annual data from 1990 to 2019. The results of the CS-ARDL demonstration indicate that indicators of structural changes significantly reduce CO_2 emissions, and growth is also reduced by renewable energy and green technologies.

The role of green finance and technology is not hard to identify in the current global efforts toward minimizing the adverse effects of climate change. Shen et al. (2023) estimate that green finance and green technology significantly drive sustainable environment for a panel of the most consuming nations in green hydrogen. Sharif et al. (2022) examine the impacts of green finance and green technology innovation on sustainable environment in G7 economies from 1995 to 2019. Empirical outcomes based on second-generation estimators uncover that green finance, green technology, and green financing drive environmental sustainability through their carbon-mitigating effects. Pang et al. (2022) explore the extent to which green finance drives green technology through achieving carbon efficiency based on the novel wavelet-based quantile on quantile estimator. Outcomes indicate the divergent effects of green finance on green technology and carbon efficiency. In particular, the study reveals that the influential effects of green finance are not sacrosanct on both green technology and carbon efficiency. The empirical feedback from the assessment of the extant studies reveals that not much has been done in the areas of examining how the positive and negative effects of digitalization make or mar environmental sustainability. Besides, considering eco-digitalization is a novel idea that makes this study the first in the field of environmental empirics.

Method

Data description

The analysis of the study is founded upon quarterly data spanning from the first quarter of 1990 to the last quarter of 2019, encompassing green finance, green energy, green technology, regulatory quality, and environmental sustainability. The objective of the study is to investigate the varying (positive and negative) impacts of eco-digitalization on individuals. The environmental state of the USA is computed through the utilization of three data sources, namely the World Development Indicators (WDI), US Energy Information Administration (EIA), and Organization for Economic Co-operation and Development (OECD) statistics. A comprehensive summary of the data and its sources is presented in Table 1.

Theoretical underpinning, hypotheses, and empirical modeling

This section delves into the economic principles underlying the comprehension of the correlation between regressors and regressand variables. Besides, the nexuses are explained and argued in line with the expected a priori that are supported and empirically backed by extant studies. Starting with eco-digitalization, the recent advancements in world interconnectedness have led to unprecedented progress in the relations among economies in business, trade, and economic activities. To meet up with the ever-growing interaction without losing count of standards and quality of services, digitalization is thus perceived as instrumental globally. Besides, it is assumed that adopting eco-friendly digitalization is important to achieve an equilibrium between economic progress and environmental sustainability. Empirical evidence has alluded that digitalization drives sustainable environment (Adha et al. 2022; Nosova et al. 2022). In other words, we hypothesize an inverse relationship between eco-digitalization (EDIG) and carbon emissions per capita (CO_2P) thus $\frac{\delta CO2P}{\delta EDIG} < 0$. It is important to note that the effects of financial development on the environment have been debated divergently between promoting and deterring environmental sustainability. Despite that, the role of financing cannot be overemphasized on the road to achieving carbon carbon–neutral environment in the years ahead. To keep on with the finance-led environmental sustainability, global attention is recently shifting towards green finance believed to be efficient in driving. The driving role of green finance (*GFIN*) on environmental sustainability has been empirically documented (Bai et al. 2022; Ibrahim et al. 2022a, b, c, d). Hence, we anticipate negative nexus between *GFIN* and CO_2P as thus $\frac{\delta CO2P}{\delta EFIN} < 0$.

There is no gainsaying that green technology is an effective driver of environmental quality giving its ability to drive economic growth at a decreasing rate of carbon emissions. Consequently, extant studies have advanced that green technology is a fundamental factor in achieving carbon neutrality (Cui et al. 2022; Dong et al. 2022a, b). Similarly, copious empirical studies have established the existence of a significant relationship between institutional measures and environmental indicators (Ibrahim et al. 2022a, b, c, d; Ibrahim and Ajide 2022). The nature of regulatory quality either strong or weak determines the direction of impacts (positive or negative) on the environment. Hence, we expect a two-way nexus between the two as thus $\frac{\delta CO2P}{\delta REGQ} < 0$ or $\frac{\delta CO2P}{\delta REGQ} > 0$. The pervasive adverse effects of fossil fuels on the environment have motivated the advocacy on the imperative of energy transition to renewable energy-driven economy. Consequently, copious empirical studies have established the criticality of energy transition in driving the pathway to sustainable environment (Afshan et al. 2022; Onifade and Alola 2022). The a priori expectations of

Table 1 Data description

Variables	Name	Measures	Source
CO_2P	Carbon emissions	CO_2 emissions (metric tons per capita)	WDI
EDIG	Eco-digitalization	Information and communication technologies (ICT) supporting adaptation to climate change	OECD
GFIN	Green finance	Climate change adaptation technologies	OECD
GTEC	Green technology	Environment-related technologies	OECD
REGQ	Regulatory quality	Regulatory quality: estimate	WDI
RENE	Renewable energy	Renewable electricity net generation (quad Btu)	EIA
NREN	Non-renewable energy	Coal production (quad Btu)	EIA

energy transition on carbon emissions per capita can thus be disintegrated into positive (non-renewable energy) $\frac{\delta CO2P}{\delta NREN} < 0$ and negative (renewable energy effects) $\frac{\delta CO2P}{\delta RENE} > 0$.

The above theoretical foundation and stated hypotheses form the basis for modeling the empirical model of the present study in accordance with extant studies (Dogan et al. 2022; Shen et al. 2023) as thus.

$$LCO2P_t = \sigma_0 + \sigma_1 LEDIG_t + \sigma_2 LGFIN_t + \sigma_3 LGTEC_t + \sigma_1 LREGQ_t + \sigma_1 LNRE_t + \sigma_1 LRENE_t + \varpi_t \tag{1}$$

Based on the equation stated above, CO_2P signifies carbon emissions per capita; *EDIG* implies eco-digitalization; *GFIN* denotes green finance; *GTEC* means green technology; *REGQ* denotes regulatory quality; and *NREN* and *RENE* denote non-renewable energy and renewable energy, respectively. The present study employs an autoregressive distributed lag (ARDL) model, which has its origins in the work of Pesaran and Shin (1995), to conduct an empirical analysis of the long-term and short-term dynamics of the aforementioned association. The ARDL model is constructed on the basis of Eq. (1).

$$\begin{aligned}\Delta LCO2P_t = \sigma_0 &+ \sum_{i=1}^{t} \sigma_1 \Delta CO2P_{t-1} + \sum_{i=1}^{t} \sigma_2 \Delta LEDIG_{t-1} \\ &+ \sum_{i=1}^{t} \sigma_3 \Delta LGFIN_{t-1} + \sum_{i=1}^{t} \sigma_4 \Delta LGTEC_{t-1} \\ &+ \sum_{i=1}^{t} \sigma 5_4 \Delta LREGQ_{t-1} + \sum_{i=1}^{t} \sigma_6 \Delta LNREN_{t-1} \\ &+ \sum_{i=1}^{t} \sigma_7 \Delta LRENE_{t-1} + \varphi_1 LCO2P_{t-1} + \varphi_2 LEDIG_{t-1} \\ &+ \varphi_3 LGFIN_{t-1} + \varphi_4 LGTEC_{t-1} + \varphi_5 LREGQ_{t-1} \\ &+ \varphi_6 LNREN_{t-1} + \varphi_7 LRENE_{t-1} + \varpi_t\end{aligned} \tag{2}$$

The assumption in Eq. (2) is only efficient for providing estimates for symmetric impacts. However, given the objectives of this research which consider the positive and negative impacts of eco-digitalization ($EDIG^{+ve}$ and $EDIG^{-ve}$), non-linear ARDL (NARDL) estimator becomes the most appropriate (Ibrahim et al. 2022a). Conventionally, NARDL estimation technique advanced (Shin et al. 2014) is robust in estimating both long- and short-run positive and negative (asymmetric) effects. The estimator is fit in the case of mixed order of $I(0)$ and $I(1)$ integration. Incorporating the asymmetric effects of eco-digitalization on carbon emissions per capita gives the following models;

$$LEDIG^{+} = \sum_{i=1}^{t} \Delta LEDIG^{+} \sum_{i=1}^{t} \max(EDIG_i, 0) \tag{3}$$

$$LEDIG^{-} = \sum_{i=1}^{t} \Delta LEDIG^{-} \sum_{i=1}^{t} \max(LEDIG_i, 0) \tag{4}$$

Based on Eqs. 2, 3, and 4, the NARDL model can be expanded as thus.

$$\begin{aligned}\Delta LCO2P_{2t} = \sigma_0 &+ \sum_{i=1}^{t} \sigma_1 \Delta LEDIG^{+}_{t-1} + \sum_{i=1}^{t} \sigma_2 \Delta LEDIG^{-}_{t-1} \\ &+ \sum_{i=1}^{t} \sigma_3 \Delta LGFIN_{t-1} + \sum_{i=1}^{t} \sigma_4 \Delta LGTEC_{t-1} \\ &+ \sum_{i=1}^{t} \sigma_5 \Delta LREGQ_{t-1} + \sum_{i=1}^{t} \sigma_6 \Delta LNREN_{t-1} \\ &+ \sum_{i=1}^{t} \sigma_6 \Delta LRENE_{t-1} + \sigma_1 LCO2P_{t-1} + \sigma_2 \Delta LEDIG^{+}_{t-1} \\ &+ \sigma_3 LEDIG^{-}_{t-1} + \sigma_4 \Delta LGFIN_{t-1} + \sigma_5 \Delta LGTEC_{t-1} \\ &+ \sigma_6 \Delta LNREN_{t-1} + \sigma_7 \Delta LRENE_{t-1} + \varpi_t\end{aligned} \tag{5}$$

Results

Summary statistics, trend analysis, and bivariate correlation analysis

The summary statistics presented in Table 2 reveal that each household agent in the USA contributes an average of 2.88% level of carbon emissions. Interestingly, the contributions are at a decreasing rate over the last two decades, as depicted in Fig. 8. It is worth of noting that eco-digitalization maintains a mean value of 4.77; green finance averages 6.99; and green technology has a mean value of 8.60 suggesting that the USA is doing well in advancing the contributions of these indicators towards environmental sustainability. This hypothetical view

Table 2 Summary statistics

Indicators	Description	Mean	Median	Maximum	Minimum	Std. dev
LCO_2P	Carbon emissions per capita	2.88	2.92	3.02	2.69	0.12
LEDIG	Eco-digitalization	4.77	5.10	5.73	2.83	0.91
LGFIN	Green finance	6.99	7.16	7.73	5.90	0.55
LGTEC	Green technology	8.60	8.62	9.26	7.70	0.53
LREGQ	Regulatory quality	0.41	0.44	0.53	0.22	0.10
LNREN	Non-renewable energy	3.04	3.11	3.18	2.66	0.17
LRENE	Renewable energy	1.57	1.50	1.98	1.23	0.21

Fig. 8 Trend analysis

is supported by the upward slope in these indicators in Fig. 8. The mean value of regulatory quality stands at 0.41 which is a bit far from absolute value of one thus indicating some relaxation or laxity ineffectiveness of the law and order to protect the environment. Besides, a further assessment of the trend in the figure will reveal how regulatory quality has been unstable over the past two decades. The mean value of non-renewable energy outpaces the value of renewable energy implying that the USA still relies heavily on fossil fuel energies. Notwithstanding this point, the economy is doing great in its efforts to reduce the consumption of non-renewable energy while striving to increase the contributions of renewable energy as evident in Fig. 8. The bivariate correlation analysis in Table 3 shows the model is free from the problem of multicollinearity.

Table 3 Bivariate correlation analysis

LCO_2P	*LEDIG*	*LGFIN*	*LGTEC*	*LNREN*	*LREGQ*	*LRENE*	Indicators
1	−0.44	−0.50	−0.46	0.26	0.44	−0.88	*LCO_2P*
	1	0.44	0.32	−0.37	0.35	−0.19	*LEDIG*
		1	0.27	−0.38	0.31	−0.21	*LGFIN*
			1	−0.31	0.33	−0.39	*LGTEC*
				1	0.32	0.49	*LNREN*
					1	0.44	*LREGQ*
						1	*LRENE*

Panel Unit root and long-run tests

The results on panel unit root based on Augmented Dickey-Fuller (ADF), Kwiatkowski-Philips-Schmidt-Shin (KPSS), and Zivot-Andrew (ZA) breakpoint tests are presented in Table 4. The choice of employing a battery of unit root tests lies in the need to ensure validity of the stationarity tests. For instance, while both ADF and ZA posit that the series are non-stationary, KPSS assumes stationarity. Hence, a rejection of the ADF null hypothesis should imply an acceptance of the KPSS. Besides, the incorporation of ZA is to account for the presence of structural break.

The results of the tests show that the series are $I(0)$ and $I(1)$. Likewise, the structural breakpoints relating to each of the indicators are as follows; LCO_2P (2009), *LEDIG* (2012), *LGFIN* (1995), *GTECH* (2015), *GFIN* (2014), *LNREN* (2010), *LREGQ* (2019), and *LRENE* (2010). Among many other factors, these breakpoint years may be connected to occurrences that significantly affect the US economy.

The following table presents the findings of the long-term examination (Table 5). It is noteworthy that the *F*-statistic value of 6.5 at the 5% level of significance surpasses both the lower and upper critical levels, indicating the presence of cointegration among the variables. The Gregory-Hansen cointegration test is employed to assess the resilience of long-term relationships, which can be disrupted by structural breakpoints that may confound conventional cointegration test estimators. This is a matter of significant consideration. The outcomes are displayed in Table 6, revealing a cointegration of 5%.

Long-run asymmetric results

The findings of the NARDL bound test estimator in Table 7 showcase the outcomes of the asymmetric long-term and short-term impact evaluations of eco-digitalization. The feedback received suggests that the positive impact of eco-digitalization has a moderating effect on CO_2 emissions, both in the long-term and short-term. Consequently, the extensive

Table 4 Feedback on unit root analysis

Variables	Augmented Dickey-Fuller			KPSS			Zivot-Andrew breakpoint test			
	Level	1st difference	Order	1.253[a]	1.298[a]	$I(0)$	Level	1st difference	Order	Break year
LCO_2P	−1.643	−6.532***	$I(1)$	1.239***	1.203***	$I(0)$	−1.025	−7.311***	$I(1)$	2009
LEDIG	2.334	−4.762***	$I(1)$	1.632***	1.423***	$I(0)$	−1.046	−6.872***	$I(1)$	2012
LGFIN	−2.732	−5.256***	$I(1)$	1.312***	1.235***	$I(0)$	−4.913***	−7.324***	$I(0)$	1995
LGTEC	−4.852***	−6.576***	$I(0)$	1.092***	1.005***	$I(0)$	−2.509	−6.509***	$I(1)$	2015
LNREN	−2.083	−6.506***	$I(1)$	1.051***	0.985***	$I(0)$	−2.146	−8.255***	$I(1)$	2010
LREGQ	−0.186	−7.088***	$I(1)$	0.665**	1.098***	$I(0)$	−6.415***	−8.119***	$I(0)$	2019
LRENE	5.885***	−4.889***	$I(0)$	1.007***	1.865***	$I(0)$	−1.406	−7.223***	$I(1)$	2010

*** indicates 1% level of significance

Table 5 Feedback of the asymmetric bound test long-run relationship

Model	*F*-statistics	K	Decision
($LCO_2P/LEDIG^{+ve}, LEDIG^{-ve}, LGFIN.$ $LGTEC, LREGQ, LRENE, LNREN$)	6.458	7	Cointegration exists
Significance levels	Lower bound	Upper bound	
10%	1.92	2.89	
5%	2.17	3.51	
1%	2.73	3.9	

Table 6 Feedback of Gregory-Hansen test for long-run cointegration

	Test statistic	Breakpoint	Date	Asymptotic critical values		
				1%	5%	10%
ADF	−6.25	202	2015	−6.05	5.56	−5.31
Zt	−6.33	20	2015	−6.05	−5.56	−5.31
Za	−30.23	20	2015	−70.18	−59.38	−54.38

Table 7 Long-run asymmetric results

Variables	Long-run	ΔShort-run
LCO_2P (−1)	−0.146** (0.065)	−0.089** (0.043)
LEDIG(*ve*+)	−0.135** (0.032)	−0.093*** (0.029)
LEDIG(*ve*−)	0.022 (0.015)	0.036** (0.015)
LGFIN	−0.013* (0.007)	−0.042*** (0.012)
LGTEC	−0.084*** (0.024)	−0.045*** (0.012)
LREGQ	0.090** (0.040)	0.045*** (0.012)
LRENE	−0.045** (0.016)	−0.057** (0.27)
LNREN	0.091*** (0.015)	0.063*** (0.018)
DUMMY	0.056 (0.046)	
ECM (−1)	-	−0.115*** (0.034)
Post estimation diagnostics		
R-squared	0.85	
Adjusted *R*-square	0.87	
Fisher statistic	45.774***	
Durbin-Watson	2.19	
Breusch-Godfrey Serial Correlation LM test	2.899 ***0.118***	
Heteroscedasticity test	1.186 ***0.765***	
Jarque–Bera normality test	1.197 ***0.549***	

The values enclosed in parentheses indicate standard errors. The symbols *, **, and *** indicate levels of significance at 10%, 5%, and 1%, respectively. Values that are both bolded and italicized indicate probability values for the diagnostic tests

digitization of the economy is expected to result in a substantial decrease in carbon dioxide emissions. On the other hand, negative impacts temporarily elevate carbon emissions, but their significance diminishes over time. This retention effect of digitization aligns with prior research (Adha et al. 2022; Ibrahim et al. 2022a) which hold the submission that digitalization promotes sustainable environment through significant reduction in carbon emissions. The feedback on green finance-carbon emissions nexus reveals that improvements in green projects have the potential to reduce carbon emissions both in the short-run and long-run. This empirical feedback corroborates the findings documented by Bai et al. (2022) and Ibrahim et al. (2022a, b, c, d) that green finance reduces stock emissions thereby promoting sustainability of the ecosystem.

Furthermore, the results expose that green technology exerts negative and statistically significant effects on carbon emissions per capita implying that a substantial advancement in environmental-related technology will lead to a significant decline in carbon emissions per capita. Copious empirical outcomes in the past have held the view that technological innovation drives economic growth without halting the ecosystem thereby promoting sustainable development (Dong et al. 2022a, b; Ibrahim et al. 2022a, b, c, d). The environmental impacts of regulatory quality are noted to be carbon enhancing going by the positive and statistically significant effects. This implies that regulatory quality in the USA is not totally against activities that promote drivers of carbon emissions per capita. Quite appreciable strands of empirical studies (Ibrahim et al. 2022a, b, c, d; Ibrahim and Ajide 2022) confirm the existence of significant relationship between regulatory quality and the environment.

The role of energy transition based on the positive and negative effects of non-renewable and renewable energy proves to induce and militate carbon emissions per capita. The conflicting roles of renewable and non-renewable energy on the environment under the concept of energy transition are well documented by extant studies (Afshan et al. 2022; Onifade and Alola 2022; Wang et al. 2022). The dummy variables are not significant across the long- and short-run. Besides, the error correction term shows that the disruption in the short-run can be corrected at a speed of adjustment of 34%. The post-estimation analyses indicate the model estimated is consistent and persists in predicting the impacts of eco-digitalization and other indicators on carbon emissions per capita. The summary of the reported impacts of the exogenous variables is presented in Fig. 9.

Robustness analysis and causality reports

The present study extends the contributions to the subject matter of investigation by employing three different estimators in evaluating similar empirical models (Fig. 10). The essence of the robustness analysis is to find out if the outcome variable will respond similarly to explanatory variables or not. Consequently, we employ the fully modified OLS (FMOLS), dynamic OLS (DOLS), and canonical cointegration regression (CCR) robust for long-run association. As evident in Table 8, the positive shocks from eco-digitalization are statistically significant to mitigate carbon emissions per capita based on the estimates provided by FMOLS and DOLS. Similarly, the moderating roles of green finance, green technology, and renewable energy are statistically significant. On the flip side, the inducing roles of regulatory quality and non-renewable energy on carbon emissions per capita are empirically supported by the estimates of the robustness estimators.

Feedback on causality is presented in Table 9. The results reveal the existence of unidirectional causality running from

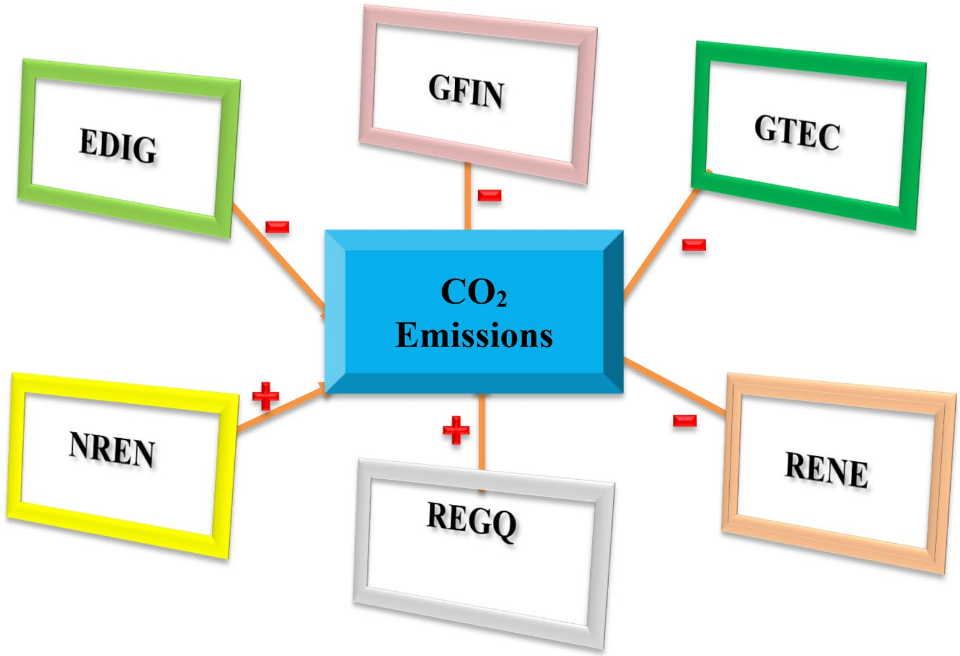


Fig. 9 Graphical summary of the reported exogenous effects

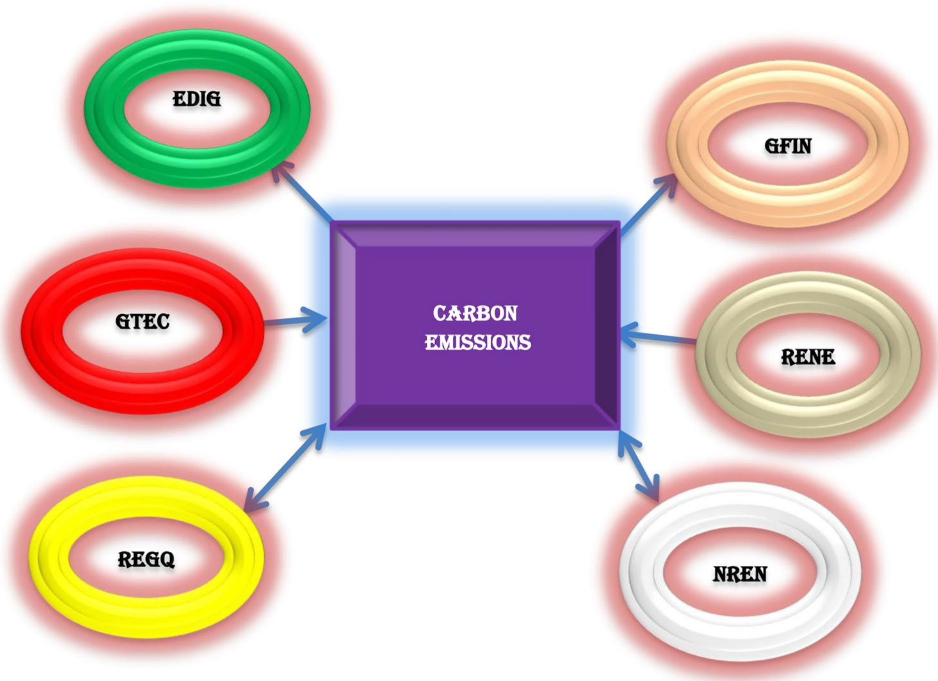


Fig. 10 Graphical summary of the causality nexus. Note: Two-sided arrows represent bidirectional and one-sided arrows denote unidirectional causalities

eco-digitalization, green finance, green technology, and renewable energy. These empirical outcomes imply that policy measures implemented to drive the highlighted indicators will have a multiplier moderating impact on carbon emissions per capita. Conversely, bidirectional causality is reportedly running from regulatory quality and non-renewable energy to carbon emissions per capita. Similar causality runs from carbon emissions per capita to both exogenous indicators.

Table 8 Robustness checks based on FMOLS, DOLS, and CCR estimators

Variables	Dependent variable: LCO_2P		
	FMOLS	DOLS	CCR
LEDIG(+*ve*)	−0.021** (0.010)	−0.062*** (0.018)	−0.021 (0.014)
LEDIG(−*ve*)	−0.059 (0.034)	−0.019 (0.012)	−0.051 (0.029)
LGFIN	−0.042** (0.017)	−0.040*** (0.020)	0.041** (0.017)
LGTEC	−0.097*** (0.018)	−0.102*** (0.027)	−0.098*** (0.019)
LREGQ	0.152*** (0.044)	0.142** (0.059)	0.152*** (0.044)
LRENE	−0.211*** (0.047)	−0.211*** (0.074)	−0.212*** (0.047)
LNREN	0.272*** (0.067)	0.278** (0.114)	0.273*** (0.068)
C	2.896*** (0.279)	2.922*** (0.407)	2.901*** (0.280)

The values enclosed in parentheses indicate standard errors. The symbols *, **, and *** indicate levels of significance at 10%, 5%, and 1%, respectively. Values that are both bolded and italicized indicate probability values for the diagnostic tests

Table 9 Outcomes of the heterogeneous causality test

Null hypothesis	*F*-statistic	Probability	Decision
$LEDIG \rightarrow LCO_2P$	2.384	0.098	Unidirectional
$LCO_2P \rightarrow LEDIG$	1.063	0.934	
$LGFIN \rightarrow LCO_2P$	4.0231	0.046	Unidirectional
$LCO_2P \rightarrow LGFIN$	1.353	0.704	
$LGTEC \rightarrow LCO_2P$	3.794	0.026	Unidirectional
$LCO_2P \rightarrow LGTEC$	1.104	0.906	
$LREGQ \rightarrow LCO_2P$	5.145	0.003	Bidirectional
$LCO_2P \rightarrow LREQG$	6.319	0.002	
$LRENE \rightarrow LCO_2P$	4.134	0.005	Unidirectional
$LCO_2P \rightarrow LRENE$	1.022	0.423	
$LNREN \rightarrow LCO_2P$	5.052	0.008	Bidirectional
$LCO_2P \rightarrow LNREN$	2.439	0.093	

The values enclosed in parentheses indicate standard errors. The symbols *, **, and *** indicate levels of significance at 10%, 5%, and 1%, respectively

Conclusion, policy implications, and limitations

The current research probes the long- and short-run asymmetric effects of eco-digitalization, green finance, green finance, regulatory quality, and energy transition on environmental sustainability in the USA based on data running from 1995Q1 to 2019Q4. The study employs a battery of estimation methods comprising non-linear ARDL bound testing for asymmetric long-run and short effects and FMOLS, DOLS, and CCR for the long-run association. Outcomes of the study show that positive shocks from eco-digitalization promote environmental sustainability short- and long-run by moderating the surge in carbon emissions per capita. Besides, moderating effects of green finance, green technology, and renewable energy are empirically confirmed, whereas regulatory quality and non-renewable energy contribute substantially to the surge. Interestingly, the reported nexuses are noted to be robust and consistent with the consideration of other estimators comprising FMOLS, DOLS, and CCR estimators. The Granger causality test reveals the existence of both bidirectional and unidirectional causality in the estimated model.

The policy implications that can drive the pathways toward sustaining the American environment are provided below.

First, the positive shocks of eco-digitalization on environmental sustainability should be sustained by the government and private bodies by sponsoring and making policies that will incentivize huge and consistent investments in digitalization. Pursuing these policy options is sacrosanct for the US government which is experiencing a significant rise in digital economy. The government can make laws that will mandate and motivate corporations and individuals to continually adopt digitalization of their economic activities. In addition, the US government and policymakers must allocate sufficient funding towards the basic digital infrastructure. Besides, the governments should implement policies that ensure they prioritize investments that may not be accessible or lucrative for private service providers while acknowledging the shared responsibility of both governmental bodies and private enterprises in this endeavor.

Second, to keep the pace of more green finance, projects that support green growth and environment should be encouraged by the US government. This can be achieved by the government committing its resources to green bonds and encouraging financial institutions to support investments and initiatives that drive green projects. The government of the US can also equally strengthen domestic regulatory frameworks, enhance the alignment of public financial incentives, stimulate significant increase in green financing across diverse sectors, legally ensure the integration of environmental considerations into public sector financial decisions in line with sustainable development goals and the promotion of investments in green financial technologies. Pursuing these policy options will be resourceful in promoting green finance in the USA.

Third, to keep pace with renewable energy development, government should continue to sponsor research and developments, science and innovations and all technologically driven projects to ensure the current moderating roles of technology on the level of carbon emissions per capita in the USA are maintained. Besides, developing and implementing a policy and regulatory framework that facilitates the advancement and utilization of renewable energy sources is deemed one of the most efficacious approaches the US government can adopt to foster its growth. Incorporating intricate objectives and mandates about the proportion of renewable energy, mitigating carbon dioxide emissions, and enhancing energy efficiency can be integral components through which renewable energy is enhanced. Fourth, more focus and priority should be given to reviewing environmental laws and regulations in the USA to further heighten the quality of the environment and the drive toward achieving carbon neutrality. The government must take the lead by abiding by environmental law in the USA. Besides, the enforcement of environmental law should be taken with utmost seriousness in order to ensure citizens follow the various laws. Fifth, there is no denying the fact that the USA is doing pretty well in the pursuit of carbon neutrality by increasing the consumption of renewable energy at the expense of non-renewable energy. The government should strive to consciously keep this current trend in energy transition.

The present study is not short of certain limitations which leave much to be desired by future studies. Specifically, the present study focuses on carbon emissions per capita to proxy environmental sustainability which for far-reaching investigation could be extended to other indicators of the environment such as ecological footprint, $PM_{2.5}$ air pollution, and nitrous oxide among others. Besides, this study can be extrapolated to panel analysis of globally recognized intergovernmental organizations such as G7, G20, and E7 economies.

Author contribution Conceptualization (ideas; formulation or evolution of overarching research goals and aims: Fangbin Han, Ridwan Lanre Ibrahim, Usama Al-Mulali, and Jun Tang. Methodology (development or design of methodology; creation of models): Ridwan Lanre Ibrahim, Fangbin Han, and Jun Tang. Software (programming, software development; designing computer programs; implementation of the computer code and supporting algorithms; testing of existing code components): Ridwan Lanre Ibrahim, Fangbin Han, and Jun Tang. Validation (verification, whether as a part of the activity or separate, of the overall replication/ reproducibility of results/experiments and other research outputs): Ridwan Lanre Ibrahim, Fangbin Han, Usama Al-Mulali, and Jun Tang. Formal analysis (application of statistical, mathematical, computational, or other formal techniques to analyze or synthesize study data): Ridwan Lanre Ibrahim, Fangbin Han, and Jun Tang. Investigation (conducting a research and investigation process, specifically performing the experiments, or data/evidence collection): Ridwan Lanre Ibrahim, Fangbin Han, Usama Al-Mulali, and Jun Tang. Resources (provision of study materials, reagents, materials, patients, laboratory samples, animals, instrumentation, computing resources, or other analysis tools): Ridwan Lanre Ibrahim, Fangbin Han, and Jun Tang. Data curation (management activities to annotate (produce metadata), scrub data, and maintain research data (including software code, where it is necessary for interpreting the data itself) for initial use and later reuse): Ridwan Lanre Ibrahim, Fangbin Han, and Jun Tang. Writing — original draft (preparation, creation and/or presentation of the published work, specifically writing the initial draft (including substantive translation): Ridwan Lanre Ibrahim, Fangbin Han, Usama Al-Mulali, and Jun Tang. Writing — review and editing (preparation, creation and/or presentation of the published work by those from the original research group, specifically critical review, commentary or revision — including pre-or post-publication stages): Ridwan Lanre Ibrahim, Fangbin Han, Usama Al-Mulali, and Jun Tang. Visualization (preparation, creation and/or presentation of the published work, specifically visualization/data presentation): Fangbin Han, Ridwan Lanre Ibrahim, and Usama Al-Mulali. Supervision (oversight and leadership responsibility for the research activity planning and execution, including mentorship external to the core team): Usama Al-Mulali and Ridwan Lanre Ibrahim. Project administration (management and coordination responsibility for the research activity planning and execution): Ridwan Lanre Ibrahim. Funding acquisition (acquisition of the financial support for the project leading to this publication): not applicable.

Data availability The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

References

Adha R, Hong C-Y, Agrawal S, Li L-H (2022) ICT, carbon emissions, climate change, and energy demand nexus: the potential benefit of digitalization in Taiwan. Energy Environ 0958305X221093458. https://doi.org/10.1177/0958305X221093458

Afshan S, Ozturk I, Yaqoob T (2022) Facilitating renewable energy transition, ecological innovations and stringent environmental policies to improve ecological sustainability: evidence from MM-QR method. Renewable Energy 196:151–160. https://doi.org/10.1016/j.renene.2022.06.125

Ahmed Z, Ahmad M, Murshed M, Ibrahim Shah M, Mahmood H, Abbas S (2022) How do green energy technology investments, technological innovation, and trade globalization enhance green energy supply and stimulate environmental sustainability in the G7 countries? Gondwana Res 112:105–115. https://doi.org/10.1016/j.gr.2022.09.014

Anwar A, Sinha A, Sharif A, Siddique M, Irshad S, Anwar W, Malik S (2022) The nexus between urbanization, renewable energy consumption, financial development, and CO2 emissions: evidence from selected Asian countries. Environ Dev Sustain 24(5):6556–6576. https://doi.org/10.1007/s10668-021-01716-2

Bai J, Chen Z, Yan X, Zhang Y (2022) Research on the impact of green finance on carbon emissions: evidence from China. Econ Res-Ekonomska Istraživanja 0(0):1–20. https://doi.org/10.1080/1331677X.2022.2054455

Balcilar M, Usman O, Ike GN (2023) Operational behaviours of multinational corporations, renewable energy transition, and environmental sustainability in Africa: does the level of natural resource rents matter? Resour Policy 81:103344. https://doi.org/10.1016/j.resourpol.2023.103344

Bashir MF, Pan Y, Shahbaz M, Ghosh S (2023) How energy transition and environmental innovation ensure environmental sustainability? Contextual evidence from top-10 manufacturing countries. Renewable Energy 204:697–709. https://doi.org/10.1016/j.renene.2023.01.049

Cui J, Dai J, Wang Z, Zhao X (2022) Does environmental regulation induce green innovation? A panel study of Chinese listed firms. Technol Forecast Soc Chang 176:121492. https://doi.org/10.1016/j.techfore.2022.121492

Dogan E, Madaleno M, Taskin D, Tzeremes P (2022) Investigating the spillovers and connectedness between green finance and renewable energy sources. Renewable Energy 197:709–722. https://doi.org/10.1016/j.renene.2022.07.131

Dong F, Hu M, Gao Y, Liu Y, Zhu J, Pan Y (2022) How does digital economy affect carbon emissions? Evidence from global 60 countries. Sci Total Environ 852:158401. https://doi.org/10.1016/j.scitotenv.2022.158401

Dong F, Zhu J, Li Y, Chen Y, Gao Y, Hu M, Qin C, Sun J (2022) How green technology innovation affects carbon emission efficiency: evidence from developed countries proposing carbon neutrality targets. Environ Sci Pollut Res 29(24):35780–35799. https://doi.org/10.1007/s11356-022-18581-9

Gao P, Wang Y, Zou Y, Su X, Che X, Yang X (2022) Green technology innovation and carbon emissions nexus in China: does industrial structure upgrading matter? Front Psychol 13:951172. https://doi.org/10.3389/fpsyg.2022.951172

Huang Y, Zhang Y (2023) Digitalization, positioning in global value chain and carbon emissions embodied in exports: evidence from global manufacturing production-based emissions. Ecol Econ 205:107674. https://doi.org/10.1016/j.ecolecon.2022.107674

Ibrahim RL (2022) Beyond COP26: can income level moderate fossil fuels, carbon emissions, and human capital for healthy life expectancy in Africa? Environ Sci Pollut Res. https://doi.org/10.1007/s11356-022-21872-w

Ibrahim RL, Ajide KB (2022) Trade facilitation, institutional quality, and sustainable environment: renewed evidence from Sub-Saharan African countries. J Afr Bus 23(2):281–303. https://doi.org/10.1080/15228916.2020.1826886

Ibrahim RL, Al-mulali U, Ozturk I, Bello AK, Raimi L (2022) On the criticality of renewable energy to sustainable development: do green financial development, technological innovation, and economic complexity matter for China? Renewable Energy. https://doi.org/10.1016/j.renene.2022.08.101

Ibrahim RL, Ozturk I, Al-Faryan MAS, Al-Mulali U (2022d) Exploring the nexuses of disintegrated energy consumption, structural change, and financial development on environmental sustainability in BRICS: modulating roles of green innovations and regulatory quality. Sustain Energy Technol Assess 53:102529. https://doi.org/10.1016/j.seta.2022.102529

Ibrahim RL, Al-mulali U, Solarin SA, Ajide KB, Al-Faryan MAS, Mohammed A (2023) Probing environmental sustainability pathways in G7 economies: the role of energy transition, technological innovation, and demographic mobility. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-023-27472-6

Ibrahim RL, Adebayo TS, Awosusi AA, Ajide KB, Adewuyi AO, Bolarinwa FO (2022) Investigating the asymmetric effects of renewable energy-carbon neutrality nexus: can technological innovation, trade openness, and transport services deliver the target for Germany? Energy Environ 0958305X221127020. https://doi.org/10.1177/0958305X221127020

Ibrahim RL, Huang Y, Mohammed A, Adebayo TS (2022) Natural resources-sustainable environment conflicts amidst COP26 resolutions: investigating the role of renewable energy, technology innovations, green finance, and structural change. Int J Sustain Dev World Ecol0(0):1–13. https://doi.org/10.1080/13504509.2022.2162147

International Energy Agency, I. E. A. (2020, March).Consumption – coal information: overview – analysis. IEA. https://www.iea.org/reports/coal-information-overview/consumption. Accessed Jul 2023

Lanre Ibrahim R, Bello Ajide K, Usman M, Kousar R (2022) Heterogeneous effects of renewable energy and structural change on environmental pollution in Africa: do natural resources and environmental technologies reduce pressure on the environment? Renew Energy 200:244–256. https://doi.org/10.1016/j.renene.2022.09.134

Murshed M, Apergis N, Alam MS, Khan U, Mahmud S (2022) The impacts of renewable energy, financial inclusivity, globalization, economic growth, and urbanization on carbon productivity: evidence from net moderation and mediation effects of energy efficiency gains. Renew Energy 196:824–838. https://doi.org/10.1016/j.renene.2022.07.012

Nosova S, Norkina A, Makar S, Arakelova I, Fadeicheva G (2022) Digitalization as a new paradigm of economic progress. Biologically Inspired Cogn Architectures 2021:344–354. https://doi.org/10.1007/978-3-030-96993-6_38

Oke DM, Ibrahim RL, Bokana KG (2021) Can renewable energy deliver African quests for sustainable development? J Dev Areas 55(1). https://doi.org/10.1353/jda.2021.0022

Onifade ST, Alola AA (2022) Energy transition and environmental quality prospects in leading emerging economies: the role of environmental-related technological innovation. Sustain Dev n/a(n/a). https://doi.org/10.1002/sd.2346

Pang L, Zhu MN, Yu H (2022) Is green finance really a blessing for green technology and carbon efficiency? Energy Econ 114:106272. https://doi.org/10.1016/j.eneco.2022.106272

Pesaran MH, Shin Y (1995) Autoregressive distributed lag modelling approach to cointegration analysis. DAE Working Paper Series No. 9514, Department of Economics, University of Cambridge, Cambridge

Rehman A, Ma H, Ozturk I, Ahmad MI (2022) Examining the carbon emissions and climate impacts on main agricultural crops production and land use: updated evidence from Pakistan. Environ Sci Pollut Res 29(1):868–882. https://doi.org/10.1007/s11356-021-15481-2

Sharif A, Saqib N, Dong K, Khan SAR (2022) Nexus between green technology innovation, green financing, and CO2 emissions in the G7 countries: the moderating role of social globalisation. Sustain Dev n/a(n/a). https://doi.org/10.1002/sd.2360

Shen J, Ridwan LI, Raimi L, Al-Faryan MAS (2023) Recent developments in green hydrogen–environmental sustainability nexus amidst energy efficiency, green finance, eco-innovation, and digitalization in top hydrogen-consuming economies. Energy Environ 0958305X231153936. https://doi.org/10.1177/0958305X231153936

Shin Y, Yu B, Greenwood-Nimmo M (2014) Modelling asymmetric cointegration and dynamic multipliers in a nonlinear ARDL framework. In R. C. Sickles & W. C. Horrace (Eds), Festschrift in honor of Peter Schmidt (pp 281–314). Springer New York. https://doi.org/10.1007/978-1-4899-8008-3_9

Tang L, Lu B, Tian T (2023) The effect of input digitalization on carbon emission intensity: an empirical analysis based on China's manufacturing. Int J Environ Res Publ Health 20(4):4. https://doi.org/10.3390/ijerph20043174

Wang Z, Yen-Ku K, Li Z, An NB, Abdul-Samad Z (2022) The transition of renewable energy and ecological sustainability through environmental policy stringency: estimations from advance panel estimators. Renewable Energy 188:70–80. https://doi.org/10.1016/j.renene.2022.01.075

Yang Z, Gao W, Han Q, Qi L, Cui Y, Chen Y (2022) Digitalization and carbon emissions: how does digital city construction affect China's carbon emission reduction? Sustain Cities Soc 87:104201. https://doi.org/10.1016/j.scs.2022.104201

Zhao J, Sinha A, Inuwa N, Wang Y, Murshed M, Abbasi KR (2022) Does structural transformation in economy impact inequality in renewable energy productivity? Implications for sustainable development. Renew Energy 189:853–864. https://doi.org/10.1016/j.renene.2022.03.050

Zheng R, Wu G, Cheng Y, Liu H, Wang Y, Wang X (2023) How does digitalization drive carbon emissions? The inverted U-shaped effect in China. Environ Impact Assess Rev 102:107203. https://doi.org/10.1016/j.eiar.2023.107203

Zou X, Yang S, Ibrahim RL, Al-Faryan MAS (2023) Probing the environmental impacts of structural transition and demographic mobility in Africa: does technological innovation matter? Energy Environ 0958305X231153967. https://doi.org/10.1177/0958305X231153967

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.