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A step toward the attainment of carbon neutrality and SDG-13: Role of financial depth and green technology innovation

Sunil Tiwari [a,1], Arshian Sharif [b,f,g,2], Emrah Sofuoğlu [c], Florian Nuta [d,e,*,3]

[a] Department of Tourism Studies, School of Business Studies, Central University of Kerala, India
[b] Department of Economics and Finance, Sunway Business School, Sunway University, Subang Jaya, Malaysia
[c] Kırşehir Ahi Evran University, Turkey
[d] Human and Social Sciences Doctoral School, Ştefan cel Mare University of Suceava, Suceava, Romania
[e] School of Economics and Business, Western Caspian University, Baku, Azerbaijan
[f] University of Economics and Human Sciences in Warsaw, Warsaw, Poland
[g] College of International Studies, Korea University, Seoul, South Korea

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ABSTRACT

Following the recommendations of COP28 and Sustainable Development Goal −13 (Climate Action), the present study examines the role of financial depth and green technology innovation in carbon neutrality and climate change. This study measures the relationship between green innovation, technological innovation, ICT, financial depth, economic growth, carbon emission, and ecological footprint from 1990 to 2021 in the USA. The autoregressive distributed lag (ARDL) model examines the relationship between the above-mentioned variables and their impacts on each other. Results reveal that green innovation, technological innovation, ICT, and financial depth significantly negatively impact ecological footprint and carbon emissions in both the short and long run. In contrast, economic growth positively impacts carbon emissions and ecological footprint. Green and financial innovation-centric policies are suggested to the USA to attain net zero emission and SDG-13.

1. Introduction

As one of the most relevant inputs in producing goods and services, energy increases output by triggering the finance and industry sectors. However, while it enhances economic activities, it also affects ecological integrity (Song and Wang, 2018) since it is mainly based on fossil fuel resources, accounting for 82 % of the global primary energy usage (Ritchie et al., 2022). Thus, many studies have confirmed that energy consumption is a significant driver of environmental degradation. The international community has been trying to take measures against climate change and environmental degradation since the 1980s. The aim is to achieve sustainable development with green growth policies. In this context, countries are trying to establish low-carbon and climate-resistant economies. Green finance and technology innovation are essential strategies to enhance environmental sustainability and reduce carbon emissions (Su

* Corresponding author at: Human and Social Sciences Doctoral School, Ştefan cel Mare University of Suceava, Suceava, Romania.
E-mail addresses: sunilkumar@cukerala.ac.in (S. Tiwari), arshian.aslam@gmail.com (A. Sharif), emrahsofuoglu@gmail.com (E. Sofuoğlu), florian100780@gmail.com (F. Nuta).
[1] https://orcid.org/0000-0002-0180-9237
[2] https://orcid.org/0000-0002-1155-4151
[3] https://orcid.org/0000-0001-8663-4183

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et al., 2024). Climate change resilience and mitigation policies have created several bi-directional impacts between the environment and the financial sector. The impact of financial depth has a crucial role in promoting green investments and eco-innovation. It refers to the extent of productivity in domestic financial sectors (Alshubiri et al., 2021) and a multilateral process in financial markets that links financial instruments and financial stakeholders. In brief, financial depth is the size and liquidity of financial markets. As the financial asset supplies increase in the economy, asset diversification increases, new participants join the market, and financial markets develop further (Shaw, 1973). This progress undoubtedly contributes to economic growth and affects environmental sustainability in two ways. First, it can enhance environmental sustainability by effectively using financial resources and sound green investments required to ensure environmental quality. Green bonds are effective strategies for lowering CO2 emissions, environmental regeneration, and realizing the commitments of the Paris Agreement, according to Gianfrate and Peri (2019). In addition, financial depth might ease access to affordable loans, creating the premises for inclusivity and promoting green technologies (Kahia et al., 2017), thus improving environmental sustainability (Tamazian et al., 2009). Financial development can also promote renewable energy (Kim and Park, 2016; Kutan et al., 2018; Shahbaz et al., 2021), the most crucial part of tackling environmental degradation and climate change. This way, the financial depth can promote eco-innovations and green investments in the energy and environmental sectors (Ramzan et al., 2023). However, financial depth might also be a depressing factor for environmental protection.

Three effects of financial depth on the energy demand are i) direct, ii) business, and iii) wealth effects (Sadorsky, 2011). According to the direct effect, the financial sector facilitates loans, enables people to make physical investments, and increases energy demand, primarily based on fossil sources. Under such circumstances, energy-related pollution and environmental degradation will increase (Sadorsky, 2010). The positive effect of technological developments on energy efficiency enhances the environmental quality by reducing the carbon intensity of the products. To this end, national efforts promote environmental technologies (De Jong et al., 2016). In the literature, several studies confirm the positive impact of green technology innovations on environmental sustainability (Obobisa et al., 2022). These contradictory results prove that the debate is still open about the benefits of technological advancements, the economic context, and the meaning of implementation.

Nevertheless, another important feature of green technology innovation is its positive contribution to economic growth. Green technology innovations ensure environmental sustainability and trigger economic development. Thus, green technology innovations ease the decoupling between economic growth and environmental pollution, which is the ultimate aim of sustainable development goals. In addition, it provides solutions for recycling, waste control, and lower CO2 emissions while the industry performs (Sharif et al., 2022). However, the human capital stock must be high for green technology innovations to improve environmental quality (Lin and Ma, 2022).

Despite the recommendation of COP26 and commitments of various organizations, recent data reflect no visible change in the reduction of CO_2 emissions and climate change impacts, with global carbon emissions increasing daily (EIA., 2020). Even after the most significant economic power, the United States is the second highest contributor to total emissions worldwide—one-quarter of the world's GDP shared by the USA (WDI, 2019). In 2021, 1551 million metric tonnes of carbon were emitted by the USA, and 32 % belong to the energy sector. In this direction, the USA has become the focal point of discussion worldwide because of carbon emission, climate change, and environmental sustainability. Therefore, the scholarly community is very interested in understanding the source of CO2 emissions in the USA and how green technological and financial innovation help mitigate the impacts of carbon emissions and climate change impacts. In this regard, the present study is a serious attempt to examine the carbon emission phenomenon and how it relates to ecological footprint, economic development, green innovation, technological innovation, information, communication and technology (ICT), and financial depth. Recently, green innovation and environmentally friendly technologies have been a matter of serious discussions and scholars exploring them in different ways to reduce carbon emissions and facilitate environmental sustainability. In this view, the impacts of economic, financial, and energy-related innovations on environmental degradation in USA studies by Abbasi et al. (2022) and Xu et al. (2023). In light of previous works, the current study explores green innovation in the context of carbon emission and climate change more comprehensively and deeply. This study is the first-ever work investigating carbon emission and climate change in the USA, discussing ecological footprint, economic development, green innovation, technological innovation, information, communication and technology (ICT), and financial depth. It is a worthy choice to select the USA for conducting this uncommon research and studying the world's second-highest greenhouse emitter and largest economy.

With this motivation, the present study makes the following contributions to the existing literature (theoretically and practically). First, this study performed two empirical models using CO_2 emissions and ecological footprint as independent variables. As it is known, while CO_2 emissions provide insight into air pollution, ecological footprint considers human pressure on the ecosystem by focusing on lands, oceans, forests, and infrastructure. In this way, we separately observe the impacts of dependent variables (financial depth and GTIs) on carbon emissions and EFP to compare the empirical findings. Second, to the best of our knowledge, this is the first study combining the effects of financial depth and green technology innovation on the environment in the United States. In this way, we suggest specific policy recommendations for the USA. Lastly, the study performs the Bootstrap (ARDL) method developed by McNown et al. (2018). This approach considers three tests (F, t dependent, and F independent) to determine the cointegration nexus explained by Pesaran et al. (2001). We also employ the Bootstrap ARDL analysis for the empirical analysis since it gives robust results in small samples.

This study consists of five main chapters. The first part provides a theoretical background on financial depth, green technology innovation, and environmental quality. The second part presents a thorough literature review. The third part introduces the methodology and reports on empirical modeling. The fourth part entails data estimations and discusses empirical findings. The final section concludes the study and suggests several policy recommendations for American policymakers based on the original findings described previously.

2. Literature

2.1. Financial depth and environmental sustainability

Recently, many researchers have been researching environmental economics and contributing to the literature on specific issues. Various studies focus on the determinants of environmental pollution. This section examines studies discussing the nexus between environmental degradation and financial depth.

The financial system has a crucial role in financing investments and promoting technologies. One of the essential effects of green investment is enhancing sustainable development and mitigating CO2 emissions (Priyan, 2023; Sun et al., 2024; Hua et al., 2024). To realize green and sustainable investments and increase their carbon performance (Du et al., 2024), firms need financial resources. Thus, a sound financial system is required to realize green investments and stimulate economic growth. Although green financing does not directly affect the environment, it improves it through funding green businesses and programs (Chen et al., 2020). In this context, financial development can affect the environment positively and negatively since it can provide cheap loans to dirty or clean investments. Due to this reason, there needs to be clear proof of the link between financial development and the environment. While some studies found that financial development could be an essential tool to mitigate environmental pollution and tackle climate change (Jiakui et al., 2023), the negative impacts were also determined (Ahmad et al., 2022). Ozkan et al. (2023) estimated the financial development, trade openness, and green technological innovation given environmental degradation in China. Outcomes demonstrated that green technological and financial innovation positively impacts carbon efficiency and reduces carbon emission and climate change impacts. In the same vein, Tao et al. (2023) concluded that financial deepening significantly diminish the carbon emissions intensity in OECD countries, while identifying a moderating effect from information technologies. The findings in the current literature still need to be clarified to establish the role of financial development features under different macroeconomic conditions. For instance, Acheampong et al. (2020) substantiate an improvement in environmental quality for financially advanced and emerging economies and contrary effects for less developed countries. The arguments are that less financially developed countries did not reach the level of efficiency that ensures financial resources to promote green technologies and push innovation. Similar results were documented by Yu et al. (2023), reaching to the conclusion that financial depth affects differently developed and developing economies.

Numerous studies refer to financial development while examining the impact of financial depth in the literature review (Ramzan et al., 2023; Yuan et al., 2022). These terms have different meanings. Financial development indicates advances in the quantity, quality, and efficiency of financial intermediation services. In contrast, financial depth means that all segments of society utilize financial service options in a broader sense. As an essential component of financial development, financial depth also has specific impacts on environmental quality. A recent paper by Ramzan et al. (2023) found that GTIs and financial depth positively impact environmental quality. The authors employed the quantile approach and causality test for the top ten greenest economies covering 1980–2019. They also capture the same findings for EFP and carbon emissions. The study suggests that policymakers should improve financial development, which will provide resources for green innovation technologies. Yuan et al. (2022) examined how financial depth may help to achieve green growth in China. They determined that financial depth contributes to the greening of China's economy. In addition, there is a U-shaped linkage between the variables, meaning that while financial depth initially hinders green growth, it stimulates it after a certain period. Finally, they argue that a decoupling between environmental pollution and economic growth could be achieved by developing stock and debt markets in China. Chen et al. (2020) seek an answer to whether financial depth or financial breadth matters for the environment in China. They found an important finding. Accordingly, the depth of national financial development could increase environmental sustainability by prompting the inflection point of the inverted U-shaped EKC.

Additionally, proxy variables of green innovation (Green energy and green patents) and financial development (Circular economy and Linear economy) were recently examined by Tiwari and Mohammed (2024) in the context of environmental sustainability in OECD nations. Findings confirmed that green patents and green energy reduce carbon emissions and positively impact environmental sustainability in the short and long run. Conversely, circular and linear economies have negative impacts initially, and later, both facilitate eco-innovation and environmental well-being. Hence, it is a new contribution to financial development and environmental sustainability literature. Both are crucial for green innovation that mitigates carbon emissions, and climate change impacts worldwide.

Furthermore, the nexus between technological progress and ecological efficiency is also negatively influenced by financial depth. Based on the empirical findings, they suggest policymakers combine financial and ecological policies. Specifically, they recommend green financing policies for the micro, meso, and macro dimensions. Financial markets and institutions must allocate more credits and resources to green projects to protect the ecosystem for future generations.

2.2. Green technology innovations and environmental sustainability

Green technology innovations are essential to combating environmental degradation since they can lower emissions and environmental pollution through energy efficiency and renewable energy expansion (Abban et al., 2022; Cheng et al., 2024). Hashmi and Alam (2019) examine the linkage among environmental regulations, green technology, and environmental quality in OECD countries by using the STIRPAT model. Results show that environmental patents mitigate environmental degradation. They also found a similar finding between environmental tax and CO2 emissions. They recommend that policymakers better encourage environmental technologies to tackle CO2 emissions. Li et al. (2021) determined an inverted U-shaped link between patents and CO2 emissions. As an essential component of green technology innovations, several studies capture a positive nexus between environmental patents and environmental sustainability (Yii and Geetha, 2017). However, carbon risk inhibits the firms' willingness to invest in innovation (Li et al., 2024). Cho & Sun (2018) and Wang et al. (2012) claim that the key factor triggering green patents is R&D investment. Therefore, R&D activities also play an essential role in mitigating environmental degradation by promoting green technology innovations. Petrović and Lobanov (2020) confirm that R&D spending lowers CO2 emissions. Safi et al. (2021) examined the association between environmental taxes, environmental R&D, and CO2 emissions in G7 countries by using the Dumitrescu and Hurlin causality test covering the period 1990–2019. Findings depict that environmental taxes and R&D positively impact environmental sustainability. Therefore, the authors suggest that environmental taxation and R&D have excellent potential as a strategy to achieve a carbon-neutral economy.

Su and Moaniba (2017) found that green technology innovation strongly impacts climate change and moderates environmental pollution. Lin and Ma (2022) conducted a study in China from 2006 to 2017 and investigated the impact of green technology innovation on CO2 emissions. They found that green technology innovation could mitigate CO2 emissions through the industrial structure as the output of linear functional-coefficient models. However, human capital must be high to see green technology innovation's positive impact on emissions. Kuang et al. (2022) examined a similar issue for China over the period 1990–2018 by using AMG and CCEMG tests. According to the findings, green technology innovation and renewable energy inhibit environmental pollution (El Khoury et al., 2025). Referring to the positive externalities of green technology innovations, the authors recommended applying long-term policies to fight against environmental degradation. These innovations lower emissions, particularly in developed countries (Du et al., 2019), since they have better financial and industrial conditions. Based on these findings, Du and Li (2019) measured the association between green technology advances and CO2 emissions in 76 countries from 1996 to 2012, with countries considered as high-income and low-income economies. While the findings demonstrate an insignificant association in terms of low-income countries, the impact of the nexus is statistically significant for high-income countries. Shao et al. (2021) captured an adverse nexus between green innovation and environmental pollution in N11 countries from 1980 to 2018, employing the CS-ARDL test. They suggest policymakers combine renewable energy and green technology innovation policies to enhance environmental quality.

Sharif et al. (2023) investigated the impact of economic development, renewable energy, and environmental tax on green technology innovation in ASEAN countries. Results reported that green investment, green energy, environmental tax, and economic growth have significant positive impacts on green technology innovation, and these impacts are getting more robust over the higher quantiles.

Ramzan (2023) recently examined the ten greenest countries with a similar research question. They observe the impacts of financial depth and green technology innovation on CO2 emissions and ecological footprint. In this study, we focus on the US, the world's largest polluter, and suggest specific policy recommendations through individual results. Therefore, we contribute to filling this gap in the literature since no paper has explored the linkage among financial depth, green technology innovation, and environmental sustainability with time series for the USA.

3. Data, methodology, and empirical modeling

In order to investigate the role of green innovations, technological innovations, ICT, financial depth, and economic growth for carbon emissions and EFP in the USA, a data set of the variables was taken from 1990 to 2021 (Table 1). Data for ecological footprint and carbon emissions are measured in terms of EFP per capita (total) and Carbon emissions per capita (metric tons) and collected from GFN and WDI websites, respectively. Furthermore, for green innovation, the study uses the number of reported patents on environmental technologies as a proxy collected from the OECD. At the same time, the financial depth is described by the financial institutions' depth index collected from the IMF. Technological innovation, ICT, and Economic growth are measured through resident patent applications, subscriptions of telephone, and GDP per capita (current US$), data collected from World Development Indicators (WDI). Finally, from per capita values, all data sets are converted into a natural logarithmic form to receive a more efficient estimation.

For examining the co-integrating link among the selected variables (Ecological footprint, Carbon emissions, Green innovation, Technological innovation, ICT, Financial depth, and Economic growth), we employ "ARDL cointegration approach" suggested by McNown et al. (2018). Additionally, one of the significant advantages of utilizing the bootstrapping ARDL approach is the ability to cope with low side and power properties (Pesaran et al., 2001 &Pesaran et al., 1999). The strength of both the "T-test" and "F-test" increases due to the bootstrapping of ARDL cointegration, its potential, and the latest integration. There are two criteria suggested by Pesaran et al. (2001) for the integration of bootstrapping ARDL. The first is based on the coefficient of error-correction term with their key results. The second crucial pre-requite condition is that the lagged values of explanatory variables must be significant along with their coefficients.

For this reason, both the bottom and top limits (the critical limits) should be specified clearly (Pesaran et al., 2001). Perhaps the

Table 1
Description of variables.

Variable Name	Symbol	Description	Source
Ecological Footprint	EFP	EFP per capita (Total)	GFN
Carbon Emission	CE	Carbon emission per capita (metric tons)	WDI
Green Innovation	GIN	Number of reported patents on environmental technologies	OECD
Technological Innovation	TIN	Number of patent applications by residents	WDI
Information, Communication and Technology	ICT	Fixed telephone subscription (per 100 people)	WDI
Financial Depth	FDT	Financial Institution Depth Index	IMF
Economic Development	GDP	GDP per capita (Current US $)	WDI

critical limits and bound test are unnecessary for fulfilling the first condition when the research variables are incorporated with the coefficient for error-correction terms and essential findings in the model of dimension. Because of reduced power characteristics and explanatory, traditional 'unit root' tests are uncomfortable and in use (Goh et al., 2017). Later on, the problem of the ARDL bound test was fairly handled by McNown et al. (2018) while offering bootstrap.

The integration- properties, and vulnerability according to the parameters are core and unique groundings of bound ARDL test while bootstrapping. In case of issues related to traditional bound ARDL evaluation, like inclusive instances and complex time series analysis, the bound ARDL test is applicable (McNown et al., 2018). Another advantage of implementing the ARDL bound analysis is removing the uncertain areas and cases in the measured production values. Based on the research variable, the procedure for traditional bootstrapping ARDL bound testing equation is reported in Eq. 1.

$$Yt = \sum_{i=1}^{P} aiyt - i + \sum_{j=o}^{q} \beta jxt - j + \sum_{k=o}^{r} \gamma kZt - k + \sum_{j=1}^{s} + \tau jDt, l + \mu t \tag{1}$$

In the above model Eq. (1), lag-terms are specified by the symbols like "*i*", "*j*", "*k*", and "*l*" for example, "i" = "1,2.p"; "j" = "0,1,2,… q"; "k" = "0,1,2,…r"; "*l*" = "0,1,2, and time is reflected by s"; and "*t*". In addition, the study's explanatory and response variables are shown as xt, *zt, and yt,* respectively. Moreover, Dt, a dummy variable, is indicated by Dt,l, based on the unit root test showing the yearly brakes (Carrion-i-Silvestre et al., 2009). The coefficient of the dummy variable and variables that are lagged and explanatory in nature in the model shown by β and y in the equation. With the finite variance, zero mean error-term indicated by μ*t.* In the above model, the error correction form is represented in equation −3.

$$\Delta yt = \varphi yt - 1 + \gamma x1 + \psi zt - 1 + \sum_{i=1}^{P-1} \lambda iyt - i + \sum_{j=1}^{q-1} \delta jxt - j + \sum_{i=1}^{r-1} \pi kz - k + \sum_{i=1}^{s} + \omega iDt, l + \mu t \tag{2}$$

In the above equation,

$$\varnothing = \sum_{I=1}^{P} ai, \quad \gamma = \sum_{I=1}^{q} \beta i, \psi = \sum_{I=0}^{r} \gamma i,$$

The associated functions are symbolized by λ*i*,δ*j*, πk, and ωi in Eq. 2. While using a constant term, this equation can be estimated through the below listed model (equation 3).

$$\Delta yt = \tilde{c} + \varphi yt - 1 + \tilde{y} xt - 1 + \tilde{\psi} zt - 1$$
$$= \sum_{i=1}^{p-1} \tilde{\lambda} iyt - j + \sum_{j=1}^{q-1} \tilde{\delta} ixt - i + \sum_{k=1}^{r-1} \tilde{\pi} izt - k + \sum_{i=1}^{s} \tilde{\omega} iDt, 1 + \tilde{\mu} t$$

With the help of the ARDL approach, a bound test value is generated in both T and F1 tests, which is a crucial notation. Moreover, the test score for the F2 test gets denied due to lagging explanatory variables. We can have critical values of all research variables by applying the BARDL method McNown et al. (2018). To get robust empirical findings, we used critical values during the tabulation. Additionally, stationary testing is a prerequisite for every cointegration test. Whenever significant structural breaks in time-series properties influence the findings of other studies, it is not good to apply the ADF unit root test as done by some previous works. In this sense, Zivot and Andrews (2002) contributed significantly and measurably without defining the breakpoint time and allowed different breaks of structural modeling of time series data. Therefore, leaving the issue related to selecting the breakpoint, the endogenous breakpoint in the structural modeling is possibly determined. This proves that the selection of breakpoints endogenously has a significant impact on the output of the unit root. Hence, we utilized ADF and ZA to make effective use of them. With the help of the unit root test and stationarity, the stationary property of the data is measured. It is said that, data is suitable to perform the ARDL model and selected variables are following the prerequisites of the model.

4. Empirical findings and discussion

Descriptive statistics of selected variables is presented in Table 2 in the form of means scores where FDT has shown the highest mean value, followed by the GIN, TIN, CE, ICT, EFP, and GDP. This means that the financial depth is substantially higher than economic growth, while green innovations remain higher than technological innovations, information communication, and technology. Moreover, carbon trends are more than an ecological footprint. Additionally, it has been noticed that the ecological footprint is more volatile than any other variable, with carbon emissions reflecting more deviation compared to GIN, TIN, ICT, GDP, and FDT.

Table 2
Results of Descriptive statistics.

Variables	EFP_t	CE_t	GIN_t	TIN_t	ICT_t	FDT_t	GDP_t
Mean	2.364	2.562	2.660	2.583	2.449	2.655	2.252
Maximum	3.718	2.949	3.317	2.836	3.306	3.323	3.267
Minimum	1.843	1.829	1.810	1.887	1.863	1.815	1.875
Std. Dev.	0.866	0.861	0.801	0.576	0.791	0.685	0.802
Jarque-Bera	0.379	0.896	0.385	0.318	1.878	0.588	1.399
Probability	0.421	0.489	0.578	0.470	0.321	0.551	0.377

Source: Author Estimation

Furthermore, Jarque-Bera is the key to determining the normal distribution of data and measuring goodness of fit, which is possible with the help of skewness and kurtosis. Here, values of Jarque- Bera are far from zero and non-negative to each studied variable. That means the distribution of data varies from variable to variable under ranges. The findings of Jarque-Bera show that each variable, EFP, CE, GIN, TIN, ICT, FDT, and GDP, is normally distributed.

A pair-wise correlation among the selected constructs is reported in Table 3, which shows a positive correlation between ecological footprint economic growth and carbon emissions. Likewise, carbon emissions with economic growth, green innovations with technological innovations, ICT with financial depth and economic growth, technological innovations with ICT, financial depth and economic growth, ICT with financial depth and economic growth, and financial depth with economic growth. However, ecological footprint is negatively associated with green innovations, technological innovations, ICT, and financial depth. Interestingly, carbon emission also negatively correlates with the same variables: green innovations, technological innovations, ICT, and financial depth. Furthermore, a significant correlation is found between "information communication and technology and technology innovation" in the United States of America. This shows that green innovation and technological innovation are closely related and interchangeable. Both can work in the same direction, in line with reducing carbon emissions and climate change impacts. However, information, communication, and technology are working toward green innovation, but it is a generalized and common technology for communication. Therefore, it facilitates green and technological innovation toward carbon reduction and attaining environmental sustainability—lastly, economic growth and development cause carbon emissions and climate change.

"Source: Author Estimation"

In the next step, we need to measure the stationarity of ecological footprint, carbon emissions, green innovations, technological innovations, information communication and technology, financial depth, and economic development. The stationarity of the above variables helps us determine the most suitable cointegration approach for investigating the cointegration nexus between carbon neutrality and its determinants. Inappropriate cointegration order of studied variables leads to unclear results and incorrect findings and implications. However, we used the ADF test for the unit root. This is most useful and impactful in the case of managing unspecified single breaks in the structure of data series and solving data sequencing errors (Carrion-i-Silvestre et al., 2009). ADF test is utilized to see what kind of integration variables are showing: stationary, first difference, and mixed.

Furthermore, ADF is the best-suited approach for dealing with a small sample size. Similarly, these tests pertaining to unit root can resolve the problem of low explanatory power by rejecting the null hypothesis, as explained by Dickey and Fuller (1981) and later by (Phillips and Perron (1988). ADF test also provides higher explanatory powers for the time series structural breaks and consistent empirical facts. Table 4 presents the measures of structural breaks with the help of the ADF method. Ecological footprint, carbon emissions, green innovations, technological innovations, information communication and technology, financial depth, and economic development contain unit root issues at the ADF level. As highlighted earlier, these standardized tests for unit root tests can reflect some deceptive results, mainly in time-series data. Therefore, we applied the ZA test to resolve this problem by considering one structural break (Zivot and Andrews, 2002). Table 4 also contains the results of ZA test. With the help of ZA (Δ) and ADF (**Δ**) we come all variables (EFP, CE, GIN, TIN, ICT, FDT, and GDP) are stationary and show differences in their structural breaks.

The results of the ARDL cointegration analysis are predicted in Table 5. The F-test and T-test results reject the null hypothesis between the studied variables by bootstrapping the ARDL approach. We reject the null hypothesis, which states that carbon emission and ecological footprint are dependent variables. To highlight the existence of cointegration vectors in carbon emission and the ecological footprint system of the USA, mostly on lagged independent and lagged dependent, the T-test and F-test were collectively and respectively used. It is also observed that ecological footprint and carbon emission have a long-term nexus with green innovations, technological innovations, information communication and technology, financial depth, and economic development in the United States of America. Moreover, values of R^2 0.526 and 0.682 depict that all the explanatory variables (green innovations, technological innovations, information communication and technology, financial depth, and economic development) explain the carbon emissions and ecological footprint. Lastly, the findings of JB test confirm the normalcy of the data distribution of research variables.

Estimations of long-run analysis are depicted in Table 6. We observe green technology innovations' significant and negative impact on carbon emissions. This negative nexus means a 1 % increase in carbon emissions, which leads to a 0.70.5 % decline in green technology innovation by keeping other variables constant. This finding supports the study of Paramati et al. (2020), who said green technology innovations reduce carbon emissions in OECD economies. The same has been reported by Jordaan et al. (2017) in the case of Canada.

Moreover, the nexus between technology innovations and carbon emissions is also significantly negative and higher than green technology innovations. The results show that technological innovations reduce carbon emissions, and a 1 % increase in technology innovations causes a 0.76.6 % decline in CO_2 emissions. This empirical finding aligns with a recent study by Sharif et al. (2023), where

Table 3
Results of Pair-wise Correlation.

Variables	EFP_t	CE_t	GIN_t	TIN_t	ICT_t	FDT_t	GDP_t
EFP_t	1.000						
CE_t	0.250	1.000					
GIN_t	−0.370	−0.283	1.000				
TIN_t	−0.237	−0.306	0.335	1.000			
ICT_t	−0.366	−0.241	0.362	0.235	1.000		
FDT_t	−0.234	−0.350	0.251	0.314	0.364	1.000	
GDP_t	0.355	0.308	0.287	0.238	0.325	0.300	1.000

Table-4
Results of Traditional and Structural Break Unit root test.

Variables	ADF (Level)	ADF (Δ)	ZA (Level)	Break Year	ZA (Δ)	Break Year
EFP$_t$	0.304	−4.731***	0.009	2009 Q3	−8.472***	2020 Q3
CE$_t$	1.842	−4.524***	−0.486	2008 Q4	−5.736***	2020 Q2
GIN$_t$	−0.752	−5.887***	1.814	2006 Q1	−6.472***	2007 Q3
TIN$_t$	−1.223	−6.164***	−1.508	2008 Q1	−7.940***	2009 Q2
ICT$_t$	0.916	−5.554***	−1.806	2005 Q4	−8.403***	2011 Q1
FDT$_t$	−0.336	−7.680***	0.178	2009 Q4	−7.092***	2017 Q4
GDP$_t$	0.148	−3.330***	−0.722	2008 Q3	−6.708***	2014 Q4

Source: Author Estimation

Table 5
Results of ARDL Analysis.

ARDL Bootstrapped						Diagnostic tests			
Designed Models	Lag length	Break Year	F_{PSS}	T_{DV}	T_{IV}	$\overline{R}^2$	Q-stat	LM (2)	JB
$CO2_t = f(GIN_t, TINt, ICT_t, FDT_t, GDP_t, INT1_t, INT2_t)$	1, 2, 2, 2, 3	2009 Q1	8.843***	−5.730***	−5.315***	0.526	2.837	1.861	0.547
$EFP_t = f(GIN_t, TINt, ICT_t, FDT_t, GDP_t, INT1_t, INT2_t)$	1, 2, 1, 2, 2	2005 Q3	9.648***	−6.086***	−6.739***	0.682	3.558	1.885	0.616

INT1=GIN*FDT and INT2=TIN*FDT

Table 6
ARDL Analysis (Long Run).

DV = $CO2_t$				DV = EFP_t		
Variable	**Coefficient**	**T-Statistics**	**P. Value**	**Coefficient**	**T-Statistics**	**P. Value**
Constant	1.339***	6.5831	0.000	1.386***	4.9523	0.000
GIN_t	−0.705***	−5.394	0.000	−0.660***	−7.083	0.000
TIN_t	−0.766***	−6.722	0.000	−0.325***	−8.503	0.000
ICT_t	−0.471***	−4.021	0.000	−0.773***	−4.864	0.000
FDT_t	−0.525***	−8.384	0.000	−0.317***	−5.842	0.000
GDP_t	0.724***	6.337	0.000	0.519***	6.647	0.000
$INT1_t$	−0.466***	−5.044	0.000	−0.712***	−5.741	0.000
$INT2_t$	−0.797***	−8.883	0.000	−0.540***	−5.847	0.000
D_t	1.142***	6.048	0.000	0.957***	7.201	0.000
R^2	0.664			0.877		
$Adj - R^2$	0.543			0.872		
Durbin Watson	2.028			1.931		
Stability analysis						
Test		**F-Statistics**	**P. Value**		**F-Statistics**	**P. Value**
x^2NORMAL		0.881	0.462		0.537	0.658
x^2SERIAL		0.637	0.663		0.548	0.511
x^2ARCH		0.741	0.418		0.744	0.434
x^2HETERO		0.710	0.313		0.514	0.625
x^2RESET		0.555	0.448		0.529	0.480
CUSUM		Stable			Stable	
CUSUMsq		Stable			Stable	

INT1=GIN*FDT and INT2=TIN*FDT

they highlighted technological innovations as a critical driver of carbon neutralization. The negative and significant nexus of carbon emissions with information communication technology financial depth is also found with respective percentages of 0.47.1 % and 0.52.5 %. However, carbon emissions have a significantly positive nexus, with only economic development at 0.72.4 %. That means a one percentage increase in GDP causes a 0.72.4 % increase in CO_2 emissions in the USA and vice versa.

Similarly, Table 6 also reported the long-run association of ecological footprint with green innovations, technological innovations, information communication and technology, financial depth, and economic development. Green innovation has a significant and negative correlation with ecological footprint. If we keep other variables constant, a 1 % increase in ecological footprint leads to a 0.66 % decline in green innovations and vice-versa. Similarly, technological innovations, information communication, technology, and financial depth show significant negative association with ecological footprints with the following percentages: 0.32.5 %, 0.77.3, and 0.31.7 %. Only economic growth positively affects the EFP by 0.51.9 %. From the long-run estimations of ARDL, it is concluded that technological innovations, information communication, and technology are boons for the United States of America in reducing carbon emissions and the country's ecological footprint. At the same time, economic development by keeping other variables constant or without counterbalance is a curve for ecological footprint and carbon emissions in the USA.

Regarding adjusted carbon emissions and ecological footprint, the explained variations are 0.543 and 0.872, respectively, via all the selected research variables. Simultaneously, no autocorrelation is confirmed by Durbin Watson's statistics for both ecological footprint and CO_2 emissions in the sample study. Hence, the present estimation is free from any issues related to specification, serial correlation, autoregressive conditional heteroskedasticity, normality, and heteroskedasticity. Stability parameters for the long run are analyzed through CUSUM and CUSUMsq, as suggested by Monk and Brown (1975).

The short-run estimations of the ARDL cointegration analysis are reported in Table 7, explaining that green innovations significantly decrease the ecological footprint and carbon emissions in the short run. Technological innovations, information communication and technology, and financial depth are negatively linked to carbon emissions and ecological footprint at a 1 % significance level in the short run. That means green innovations, technological innovations, information communication and technology, and financial depth are crucial for carbon neutrality via reducing ecological footprint and carbon emissions in the USA. Interestingly, GDP is negatively associated with carbon emissions at a 1 % significance level in the short run with 0.32.2 %. This means that economic development will reduce carbon emissions in the USA in the short run. However, economic growth is positively associated with an ecological footprint of 0.43.4 % in the short run, which is the opposite of carbon emissions. At this point, policymakers of the USA need to deal strategically with both carbon emissions and ecological footprint policies differently in the short run. In the case of the short run, there is an absence of non-specification, non-serial correlation, non-autoregressive conditional heteroskedasticity, non-normality, and non-heteroskedasticity, and variance is homoscedastic. Stability parameters are also fulfilled by CUSUM and CUSUMsq during the short run. Additionally, results of short and long-run ARDL estimations are presented with the help of Fig. 1.

Lastly, Table 8 presents the causal nexus between the studied variables examined through the VECM Granger causality approach. This approach helps forecast another time series by the present one; therefore, the significance of Granger causality cannot be ignored. In Table 8, all the proposed null hypotheses are rejected at a 1 % significance level as the value of F- statistics is significant. GIN granger causes carbon emissions, and carbon emissions cause GIN. Hence, the first null hypotheses are rejected with the F- statistics of 22.377 and 13.529.

Similarly, GIN and EFP cause Granger to each other at 1 % significance with F-statistics of 11.709 and 19.521. Likewise, both TIN and CE, TIN and EPF, ICT and CE, ICT and EFP, FDT and CE, FDT and EFP, GDP and CE, GDP and EFP, INT1 and CE, INT1 and EFP, INT2 and CE, and INT2 and EFP granger cause to each other at 1 % level of significance. With the help of Granger causality test, all the proposed hypotheses are empirically tested and predicted by one another. Suggested null hypotheses are rejected at a 0.01 (1 %) significance level. First, the homogenous cause between green innovation and carbon emission is tested. It is reported that green innovation can predict reducing carbon emissions and vice-versa. An increased level of CO_2 determines the demand for green innovation. Hence, the null hypothesis between them is rejected at a 1 % significance level. Likewise, the prediction relationship between green innovation and ecological footprint, technological innovation and carbon emission, and technological innovation and ecological footprint is tested. It also reflects the similar trends as shown by green innovation. Technological innovation predicts the reduction level of carbon and ecological footprint, and vice-versa. Similarly, information, communication, technology, financial depth, and economic development report the prediction of the relationship between carbon emission and ecological footprint. Increased ICT,

Table 7
ARDL Analysis (Short Run).

DV = $CO2_t$				DV= EFP_t		
Variable	**Coefficient**	**T-Statistics**	**P. Value**	**Coefficient**	**T-Statistics**	**P. Value**
Constant	1.236***	6.5831	0.000	1.137***	4.9523	0.000
GIN_t	−0.324***	−5.508	0.000	−0.406***	−5.679	0.000
TIN_t	−0.545***	−3.802	0.000	−0.524***	−3.849	0.000
ICT_t	−0.374***	−3.890	0.000	−0.552***	−8.483	0.000
FDT_t	−0.635***	−4.658	0.000	−0.499***	−5.235	0.000
GDP_t	−0.322***	7.947	0.000	0.434***	8.772	0.000
$INT1_t$	−0.356***	−7.988	0.000	−0.734***	−8.892	0.000
$INT2_t$	−0.712***	−7.709	0.000	−0.400***	−8.669	0.000
D_t	0.830***	6.208	0.000	0.628***	4.580	0.000
R^2	0.525			0.851		
$Adj - R^2$	0.789			0.684		
Durbin Watson	1.974			2.003		
Stability analysis						
Test		**F-Statistics**	**P. Value**		**F-Statistics**	**P. Value**
x^2NORMAL		0.755	0.486		0.808	0.421
x^2SERIAL		0.844	0.667		0.629	0.565
x^2ARCH		0.783	0.427		0.824	0.339
x^2HETERO		0.552	0.546		0.732	0.466
x^2RESET		0.898	0.683		0.513	0.385
CUSUM		Stable			Stable	
CUSUMsq		Stable			Stable	

INT1=GIN*FDT and INT2=TIN*FDT

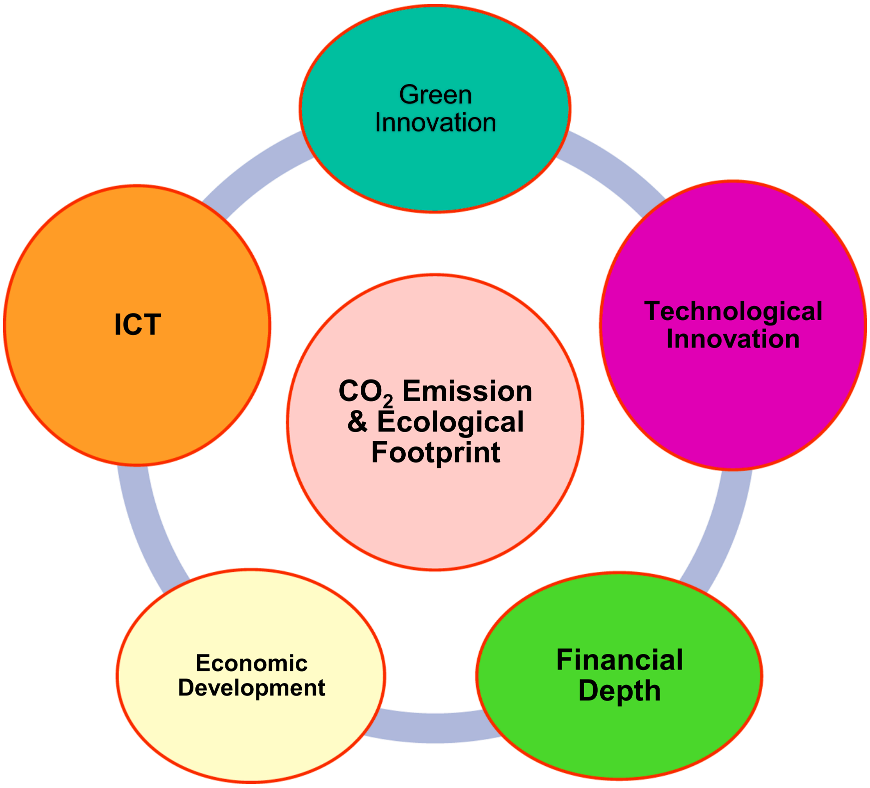

Fig. 1. Association of CO2 emission and Ecological footprint with selected variables.

Table-8
Results of Granger Causality.

Null Hypothesis	F-Statistic	Prob.
GIN does not homogenously cause CE	22.377***	0.000
CE does not homogenously cause GIN	13.529***	0.000
GIN does not homogenously cause EPF	11.709***	0.000
EPF does not homogenously cause GIN	19.521***	0.000
TIN does not homogenously cause CE	15.318***	0.000
CE does not homogenously cause TIN	16.649***	0.000
TIN does not homogenously cause EPF	17.281***	0.000
EPF does not homogenously cause TIN	19.196***	0.000
ICT does not homogenously cause CE	23.448***	0.000
CE does not homogenously cause ICT	18.132***	0.000
ICT does not homogenously cause EPF	15.112***	0.000
EPF does not homogenously cause ICT	17.954***	0.000
FDT does not homogenously cause CE	9.471***	0.000
CE does not homogenously cause FDT	11.229***	0.000
FDT does not homogenously cause EPF	8.235***	0.000
EPF does not homogenously cause FDT	24.492***	0.000
GDP does not homogenously cause CE	23.178***	0.000
CE does not homogenously cause GDP	14.956***	0.000
GDP does not homogenously cause EPF	10.070***	0.000
EPF does not homogenously cause GDP	11.730***	0.000
INT1 does not homogenously cause CE	19.028***	0.000
CE does not homogenously cause INT1	10.948***	0.000
INT1 does not homogenously cause EPF	16.289***	0.000
EPF does not homogenously cause INT1	13.119***	0.000
INT2 does not homogenously cause CE	13.334***	0.000
CE does not homogenously cause INT2	17.663***	0.000
INT2 does not homogenously cause EPF	16.623***	0.000
EPF does not homogenously cause INT2	22.640***	0.000

Source: Author Estimation;
INT1=GIN*FDT and INT2=TIN*FDT

economic development, and financial depth levels will produce the potential predictability of reducing carbon emissions, climate impacts, and ecological footprint across the different levels and quantiles. Conversely, carbon emission and ecological footprint can also confirm the necessity of ICT, as well as financial depth and economic development.

5. Conclusion and policy implications

Soon after the COP28, the USA is working on a carbon neutrality target. This study is a sincere attempt towards attaining carbon neutrality and sustainable development goal-13 (Climate Action) by investigating the nexus between ecological footprint, carbon emission, green innovation, technological innovation, ICT, financial depth, and economic development in the American economy. A significant cointegration amid ecological footprint, carbon emission, green innovation, technological innovation, ICT, financial depth, and economic development is confirmed through the empirical investigation. Green innovation, technological innovation, ICT, and financial depth negatively impact ecological footprint and carbon emissions in the long run. At the same time, the impact of economic growth is positively significant on both carbon emissions and ecological footprint in the long run.

Additionally, in the short run, green innovation, technological innovation, information communication and technology, financial depth, and economic development negatively impact carbon emissions. Besides economic growth, green innovations, technological innovations, information communication and technology, and financial depth have significant negative impacts on the ecological footprint, and economic growth positively impacts EFP. Moreover, a two-way causality among ecological footprint, carbon emission, green innovation, technological innovation, information communication and technology, financial depth, and economic development has been traced through empirical results of the causality test. Therefore, it is concluded that green technological innovation, financial depth, and ICT are the core indicators for environmental well-being and are crucial in reducing carbon emissions, ecological footprint, and climate change impacts. Conversely, economic development, CO_2 emission, and ecological footprint go hand in hand and cause adverse effects on the environment, economy, and societies.

In the sense of policy consequences, green innovation, technological innovation, information communication and technology, and financial depth have detrimental influences on the neutralization of ecological footprint and carbon emission. Therefore, the US government and policymakers must focus more on green technological innovation, ICT, and financial depth to achieve the carbon neutrality target and sustainable development goal-13. For energy production purposes, the USA should replace fossil fuels and non-renewable energy resources with green and renewable energy sources that decrease carbon emissions at a larger scale. This will also help other sectors like agriculture and manufacturing reduce greenhouse gas emissions, particularly carbon emissions. Green innovation should be a top priority for policymakers and government authorities, which was previously ignored. Findings show that economic growth fosters ecological footprint and carbon emissions in the long run. In this sense, a balancing and sustainable economic model should be designed to counterbalance the economic development without causing CO_2 and EFP.

Furthermore, results also highlight that in both the long and short run, green innovation, technological innovation, ICT, and financial depth negatively impact carbon emission and the ecological footprint. In this regard, the central government of the USA seeks active support from state and local communities to plan and promote green technological innovation, ICT, and financial depth for reducing CO_2 emissions and EFP at all levels. Results confirm that green and technological innovation significantly reduces carbon emissions and climate impacts. Hence, the environmental effect of green and technology-oriented innovations should be measured, maintained, and implemented. Additionally, the government should prepare green strategies and green innovation policies to strengthen the digital and circular economy. Initiatives of green innovation, environmentally friendly technologies, and financial depth will address the environmental and climate issues in both the short and long run. At the same time, uncertainties and risks related to developing and implementing strategic frameworks and green innovation models should be lessened via technological breakthroughs and sustainable innovation without halting economic development. A good amount of financial support must be provided for the research and developmental activities, technological innovations and financial technologies (Fintech) that help mitigate carbon emissions and climate change.

Because of economic development in the short run, findings concerning carbon emissions and ecological footprint are mixed. Since economic development positively impacts the ecological footprint and negatively impacts the carbon emissions in the short run, governments, and associated stakeholders at different levels must formulate separate policies for both carbon emissions and ecological footprint and deal with them differently in the short run. In addition to the above empirical findings, the government needs to work on some other supportable policies and strategies to control carbon emissions and ecological footprint in both the short and long run. Moreover, the empirical findings of our study cleared the fact that several challenges still stand before the government and policymakers of the USA in line with controlling the carbon emissions and ecological footprint and reducing emissions to zero. Based on these challenges, our study emphasizes the need for standing strategies and plans for green innovations, technological innovations, ICT, financial depth, and economic development to reduce carbon emissions and ecological footprint.

Moreover, higher economic growth leads to carbon emissions and ecological footprint. Therefore, economists need to propose some mitigation measures for sustainable economic development and tax subsidies to facilitate the circular and linear economy in the economic system of the USA. Policymakers should remember ecological well-being while planning budgets and economic policies that reduce pollution and environmental degradation. The USA's economic programs must be reviewed and re-implemented in more sustainable and innovative ways to constrain carbon emissions and environmental destruction. In place of economic policy uncertainty, it is reported that high economic policy uncertainty causes environmental degradation and carbon emissions. Additionally, financial depth in association with green and advanced technologies offers a comprehensive model of environmental development, carbon neutralization, and diminishing the impacts of climate change without disturbing economic development. Financial depth also provides stability to the economic system during economic crises like COVID-19 and the Russian invasion in Ukraine and regulates economic activities, environmental well-being, and societal welfare during these challenging times (Nuta et al., 2024).

Lastly, the present study is conducted with several limitations. Firstly, this work is limited to the USA only, where we attempt toward attainment of carbon neutrality through investigating the nexus between ecological footprint, carbon emissions, green innovations, technological innovations, information communication and technology, financial depth, and economic development in the American economy and no other country included in this study. Secondly, our study is limited to the following research variables: ecological footprint, carbon emissions, green innovations, technological innovations, information communication and technology, financial depth, and economic development, with ecological footprint and carbon emissions as dependent variables. Thirdly, the role of financial depth and green technological innovations on environmental sustainability is widely discussed and observed in the present literature, and the theoretical groundings of our study are set up accordingly. However, trends of any other framework, like the Environmental Kuznets Curve (EKC) and Load Capacity Curve (LCC), are missing in this work. For better policy implications and generation, we highly recommend that future studies consider this study's limitations.

Authors statement/ conflict statement

All authors have approved the manuscript title **"The role of financial depth and green technology innovation towards carbon neutrality in the USA**" and agree with its submission to this journal. The current work has not been published and is not under consideration for publication elsewhere. Moreover, there is no conflict of any interests for this study.

CRediT authorship contribution statement

Emrah Sofuoglu: Writing – original draft, Formal analysis, Data curation. **Florian Marcel Nuta:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources. **Arshian Sharif:** Writing – original draft, Supervision, Software. **Sunil Tiwari:** Writing – original draft, Data curation, Conceptualization.

Data Availability

Data will be made available on request.

References

Abban, O.J., Hongxing, Y., Nuta, A.C., Dankyi, A.B., Ofori, C., Cobbinah, J., 2022. Renewable energy, economic growth, and CO2 emissions contained Co-movement in African oil-producing countries: a wavelet based analysis. Energy Strategy Rev. 44, 100977.

Abbasi, K.R., Shahbaz, M., Zhang, J., Irfan, M., Alvarado, R., 2022. Analyze the environmental sustainability factors of China: the role of fossil fuel energy and renewable energy. Renew. Energy 187, 390–402.

Acheampong, A.O., Amponsah, M., Boateng, E., 2020. Does financial development mitigate carbon emissions? Evidence from heterogeneous financial economies. Energy Econ., 104768 https://doi.org/10.1016/j.eneco.2020.104768.

Ahmad, M., Ahmed, Z., Yang, X., Hussain, N., Sinha, A., 2022. Financial development and environmental degradation: do human capital and institutional quality make a difference? Gondwana Res. *105*, 299–310.

Alshubiri, F., Elheddad, M., Jamil, S.A., Djellouli, N., 2021. The impacts of financial depth and foreign direct investment on the green and non-green energy consumption of OPEC members. SN Bus. Econ. *1* (6), 77.

Carrion-i-Silvestre, J.L., Kim, D., Perron, P., 2009. GLS-based unit root tests with multiple structural breaks under both the null and the alternative hypotheses. Econ. Theor. 1754–1792.

Chen, W., Lu, H., Liu, X., Li, D., 2020. Financial depth or breadth: What really matters for fighting air pollution in China? Chin. J. Popul., Resour. Environ. *18* (4), 331–341.

Cheng, X., Ye, K., Du, A.M., Bao, Z., Chlomou, G., 2024. Dual carbon goals and renewable energy innovations. Res. Int. Bus. Financ. 70 (b)), 102406.

De Jong, S.P., Wardenaar, T., Horlings, E., 2016. Exploring the promises of transdisciplinary research: a quantitative study of two climate research programmes. Res. Policy *45* (7), 1397–1409.

Dickey, D.A., Fuller, W.A., 1981. Likelihood ratio statistics for autoregressive time series with a unit root. Econom. J. Econom. Soc. 1057–1072.

Du, K., Li, J., 2019. Towards a green world: How do green technology innovations affect total-factor carbon productivity. Energy Policy *131*, 240–250.

Du, K., Li, P., Yan, Z., 2019. Do green technology innovations contribute to carbon dioxide emission reduction? Empirical evidence from patent data. Technol. Forecast. Soc. Change *146*, 297–303.

Du, Q., Xue, M., Li, Z., Min Du, A., Yang, T., 2024. Economic vulnerabilities and sustainability in energy utilities: managing climate change in the face of geopolitical turmoil. Res. Int. Bus. Financ. 71, 102436. https://doi.org/10.1016/j.ribaf.2024.102436.

EIA, (2020). Where greenhouse gases come from - U.S. [WWW Document]. Energy Inf. Adm. URL 〈https://www.eia.gov/energyexplained/energy-and-the-environment /where-greenhouse-gases-come-from.php〉 (accessed 12.17.20).

El Khoury, R., Min Du, A., Nasrallah, N., Marashdeh, H., Atayah, O.F., 2025. Towards sustainability: examining financial, economic, and societal determinants of environmental degradation. Res. Int. Bus. Financ. 73, 102557. https://doi.org/10.1016/j.ribaf.2024.102557.

Gianfrate, G., Peri, M., 2019. The green advantage: exploring the convenience of issuing green bonds. J. Clean. Prod. *219*, 127–135.

Goh, S.K., Sam, C.Y., McNown, R., 2017. Re-examining foreign direct investment, exports, and economic growth in asian economies using a bootstrap ARDL test for cointegration. J. Asian Econ. 51, 12–22.

Hashmi, R., Alam, K., 2019. Dynamic nexus among environmental regulation, innovation, CO2 emissions, population, and economic growth in OECD countries: a panel investigation. J. Clean. Prod. 231, 1100–1109.

Hua, M., Li, Z., Zhang, Y., Wei, X., 2024. Does green finance promote green trnasformation of the real economy? Res. Int. Bus. Financ., 102090 https://doi.org/10.1016/j.ribaf.2023.102090.

Jiakui, C., Abbas, J., Najam, H., Liu, J., Abbas, J., 2023. Green technological innovation, green finance, and financial development and their role in green total factor productivity: empirical insights from China. J. Clean. Prod. *382*, 135131.

Jordaan, S.M., Romo-Rabago, E., McLeary, R., Reidy, L., Nazari, J., Herremans, I.M., 2017. The role of energy technology innovation in reducing greenhouse gas emissions: a case study of Canada. Renew. Sustain. Energy Rev. 78, 1397–1409.

Kahia, M., Kadria, M., Aissa, M.S.B., Lanouar, C., 2017. Modelling the treatment effect of renewable energy policies on economic growth: Evaluation from MENA countries. J. Clean. Prod. *149*, 845–855.

Kim, J., Park, K., 2016. Financial development and deployment of renewable energy technologies. Energy Econ. *59*, 238–250.
Kuang, H., Akmal, Z., Li, F., 2022. Measuring the effects of green technology innovations and renewable energy investment for reducing carbon emissions in China. Renew. Energy *197*, 1–10.
Kutan, A.M., Paramati, S.R., Ummalla, M., Zakari, A., 2018. Financing renewable energy projects in major emerging market economies: evidence in the perspective of sustainable economic development. Emerg. Mark. Financ. Trade *54* (8), 1761–1777.
Li, F., Goodell, J.W., Du, A.M., Yang, T., 2024. Ecological risk management: effects of carbon risk on firm innovation investment. Int. Rev. Financ. Anal. 95, 103514. https://doi.org/10.1016/j.irfa.2024.103514.
Li, W., Elheddad, M., Doytch, N., 2021. The impact of innovation on environmental quality: evidence for the non-linear nexus of patents and CO2 emissions in China. J. Environ. Manag. *292*, 112781.
Lin, B., Ma, R., 2022. Green technology innovations, urban innovation environment and CO2 emission reduction in China: fresh evidence from a partially linear functional-coefficient panel model. Technol. Forecast. Soc. Change *176*, 121434.
McNown, R., Sam, C.Y., Goh, S.K., 2018. Bootstrapping the autoregressive distributed lag test for cointegration. Appl. Econ. 50, 1509–1521.
Monk, T.H., Brown, B., 1975. The effect of target surround density on visual search performance. Hum. Factors 17, 356–360.
Nuta, A.C., Habib, A.M., Neslihanoglu, S., Dalwai, T., Rangu, C., 2024. Analyzing the market performance of Romanian firms: do the COVID-19 crisis and classification type matter? Int. J. Emerg. Mark. https://doi.org/10.1108/IJOEM-05-2023-0842.
Obobisa, E.S., Chen, H., Mensah, I.A., 2022. The impact of green technological innovation and institutional quality on CO2 emissions in African countries. Technol. Forecast. Soc. Change *180*, 121670.
Ozkan, O., Sharif, A., Mey, L.S., Tiwari, S., 2023. The dynamic role of green technological innovation, financial development and trade openness on urban environmental degradation in China: fresh insights from carbon efficiency. Urban Clim. *52*, 101679.
Paramati, S.R., Mo, D., Huang, R., 2020. The role of financial deepening and green technology on carbon emissions: evidence from major OECD economies. Financ. Res. Lett. 41, 101794. https://doi.org/10.1016/j.frl.2020.101794.
Pesaran, M.H., Shin, Y., Smith, R.P., 1999. Pooled mean group estimation of dynamic heterogeneous panels. J. Am. Stat. Assoc. 94, 621–634.
Pesaran, M.H., Shin, Y., Smith, R.J., 2001. Bounds testing approaches to the analysis of level nexuss. J. Appl. Econom. 16, 289–326.
Petrović, P., Lobanov, M.M., 2020. The impact of R&D expenditures on CO2 emissions: evidence from sixteen OECD countries. J. Clean. Prod. *248*, 119187.
Phillips, P.C., Perron, P., 1988. Testing for a unit root in time series regression. Biometrika 75, 335–346.
Priyan, S., 2023. Effect of green investment to reduce carbon emissions in an imperfect production system. J. Clim. Financ., 100007 https://doi.org/10.1016/j.jclimf.2023.100007.
Ramzan, M., Abbasi, K.R., Salman, A., Dagar, V., Alvarado, R., Kagzi, M., 2023. Towards the dream of go green: an empirical importance of green innovation and financial depth for environmental neutrality in world's top 10 greenest economies. Technol. Forecast. Soc. Change *189*, 122370.
Ritchie, H., Roser, M., & Rosado, P. (2022). Fossil fuels. Published online at OurWorldInData.org. 〈https://ourworldindata.org/grapher/fossil-fuels-share-energy?country=~OWID_WRL〉 (Access date: 20.02.2023).
Sadorsky, P., 2010. The impact of financial development on energy consumption in emerging economies. Energy Policy *38* (5), 2528–2535.
Sadorsky, P., 2011. Financial development and energy consumption in Central and Eastern European frontier economies. Energy Policy *39* (2), 999–1006.
Safi, A., Chen, Y., Wahab, S., Zheng, L., Rjoub, H., 2021. Does environmental taxes achieve the carbon neutrality target of G7 economies? Evaluating the importance of environmental R&D. J. Environ. Manag. *293*, 112908.
Shahbaz, M., Topcu, B.A., Sarıgül, S.S., Vo, X.V., 2021. The effect of financial development on renewable energy demand: the case of developing countries. Renew. Energy *178*, 1370–1380.
Shao, X., Zhong, Y., Liu, W., Li, R.Y.M., 2021. Modeling the effect of green technology innovation and renewable energy on carbon neutrality in N-11 countries? Evidence from advance panel estimations. J. Environ. Manag. *296*, 113189.
Sharif, A., Saqib, N., Dong, K., & Khan, S.A.R. (2022). Nexus between green technology innovation, green financing, and CO2 emissions in the G7 countries: The moderating role of social globalisation. *Sustainable Development*.
Sharif, A., Kocak, S., Khan, H.H.A., Uzuner, G., Tiwari, S., 2023. Demystifying the links between green technology innovation, economic growth, and environmental tax in ASEAN-6 countries: the dynamic role of green energy and green investment. Gondwana Res. *115*, 98–106.
Shaw, E.S., 1973. Financial deepening in economic development. Oxford University Press, Inc, New York and London.
Song, M., Wang, S., 2018. Measuring environment-biased technological progress considering energy saving and emission reduction. Process Saf. Environ. Prot. *116*, 745–753.
Su, H.N., Moaniba, I.M., 2017. Does innovation respond to climate change? Empirical evidence from patents and greenhouse gas emissions. Technol. Forecast. Soc. Change *122*, 49–62.
Su, X., Qiao, R., Xu, S., 2024. Impact of green finance on carbon emissions and spatial spillover effects: empirical evidence from China. J. Clean. Prod., 142362 https://doi.org/10.1016/j.jclepro.2024.142362.
Sun, X., Meng, Z., Zhang, X., Wu, J., 2024. The role of institutional quality in the nexus between green financing and sustainable development. Res. Int. Bus. Financ., 102531 https://doi.org/10.1016/j.ribaf.2024.102531.
Tamazian, A., Chousa, J.P., Vadlamannati, K.C., 2009. Does higher economic and financial development lead to environmental degradation: evidence from BRIC countries. Energy Policy 37 (1), 246–253.
Tao, M., Sheng, M.S., Wen, L., 2023. How does financial development influence carbon emission intensity in the OECD countries Some insights from the information and communication technology perspective. J. Environ. Manag., 117553 https://doi.org/10.1016/j.jenvman.2023.117553.
Tiwari, S., & Mohammed, K.S. (2024). Unraveling the impacts of linear economy, circular economy, green energy and green patents on environmental sustainability: Empirical evidence from OECD countries. *Gondwana Research*.
Wang, Z., Yang, Z., Zhang, Y., Yin, J., 2012. Energy technology patents–CO2 emissions nexus: an empirical analysis from China. Energy Policy 42, 248–260.
WDI, (2019). The world bank indicators [WWW Document]. WDI. URL 〈https://data. worldbank.org/〉 (accessed 12.3.19).
Xu, D., Abbasi, K.R., Hussain, K., Albaker, A., Almulhim, A.I., Alvarado, R., 2023. Analyzing the factors contribute to achieving sustainable development goals in Pakistan: a novel policy framework. Energy Strateg. Rev. 45, 101050.
Yii, K.J., Geetha, C., 2017. The nexus between technology innovation and CO2 emissions in Malaysia: evidence from granger causality test. Energy Procedia 105, 3118–3124.
Yu, X., Kuruppuarachchi, Kumarasinghe, S., 2023. Financial development, FDI, and CO2 emissionsȘ does carbon pricing matter? Appl. Edonomics 2959–2974. https://doi.org/10.1080/00036846.2023.2203460.
Yuan, X., Murshed, M., Khan, S., 2022. Does the depth of the financial markets matter for establishing green growth? Assessing Financial sector's potency in decoupling Economic Growth and Environmental Pollution. Eval. Rev. 0193841X221145777.
Zivot, E., Andrews, D.W.K., 2002. Further evidence on the great crash, the oil-price shock, and the unit-root hypothesis. J. Bus. Econ. Stat. 20, 25–44.