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Role of Financial Technology and IT Management Towards Sustainability: ARDL Analysis for United States

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Abstract

This research analyzes the intricate connections among GDP, ICT use for financial inclusion, energy conservation, urbanization, and their cumulative effect on carbon emissions in the USA from 1990 to 2022. Using unit root assessments to examine the non-stationarity of key factors, the study incorporates the ARDL method to explore both short- and long-term dynamics. The results reveal that GDP expansion and urbanization negatively impact environmental health, suggesting that increased financial activities and urban population growth contribute to higher pollution levels due to greater fossil fuel consumption and resource exploitation. Conversely, ICT adoption, financial accessibility, and energy efficiency exhibit a negative link with CO_2 emissions, indicating that advancements in technology, sustainable financing, and renewable energy integration could enhance the USA's environmental sustainability. The Pairwise causality test shows one way causality from GDP, energy efficiency, access to finance, and ICT to CO_2 emissions, with no proof of inverse causality. A bidirectional causal connection within urbanization and CO_2 emissions, adds to the significance of urban development in shaping climatic results. These outcomes underscore the necessities of ICT application, financial accessibility, and green energy investments for promoting ecological sustainability. Policymakers can use these insights to create targeted strategies that strike a balance between technological innovation, financial stability, and responsible urbanization, helping to reduce biodiversity loss and promote a cleaner, more sustainable future.

Keywords: Energy efficiency, Financial accessibility, GDP, CO_2 Emission, ARDL.

1 | Introduction

Concern for the environment is a fundamental objective for attaining Sustainable Development Goals (SDGs). To attain these aspirations, we need instruments that facilitate the attainment of SDGs and COP28 objectives [1], [2].The increasing demand for earth's resources exerts substantial strain on ecosystems,

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resulting in various ecological challenges, including abnormal weather patterns, erosion of soil, biodiversity loss, and the looming risk of rising temperatures [3], [4]. Given the significant environmental issues caused by individual energy use in recent years, the public, policymakers, and academic circles have placed considerable emphasis on transitioning to alternative power sources and mitigating Greenhouse Gas (GHG) releases. In 2023, worldwide CO_2 outputs climbed by a modest 0.1% compared to 2022, subsequent rises of 5.4% and 1.9% in 2021 and 2022, correspondingly, totaling 35.8 Gt CO_2 [5]. The United States is the second-largest generator to global pollutions of CO_2, representing over 15% of the total pollutants internationally [6]. Moreover, fossil fuels constituted approximately 87% and 83% of the USA's global energy use in 1990 and 2020, respectively [7]. Recently, the United States, established a target to minimize GHG emissions by around 27% by 2025 relative to 2005 levels [8], [9]. According to Worldometers [10], the GDP per capita in the USA, with an estimated population of 341,534,046, was $61,349 in 2022, reflecting a gain of $997 from $60,352 in 2021, which corresponds to a 1.7% shift in GDP per capita. To attain climate objectives, Washington aims for net zero emissions by 2050, with a pollution cap being the most effective and efficient way to achieve this goal. However, there is a lack of consensus at the international level regarding energy efficiency and efforts to reduce climate disruption. This investigation seeks to explore the relevant concerns and analyze the implication of energy conservation and financial accessibility in the USA on cutting CO_2 emissions.

The United States is acknowledged as the biggest polluter of CO_2 releases internationally, substantially influencing overall GHG levels in the environment. This country's pivotal role highlights its impact on ecological trends and stresses the significance of its green initiatives and mitigation measures [11]. Notwithstanding extensive global initiatives, the ratio of green energy in entire consumption of electricity was merely 17.7% in 2019; the annual rate of energy efficiency enhancement from 2010 to 2019 was a mere 1.9% [12]. The objective is to twice the worlds pace of enhancement in energy efficiency by 2030, utilizing cost effective metrics [13]. The US uses more oil per year than any other country, with an annual consumption of 913.3 million tons, 50% greater than China, the next-largest consumer [14]. Current U.S. energy use is comparable to levels observed over two decades ago. The U.S. Environmental Protection Agency calculates that this initiative has dropped CO_2 pollutions by 4 billion metric tons and conserved $500 billion on residential power expenses [15]. On the other hand, businesses ought to prioritize investment in robust databases, adopt cloud-based AI solutions to minimize costs, and uphold transparency in data usage to mitigate environmental pollution[16]. But the primary empirical and theoretical studies of financial progress show different ideas about how easy it is to get money and how healthy the environment is [17], [18]. One perspective posits that financial accessibility positively influences the ecology by enhancing the access and affordability of financial assets to address economic challenges. This will assist individuals and organizations in adopting green technologies and implementing more effective environmental practices that diminish GHG emissions [19], [20].

Because of differences in economic situations, infrastructure development, legal systems, and cultural factors, the wide technological gap makes it hard to provide fair ICT access in different areas [21], [22]. The USA has adopted innovation as a means to attain a green economy and is in the top ten most creative countries globally. Moreover, it has witnessed a rapid advancement in technological growth with respect to patent claims [23]. The North America, primarily the USA, is home to over 40 percent of the $5 trillion worldwide IT business. This sector constitutes $1.8 trillion of U.S. value-added GDP [24], [25]. Besides, ICT innovations can potentially decrease world emissions by as much as 15%. An examination of current digital applications in the energy, buildings, and transport sectors revealed reduction potentials of 6% and 12%, respectively, in worldwide settings [26]. Consequently, to minimize the destructive impact of high electricity usage and CO_2 releases in the USA, it is imperative to use ecologically sound ICT applications.

This inquiry provides several significant improvements to the corpus of modern research. Primarily, the existing study evaluating the implication of access to finance and power conservation on CO_2 emissions in the USA has predominantly focused on these variables, overlooking other significant factors, such as ICT utilization, GDP, and urbanization. Second, there is little literature on finance access in growing economies like the US. The research addresses this deficiency by exploring the consequences of the chosen factors on the environment of the USA, thus providing significant insight into the subject. The contradictory results of prior empirical studies may partially clarify this issue. Third, despite the theoretical and empirical evidence indicating that ICT utilization mitigates the detrimental impacts of numerous environmental pollutants. These worries remain relatively novel particularly for the USA, the second-largest carbon emitter. This investigation is unusual as it seeks to analyze the tripartite consequences of FA, EE, URBA, GDP, and ICT on ecosystem states. Finally, we employ a robust and modern econometric methodology utilizing the most recent data from 1990 to 2022 for both long- and short-term estimations, implementing advanced techniques such as the ARDL method. The study's findings provide useful perspectives for lawmakers in the USA and nations elsewhere to attain a sustainable environment while concurrently fostering equitable growth through a multifaceted approach to this problem.

The subsequent outline delineates the pertinent areas of the research. Section 2 delivers a detailed representation of the literature, encompassing a brief summary of related studies. The third chapter addresses the subjects and methodologies; the fourth chapter delivers the discoveries and discussions; and the last portion comprises the conclusion and its legislative suggestions.

2 | Literature Review

The intricate interconnections between CO_2 emissions and many socioeconomic aspects have been the focus of numerous current investigations in different places worldwide. We aim to highlight the creative aspects of our work, which we believe enhance the significance of this constantly evolving field of research. The following subsections gather the conclusions of prior research, which elucidate the elements affecting economic growth, financial accessibility, urbanization, energy efficiency, ICT utilization, and ecological sustainability in the USA.

Climate change is an escalating issue; such obstacles have rendered understanding of ecological damage and its determinants increasingly imperative [27]. Several papers performed in the past ten years have investigated the correlation within CO_2 emissions and GDP expansion. For example, Pattak et al. [28] reviewed the impact of nuclear power, population, and GDP on CO_2 releases in Italy from 1972 to 2021. By adopting the STIRPAT framework, they corroborate prior research by demonstrating that a 1% increment in Italian GDP causes an 8.08% rise in the release of CO_2 over time. Raihan et al. [29] examine the impact of GDP growth, fossil fuel usage, and green power implementation on CO_2 emissions in Malaysia from 1990 to 2021. Their conclusions indicate that heightened growth in economy correlates with increasing CO_2 emissions. At the same way, Ridwan et al. [30] in South Asian regions, Raihan et al. [31] within Vietnam, Ahmad et al. [32] in China, Islam et al. [33] in top nuclear energy consuming countries, Saudi et al. [34] in Malaysia also found same outcomes. Moreover, enhanced economic expansion and augmented foreign investment in nuclear power plants are anticipated to elevate ecological standards by reducing CO_2 outputs. For instance, Raihan et al. [35] analyze the correlation within rising GDP and CO_2 emissions in India from 1965 to 2022. The ARDL long-run elasticity results demonstrate that a minor spike in GDP development corresponded with a minimal fall in emissions. Furthermore, Mehmood et al. [36] assessed the GDP impact of the G-7 territories initiatives to mitigate GHG emissions from 1990 to 2020. They adopted the CS-ARDL methodology and demonstrate a negative correlation within GDP and CO_2 pollutions. However, Onwe et al. [37] determine the intricate relationships between GDP growth and Ecological Footprint (EF) in Japan by employing wavelet quantile correlation analysis. Their results indicate that growth in GDP generates uneven impacts on Japan's EF, affecting it variably across the distribution.

Energy usage not only stimulates revenue generation but also elevates the release of CO_2 [38], [39] Alternative energy represents an innovative and eco-friendly option for dependable power [40], [41]. Furthermore, advances in technology serves as the principal catalyst for heightened power usage and CO_2 emissions [42]. Adebayo and Ullah [43] use wavelet analytic techniques to demonstrate a substantially opposite relationship between CO_2 outputs and energy conservation policies, including coal and gas. Shahzadi et al. [44] explore the effects of energy conservation on the natural health within the G-7 regions from 1997 to 2021. Their findings of the Panel ARDL structure illustrate that efficient energy use adversely affects CO_2 releases. Wenlong et al. [45] analyze the implication of electricity use on the natural world across 10 Asian regions using CS-ARDL method. They discovered that energy efficiency improve the ecosystem. Likewise, several studies by Bilgili et al. [46], Jin et al. [47], Zhang et al. [48], Ehsanullah et al. [49], Akram et al. [50] demonstrates same conclusion. Robaina and Arshad [50] illustrated the effect of power conservation on reducing CO2 releases by estimating the existence of the "rebound effect" in ASEAN nations from 1990 to 2014. The researchers employed Stochastic Frontier Analysis and two-stage GMM, indicating that enhancements in energy conservation may result in elevated CO_2 outputs due to a "backfire effect" in the immediate term when rising energy demand surpasses efficiency gains.

Financial development can favorably impact the natural world through accessible, low-cost financing, green technologies, and enhanced conservation efforts [51]. For example, Bala et al. [52] examine the influence of financial accessibility on the ecosystem in the G-7 region from 2010 to 2022. They implemented the Panel ARDL and Quantile Regression methodologies, demonstrating a strong positive correlation between access to finance and the ecosystem. Abir et al. [53] reviewed the implication of FA and AI innovation on the LCF in the USA from 1990 to 2019. Their results demonstrated that FA positively affects natural health in both term. Additionally, Chaudhry et al. [54] determined the variable impacts of monetary expansion on CO_2 emissions in OECD areas from 2004 to 2017 utilizing the DCCE methodology. Enhanced access to finance has demonstrated both immediate and enduring implications on the decrease in CO_2 emissions. Conversely, Ridwan et al. [55] examine the implication of financial progress on the LCF in the USA from 1990 to 2022. The ARDL model's results show an opposite connection within FA and LCF. Raihan et al. [56] analyze the implication of technological development, and FA on CO_2 emissions in the G-7 region from 1990 to 2019. The results demonstrate that inclusion to finance elevates CO_2 releases in the selected location. Raihan et al. [57] examine the intricate interconnections between economic growth, financial stability, and CO_2 outputs in Bangladesh from 1974 to 2022. They determined that a 1% increment in monetary advancement causes a 0.39% increase in CO_2 pollutions. At the same way, Raihan et al. [58] in Indonesia, Hossain et al. [59] in Nordic region, and Zaidi et al. [60] in OECD countries observed identical results.

The advancement of creative technology has enabled the production of many items while significantly reducing the globes electricity use [61], [62]. The decrease in manufacturing expenses facilitates this [63]. The earliest body of inquiry involving the connection within ICT and the ecosystem presents numerous studies with conflicting results. The implication of ICT on CO_2 emissions exhibits heterogeneity among various research and geographic areas [64]. In this instance, Ridwan et al. [65] evaluate the impacts of monetary progress, ICT utilization, and GDP expansion on biodiversity quality in the USA from 1990 to 2019. Employing the ARDL model, they established that the application of ICT correlates favorably with the natural world. Sun et al. [66] reveal that the favorable long-term ecological effects of ICT are almost tenfold greater in wealthy countries compared to middle-income ones. Xie et al. [67] analyze the influence of ICT on CO_2 releases in the BRI regions. This study employs the DKSE technique and demonstrates that the combined use of ICT mitigates pollution levels. Additionally, Lu [68], Chen et al. [69] Awan et al. [70] Ahmed et al. [71], Wang and Xu [72] and Usman et al. [73] illustrate same conclusion. On the other hand, Rahman and Ferdaous [16] investigate the probable link within ICT and CO_2 emissions in 28 countries from 1998 to 2019. They use the panel ARDL simulation to demonstrate that ICT development causes an increment in CO_2 outputs. However, MENA and OECD countries illustrated an encouraging correlation between ICT diffusion and CO_2 emissions, while SAARC countries identified a negative correlation. In a similar vein, Nguyen et al. [74] in G-20 countries, Godil et al. [75] within Pakistan, and Cui et al. [76] within China also observed the negative relation between ICT utilization and ecological condition. However, several studies by Faisal et al [77] in rapidly emerging regions and Raheem et al. [78] in G-7 economies have not reached a definitive judgment about the pertinent connection.

One of the most notable benefits of urbanization is the possibility for enhanced production and efficiency [79]. Urbanization (URBA) influences the atmospheric carbon patterns in ecological regions by altering business operations, lifestyles, and utilization of land [80], [81]. Ridwan et al. [82] examine the implication of AI innovation and urbanization on ecological health in G-7 countries from 2010 to 2022. By using the MMQR and demonstrates that urbanization dramatically diminishes ecosystem quality. Raihan et al. [83] explore the implication of URBA on CO_2 outputs in China utilizing the ARDL approach. They revealed that extensive urbanization diminishes ecosystem condition. Similarly several researchers also aligns with this outcome such as Raihan et al. [6] in USA, and Song et al. [84] in China. Conversely, Shahbaz et al. [85] reviewed the implication of URBA on CO_2 releases by utilizing the STIRPAT structure in Malaysia from 1970 to 2011. They observed a U-shaped link between URBA and CO_2 outputs, indicating that URBA primarily decreases CO_2, but above a specific threshold, it results in a spike in pollutions. Anser et al. [86] used the Fourier testing methods to explore the consequences of URBA on CO_2 outputs in Finland from 1990 to 2020. The empirical investigation illustrated that URBA decreased CO_2 emissions. Moreover, Zhang et al. [87] observe the implications of new-type URBA on CO_2 emissions in northern China from 2012 to 2019. Their discovery implies that CO_2 emissions decline by 7.58% for each 1% increase in urbanization. Additionally, Haseeb et al. [88] illustrate the consequence of URBA on CO_2 outputs in the BRICS region from 1995 to 2014. They adopted the FMOLS simulation and suggested that URBA had no substantial impacts on the biodiversity.

As per as we aware no analyses have been executed on the connections within CO_2 emissions, financial accessibility, energy efficiency, ICT use, economic expansion, and urbanization in the USA. Scholars in these domains have conducted individual investigations, but they have not effectively integrated their findings. Previous studies revealed numerous deficiencies, particularly a lack of thorough evaluations of the link among financial availability, energy conservation, and CO_2 releases in the USA. The savings in energy can diminish pollution levels by reducing power use, hence decreasing the quantity of fossil fuels combusted for producing energy. Furthermore, access to funding facilitates development in green technologies and ethical behaviors, consequently diminishing CO_2 emissions. These elements comprise finances and energy savings, representing a novel area of inquiry from the viewpoint of the USA. This paper investigates the connection across FA, EE, and the natural world, employing robust statistical techniques, such as the ARDL technique, to address these inadequacies. By analyzing these techniques, the USA can find out whether improving innovations in technology, integration of finance, and economic expansion could potentially reduce carbon emissions and align with global trends towards enhanced ecological responsibility.

3 | Methodology

The article seeks to observe the complex relationships among the chosen parameters for the USA. The study sourced the CO_2 emission, the endogenous factor, from the reputable World Development Indicators (WDI). The WDI supplied GDP and urbanization data, while reputable sources like Our World in Data gave data related to energy efficiency and ICT. Furthermore, the IMF provided the data on financial accessibility.

Table 1. Data and variables.

Variables	Details	Log Form	Measurement	Source
CO_2	CO_2 Emission	LCO_2	CO_2 Emission (kt)	WDI
GDP	Gross domestic product	LGDP	GDP per capita (current US$)	WDI
EE	Energy efficiency	LEE	Total number of patents in renewable energy technologies	Our World in Data
FA	Financial accessibility	LFA	Financial accessibility index	IMF
ICT	Technological innovation	LICT	ICT good imports (% of total goods imports)	Our World in Data
URBA	Urbanization	LURBA	Urban Population (% of total population)	WDI

The IPAT structure serves as a layout for evaluating the effects of financial activities on ecosystems and power consumption [89]. Numerous researchers have recognized this strategy as a valid option, including Owusu et al. [90], Li et al. [91], and Wu et al. [92] in various regions. The model employs an effect-based model to assess the ecological effects caused by population factors, affluence, and technological progress [93]. This examination is conducted from the perspective of aspects including population growth, financial conditions, and progress in technology. The basic formation for this model is like below:

$$I = \int PAT. \tag{1}$$

The STIRPAT model permits the incorporation of further independent variables, like power consumption and business structure, in order to explore the consequences of various elements on the natural world [94]. In this work, we utilized CO_2 emissions as a surrogate for ecological damage.

$$I_i = C.P_i^{\beta}.A_i^{\gamma}.T_i^{\delta}.\varepsilon_i \tag{2}$$

$$ED = f(\text{Population, Affluance, Technology}). \tag{3}$$

In conjunction with exogenous characteristics, we added the ecological effects and utilized CO_2 emissions as a substitute measure. To derive *Eq. (4),* execute the subsequent process:

$$EFP_{it} = \alpha_0 + \alpha_1 GDP_{it} + \alpha_2 EE_{it} + \alpha_3 FA_{it} + \alpha_4 ICT_{it} + \alpha_5 URBA_{it}. \tag{4}$$

Here, GDP illustrates economic growth, EE means energy efficiency, FA indicates access to finances, ICT represent technological innovation and URBA for urbanization. In *Eq. (4)* we included α_1 to α_5 for coefficients of the exogenous factors and α_0 indicate the intercept term. The logarithmic version of the elements is incorporated in *Eq. (5)* to confirm normal distribution.

$$LEFP_{it} = \alpha_0 + \alpha_1 LGDP_{it} + \alpha_2 LEE_{it} + \alpha_3 LFA_{it} + \alpha_4 LICT_{it} + \alpha_5 LURBA_{it}. \tag{5}$$

To achieve trend stationarity, unit root testing can determine whether to incorporate non-stationary data into unpredictable time series before regression [95]. The existence of a time trend in time series data results in erroneous regression outcomes [96]. Furthermore, data exhibit non-stationarity in the presence of a trend, thereby distorting the findings of estimations [97]. The study used the P-P, the DF-GLS and the ADF unit root test [98] to check if the data sample was stationary. The ADF method has gained popularity due to its capacity to manage serial autocorrelation. Each evaluation was conducted utilizing the level and initial difference methodologies.

This investigation utilizes the ARDL bound [99] test to ascertain the cointegration across parameters. The ARDL model exhibits no residual correlation and effectively addresses both serial correlation and variability, mitigating concerns over the endogeneity problem [100]. This approach is beneficial in any scenario that involves the integration of exploratory sequences [101]. Moreover, it is especially suitable in situations with small sample sizes, as it produces solid and consistent predictions regardless of the limited number of observations [102]. The existing approach is highly adaptable and applicable for the analysis of I(0) and/or I(1) data series. Furthermore, this technique is a single-equation assessment that is simple to modify and comprehensible [103]. The below equation represent the long run scenario:

$$\begin{aligned}\Delta LCO_{2t} = {} & \delta_0 + \delta_1 LCO_{2t-1} + \delta_2 LGDP_{t-1} + \delta_3 LEE_{t-1} + \delta_4 LFA_{t-1} + \delta_5 LICT_{t-1} + \\ & \delta_6 LURBA_{t-1} + \sum_{i=1}^{p} \gamma_1 \Delta LCO_{2t-i} + \sum_{i=1}^{p} \gamma_2 \Delta LGDP_{t-i} + \sum_{i=1}^{p} \gamma_3 \Delta LEE_{t-i} + \\ & \sum_{i=1}^{p} \gamma_4 \Delta LFA_{t-i} + \sum_{i=1}^{p} \gamma_5 \Delta LICT_{t-i} + \sum_{i=1}^{p} \gamma_6 \Delta LURBA_{t-i} + \varepsilon_t\end{aligned} \tag{6}$$

After establishing long-term associations, we analyze the ECT and short-term linkages adopting the Engle and Granger [104] ECM structure. *Eq. (7)* employs the ARDL analysis, along with ECM term to clarify the short-term relationship between the factors.

$$\Delta LCO_{2t} = \delta_0 + \delta_1 LCO_{2t-1} + \delta_2 LGDP_{t-1} + \delta_3 LEE_{t-1} + \delta_4 LFA_{t-1} + \delta_5 LICT_{t-1} + \delta_6 LURBA_{t-1} + \sum_{i=1}^{p} \gamma_1 \Delta LCO_{2t-i} + \sum_{i=1}^{p} \gamma_2 \Delta LGDP_{t-i} + \sum_{i=1}^{p} \gamma_3 \Delta LEE_{t-i} + \sum_{i=1}^{p} \gamma_4 \Delta LFA_{t-i} + \sum_{i=1}^{p} \gamma_5 \Delta LICT_{t-i} + \sum_{i=1}^{p} \gamma_6 \Delta LURBA_{t-i} + \varphi ECM_{t-1} + \varepsilon_t \quad (7)$$

To ascertain significant issues potentially impacting the accuracy of the estimated coefficients, many diagnostic techniques were utilized, comprising the Lagrange Multiplier (LM), the Jarque-Bera (JQ) [105], and the Breusch-Pagan-Godfrey (BPG) [106] tests. The JQ test affirms the normalcy of the residuals [107]. To make certain that errors don't correlate with time, the LM test checks residuals for serial correlation. This helps to avoid distorted and deceptive findings. Moreover, heteroscedasticity may result in incorrect projections and standard errors when employing the BPG test.

The paper employs the Pairwise Granger causality test, a predictive analysis-based statistical framework for causation that offers distinct benefits compared to other time-series research methods. Establishing a causal link between X and Y requires a significant divergence of X's past and present values from 0 [108]. The causality between Y and X adheres to identical principles; deviations from zero signify mutual causation. *Eq. (8)* demonstrates that Xt and Yt exhibit a causal relationship.

$$E(Y_{t+h} | J_t, X_t) = E(Y_{t+h} | J_t). \quad (8)$$

Here, Jt denotes the collection of data obtained from all results up to a specific period (t).

4 | Result and Discussion

Table 2 delineates the statistical characteristics of the factors in question. Due to the uniformity of observations (32) across all data points, the table provides a comprehensive analysis of essential statistical metrics. All elements had positive means, with LCO_2 having the highest mean and LICT the smallest. Moreover, the standard deviations of all factors were minimal, signifying negligible variation over time and a major concentration of data values towards the average. Additionally, LEE had positive skewness, while the other factors displayed negative skewness. Finally, we conducted the JQ normality test to confirm that each variable in this study exhibited a normal distribution.

Table 2. Descriptive statistics of the variables.

Statistic	LCO_2	LGDP	LEE	LFA	LICT	LURBA
Mean	15.46444	10.64393	9.403704	4.290778	2.625053	4.377885
Median	15.45192	10.7188	9.273403	4.322085	2.631195	4.382195
Maximum	15.56919	11.1594	10.35565	4.38564	2.87106	4.41731
Minimum	15.27889	10.0812	8.515792	4.09312	2.26755	4.32148
Std. Dev.	0.080244	0.318771	0.734061	0.091946	0.132526	0.027091
Jarque-Bera	1.338404	1.994607	3.961013	7.016431	1.209162	2.080701
Probability	0.512117	0.368873	0.137999	0.02995	0.546303	0.353331
Observations	32	32	32	32	32	32

Table 3 presents the stationarity assessments for the log-transformed components at both I(0) and I(1) stages. It illustrates that ICT utilization and urbanization are stationary at level I(0), with significance levels of 5% and 1%, correspondingly. Conversely, LCO_2, LGDP, LEE, and LFA exhibited non-stationarity at I(0) but became stationarity following first differencing I(1). Given the diverse sequence of insertion, researchers will implement the ARDL approach for evaluation in the subsequent chapter.

Table 3. Stationarity check.

Variables	ADF		P-P		DF-GLS		Decision
	I(0)	I(1)	I(0)	I(1)	I(0)	I(1)	
LCO_2	0.943	-4.955***	0.765	-4.068***	0.541	-3.031**	I(1)
LGDP	-0.877	-4.845***	-0.82	-4.321***	-0.741	-4.001***	I(1)
LEE	-1.108	-4.652***	-1.065	-4.650***	-1.206	-4.753***	I(1)
LFA	-2.131	-4.141***	-2.451	-4.076***	-2.061	-4.240***	I(1)
LICT	-3.052**	-5.068***	-3.076**	-5.765***	-3.054**	-5.781***	I(0)
LURBA	-4.867***	-5.234***	-4.821***	-5.871***	-4.879***	-5.981***	I(0)

Note: ***$p < 0.01$ and **$p < 0.05$.

The conclusions of the ARDL limit tests are demonstrated in *Table 4*, where the F-statistic—a test statistic—is stated to be 6.7680. At the 10% significance level, the critical values for the lower bound, I(0), and the upper bound, I(1), are 2.08 and 3.00, respectively. These values indicate the threshold ranges for testing the null hypothesis of no level relationship in the context of bound testing. In a similar vein, the critical values for both integration orders at the 5%, 2.5%, and 1% significance levels are given. This indicates an ongoing connection among the selected parameters. These results facilitate appreciation of possible interdependence and over time fluctuations among the selected factors within the examined scenario.

Table 4. Results of ARDL bound test.

	F=6.7680	k=5
Significance level	I(0)	I(1)
10%	2.08	3
5%	2.39	3.38
2.50%	2.7	3.73
1%	3.06	4.15

Once the bound testing procedure revealed that they are cointegrated, we can evaluate their long-term relationship. According to *Table* 5, for every 1% increment in growing GDP, the environmental state degrades by 0.126% over time and by 0.171% in the immediate term. Given that the LGDP coefficient is both positive and statistically significant at 1 % level, we demonstrate that the ecological condition of US decorates as GDP increases. Growth in the economy frequently results in heightened industrial production and usage of electricity, which predominantly depend on fossil fuels, culminating in elevated releases of CO_2 emissions. Most of the authors like Caglar et al. [109] in USA, Daniyal et al. [110] within Pakistan, Adebayo & Kirikkaleli [111] in Japan, Borsha et al. [112] Bangladesh, Ali et al. [23] in USA corroborated with our conclusion and stated that GDP degrade the environment. Conversely, few analyses shows beneficial consequences of GDP on ecosystem health such as Acheampong et al. [113], Guo et al. [114], and Destek et al. [115] in different regions.

Conversely, the estimated coefficient for LEE, there is an inverse link between CO_2 emission and energy conservation, which supports ecological soundness in the USA. Specifically, a 1% upsurge in LEE results in a 0.015% reduction in CO_2 emissions over an extended period and a 0.321% drop over the initial period. The implementation of technological innovations can enhance business activity, decrease energy consumption, and mitigate alternative power expenses [116]. Moreover, energy conservation minimizes CO_2 emissions by decreasing power demand for tasks and activities; hence, reducing fossil fuel use. This results in fewer emissions of GHGs due to decreased usage of fuel for equivalent performance.

Our result is corroborate with those of researches performed by Shahzad [117], Baloch et al. [118], Yao et al. [119], Yasmeen et al. [120] and Adebayo et al. [121]. The transition from conventional to renewable energies is presently a key component of the global political strategy. However, the recognition of unpredictable global events has made the shift to cleaner energy a significant issue [122]. Likewise, LFA and LCO_2 were observed to have a strong inverse connection, according to the findings.

This serves as evidence that each 1% improvement in FA results in a 0.361% reduction in the short term and 0.321% less CO_2 pollution in the long term. Since the United States achieves financial growth, it plays an important part in protecting the environment. Moreover, access to financing decreases CO_2 emissions by facilitating funding for greener innovations and energy-efficient initiatives. It additionally promotes cost-effective structures and environmental behaviors, resulting in a fall of total CO_2 outputs. Studies by Zeraibi et al. [123], Singh et al. [124], Wei et al. [125], and Adams et al. [126] also illustrated the beneficial implication of ICT on the natural health. However, Hafeez et al. [127], Nuta et al. [128] and Usman et al. [129] have reached the opposite conclusion, holding that monetary development cause more pollution in the surrounding.

Furthermore, the LICT coefficients suggest that application of ICT in both time periods has favorable consequences on ecosystem condition. Specifically, each 1% expansion in LICT will cause 0.261% and 0.227% cut in LCO_2 accordingly. In both cases, the result is significant at 1% significance level. Multiple authors such as Danish et al. [130], Haseeb et al. [131], Amari et al. [132], and Raheem et al. [78] aligns with our result.

The proliferation of ICTs has numerous repercussions on humans and the surroundings. Moreover, ICT can stimulate greater GDP expansion and urbanization, which are phenomena linked to biodiversity loss, including the emission of CO_2 [133]. Gyamfi et al. [134] also observed that ICT is not favorable for the natural world in their examination. On the contrary, the findings presented in *Table 5* reveals that increased urban population degrades environmental quality in the USA.

An extra 1% expansion of LURBA will cause a 0.135% long run and 0.063% immediate rise in carbon emission. Moreover, the finding is significant at 1% in the short run but it is insignificant overtime. One potential reason for this is that urbanization elevates CO_2 emissions due to greater usage of energy from logistics, manufacturing, and household operations. Multiple researchers aligned with our findings such as Musah et al. [135], Tanveer et al. [136], Cetin et al. [137], Nathaniel et al. [138], and Mahmood et al. [139]. However, Xie et al. [67], Acheampong [140], Voumik et al. [141], Kocoglu et al. [142], Chien et al. [143], and Khan et al. [144] demonstrated that urbanization is not harmful for the environment state.

Table 5. Short-run and long-run estimation.

Variables	Long-run	Short-run
LGDP	0.126***(0.635)	
LEE	-0.015***(0.089)	
LFA	-0.321**(4.916)	
LICT	-0.261***(0.567)	
LURBA	0.135 (0.243)	
D.LGDP		0.171***(0.245)
D.LEE		-0.321**(7.768)
D.LFA		-0.361***(0.264)
D.LICT		-0.227***(0.287)
D.LURBA		0.063***(0.074)
ECT (Speed Adjustment)		-0.350***(0.625)
Constant		30.264(23.868)
R-square	0.854	

Note: ***p < 0.01 and **p <0.05.

Table 6 summarizes the results of the diagnostic assessments, showing that none of the tests led to the rejection of their respective null hypotheses. The JB test, with a p-value of 0.1031, confirms that the residuals are normally distributed. Similarly, the LM test yields a p-value of 0.2031, suggesting no evidence of serial correlation in the residuals. Additionally, the BPG test, with a p-value of 0.4521, verifies that heteroscedasticity is absent in the residuals.

Table 6. Results of diagnostic test.

Tests	Coefficient	p-value
Jarque Bera test	0.23152	0.1031
Lagrance Multiplier test	0.09721	0.2031
Breush Pagan Godfrey test	0.65097	0.4521

Table 7 delineates the causal linkages among several factors. The research indicates that LGDP does not cause Granger-cause LCO_2, as evidenced by an F-statistic of 4.95437 and a p-value of 0.0154. This outcome indicates that, at the 5% significance threshold, we may dismiss the null hypothesis that there prevails no causal link within LGDP and LCO_2. Furthermore, the data demonstrates a unidirectional causality from LEE, LFA, and LICT to LCO_2, which is supported by p-values below the standard significance level. Therefore, we may dismiss the null hypothesis of no causal association in these instances. Conversely, p-values beyond the traditional significance level indicate the absence of causality from LCO_2 to LGDP, LEE, LFA, and LICT. It indicates that variations in LCO_2 do not affect GDP growth, energy efficiency, economic availability, or ICT utilization. We identified bidirectional causation between LURBA and LCO_2, as shown by the P value below 0.05, which rejects the null hypothesis asserting the dearth of causal associations. Furthermore, this result underscores that alterations in urbanization might influence the release of carbon or vice versa.

Table 7. Pairwise causality test.

Null Hypothesis	Obs	F-Statistic	Prob.
$LGDP \neq LCO_2$	30	4.95437	0.0154
$LCO_2 \neq LGDP$		0.84108	0.4431
$LEE \neq LCO_2$	30	4.28132	0.0252
$LCO_2 \neq LEE$		0.74277	0.4861
$LFA \neq LCO_2$	30	6.32427	0.006
$LCO_2 \neq LFA$		0.41755	0.6632
$LICT \neq LCO_2$	30	10.79	0.0004
$LCO_2 \neq LICT$		0.06163	0.9404
$LURBA \neq LCO_2$	30	4.11134	0.0286
$LCO_2 \neq LURBA$		5.14024	0.0135

5 | Conclusion and Policy Implications

The article examined the detailed connections among GDP, the utilization of ICT for financial accessibility, energy conservation, urbanization, and their impacts on CO_2 emissions in the USA from 1990 to 2022. Initially, we used various unit root assessments such as ADF, P-P, and DF-GLS to determine the non-stationarity of the factors. This facilitated the inspection of both short-term and long-term influences through the innovative ARDL technique. Ultimately, three diagnostic procedures were utilized to assess heteroscedasticity and autocorrelation concerns within the selected dataset. The results of the ARDL calculation reveal several key conclusions. The results demonstrated that GDP expansion and urbanization had a destructive correlation with ecological health in both the short and long term. These findings suggest that the growth of economical operations and the increment in urban population will intensify emission as they consume more fossil fuels and earthly resources. On the other hand, using ICT, having access to money, and being energy efficient all had a negative connection with CO_2 emissions. This implies that using new technologies, making progress in sustainable financing, and incorporating renewable energy properly into both residential and industrial processes can improve the USA's environmental health. The Pairwise Granger causality analysis indicated a unidirectional causality from LGDP, LEE, LFA, and LICT to LCO_2. Nonetheless, there is no proof that LCO_2 Granger causes LGDP, LEE, LFA, and LICT; however, a bidirectional causal link was identified between LURBA and LCO_2. These links underscore the impact of expenditures in ICT development, financial accessibility, and funding for green power conservation on the ecological viability of the USA. Consequently, authorities can formulate specific strategies and regulations to mitigate the loss of biodiversity while fostering advanced technical advancements, a robust fiscal framework, and responsible urban development in the field of interest.

To enhance environmental sustainability while maintaining economic growth, policymakers should prioritize strategic investments in ICT development, financial accessibility, and energy efficiency. Given the findings that GDP growth and urbanization contribute to higher CO_2 emissions, regulations must be implemented to promote low-carbon urban planning and resource-efficient industries. Authorities should incentivize the adoption of renewable energy in residential and industrial sectors through tax credits, subsidies, and stricter emission controls. Expanding financial accessibility will facilitate green investments and sustainable economic practices, ensuring a transition to a low-carbon economy. Additionally, fostering ICT integration can optimize energy consumption, reduce emissions, and enhance smart city initiatives. Given the bidirectional causality between urbanization and CO_2 emissions, urban policies should emphasize sustainable infrastructure, public transportation, and green building standards. Strengthening the link between technological advancements and environmental sustainability requires targeted policies promoting research and development in energy-efficient innovations. Moreover, the government should establish stringent emission monitoring systems and enhance public awareness of eco-friendly practices. By implementing these policy measures, the USA can mitigate biodiversity loss, reduce carbon footprints, and foster economic resilience through sustainable industrial growth and urban planning. A balanced approach integrating economic progress with environmental responsibility is essential for long-term ecological and economic stability.

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Author Contributaion

Tasneem Hossain and Asif Khan Emon conceived the study and drafted the manuscript. Abdullah Al Abrar Chowdhury and Azizul Hakim Rafi contributed to data collection and analysis. Sheikh Shoaib Uddin Sayem provided methodological guidance and critical revisions. Md Sahariar Alam supervised the project and finalized the manuscript. All authors reviewed and approved the final version.

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