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RESEARCH ARTICLE

Leveraging AI for a Greener Future: Exploring the Economic and Financial Impacts on Sustainable Environment in the United States

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Abstract
In response to increasing environmental challenges, the United States has deliberately adopted technical advancements to promote sustainable development. This includes efforts to decrease pollution, improve energy efficiency, and encourage the use of environmentally friendly technology in different industries. This study investigates the role of Artificial Intelligence (AI) technology in promoting environmental sustainability in the United States from 1990 to 2019. It also examines the impacts of financial development, ICT use, and economic growth on the Load Capacity Factor (LCF). Various unit root tests revealed no unit root issues and mixed integration orders among variables. The Autoregressive Distributive Lag (ARDL) model explored cointegration, indicating long-run relationships among the variables. The ARDL findings confirm the Load Capacity Curve hypothesis for the United States, with AI technology and ICT use positively correlating with LCF in both the short and long run. Conversely, financial development and population growth significantly reduce LCF. Robustness checks using FMOLS, DOLS, and CCR estimation approaches align with the ARDL results. Granger causality tests reveal unidirectional causality from economic growth, AI, financial development, and ICT use to LCF and bidirectional causality between population and LCF. Diagnostic tests confirm the results are free from heterogeneity, serial correlation, and specification errors. This study underscores the importance of AI and ICT in enhancing environmental sustainability while highlighting the adverse impacts of financial development and population growth on LCF.

Keywords: Artificial Intelligence; Financial Development; ICT Use; Load Capacity Factor; United States

Introduction

In the modern world, environmental deterioration is a reason to be concerned (Usman et al., 2020). The main driver of rising temperatures, which promotes climate change, is fossil fuel breakdown (Isfat and Raihan, 2022; Polcyn et al.2023). Our planet will suffer tremendously due to this temperature rise phenomenon, with severe weather events, increasing sea levels, and the eventual extinction of numerous species (Raihan and Tuspekova, 2022; Pattak et al.2023).

The implications of global warming and strategies to lessen their effects on the ecosystem as a whole were explained by Rafindadi et al.(2018), Alola et al.(2019a, 2019b), and Raihan et al.(2024a). To mitigate such catastrophic repercussions, organizations and lawmakers must set policies in effect focused on reducing emissions of carbon dioxide. This may be implemented by boosting the efficiency of energy usage as well as transitioning to a more sustainable power system (Tian et al., 2022; Voumik and Ridwan, 2023). The second-highest CO_2 generator in the globe, underlying China, with around 4833.1 million tons of emissions, and the third-largest transmitter of CO_2 per individual is the USA (Germanwatch, 2019). The USA has a 133% shortage in biological capacity, which indicates that the ecological footprint exceeds the biocapacity (Alola et al.,2020). By 2018, the contribution of primary power utilized globally derived from fossil fuels, nuclear power, and green energy sources was around 85%, 4%, and 11%, respectively (BP, 2019). Due to the burning of fossil fuels, this overreliance on natural energy sources creates severe ecological issues like air pollution, rising temperatures, and climate (Bilgili et al.2017; Danish and Ulucak 2020). Moreover, the country has the biggest GDP in the globe and spends a lot of money on its power system (Danish and Ulucak , 2021). Thus, the World Bank (2020) revealed that in 2018, the US economy's share of the global GDP (constant 2010 USD) was around 21.6%. The alarming data mentioned earlier inspired this author to investigate the environmental sustainability of the USA, even despite the nation's abundance of clean energy sources and the adoption of legal initiatives intended to promote environmental sustainability. In order to combat global warming and fostering sustain prosperity, policymakers must recognize the country's ability to minimize pollution. How the USA can cut emissions is an urgent issue, which might be accomplished by assessing the implications of financial development, ICT utilization, and AI innovation on the LCF. For monitoring, anticipating, and reducing ecological risks, artificial intelligence (AI) is now a transforming force (Rane, 2023; Kunduru, 2023; Ukoba and Jen, 2022; Bahroun et al., 2023). Nonetheless, ICT can decrease damage to the environment by boosting public awareness of sustainability issues while encouraging the utilization of innovative technologies (Plepys, 2002; Laschkarizadeh and Salatin, 2012).

Conversely, the ecological footprint solely considers the demand side of the natural ecosystem and ignores its supply side (Adebayo and Samour, 2024; Voumik et al.2023a). To get over this issue, multiple research studies such as Pata (2021), Shang et al. (2022), and Xu et al. (2022) considered the level of ecology by utilizing the LCF to provide precise information on the quality of the environment. Furthermore, Siche et al. (2010) and Pata (2021) considered an LCF less than one, suggesting that the present biodiversity condition is not green, but a value greater than 1 indicates that the current system is stable. As a result, the sustainability limit is 1 (Akadiri et al.,2022). According to Worldometer (2024), 339,996,563 people are expected to live in the United States by the halfway point of 2023. Furthermore, the population (281,984,165 in 2023) constitutes 4.23% of the global population, and about 82.9% of the people reside in urban areas. In 2022, the United States' GDP expanded by 2.1%, the highest yearly growth since 1984 in 2021 (ECLAC,2023). However, global carbon emissions must drop by 7.6% annually to stay beneath the 1.5 °C rise in temperatures beyond the era of industrialization, which signals the existence of the biggest disastrous ecological risks (Evan, 2020; UNEP, 2021 IPCC, 2018). Researchers in the fields of software development and digital innovation are growing increasingly engaged in using ICT to promote awareness and boost sustainable endeavors and behaviors (Adisa and Porras, 2024; Ridwan et al.2024). Asongu et al. (2018), for instance, underlined how modern technological solutions might encourage clean environments, specifically in poor nations, by rendering education more accessible and spreading ecological practices.

Using AI to its full potential will enable us to reduce ecological damage, maximize the utilization of resources, and uncover new insights (Akter,2024; Voumik et al.2023b). According to a 2018 Microsoft/PwC study, for instance, using AI for sustainability initiatives might raise global economic output by 3.1% to 4.4% while cutting GHG pollution by 1.5% to 4% by 2030 (Microsoft, 2018; Hasan et al.2024). Moreover, cities can shift toward a more circular economy model, minimizing environmental effects and boosting sustainability, by using AI for garbage reduction and recycling (Verma et al.,2022; Magazzino et al.,2021; Rana et al.2024). Artificial intelligence (AI) tools can also aid in predicting severe weather conditions that are getting more frequent due to global warming, such as forest fires (Jaafari et al. 2019), extreme rainfall damage (Choi et al. 2018), and the level of human movement (Robinson and Dilkina 2018; Shium et al.2024a). Frequently, artificial intelligence (AI) methods can boost present forecasting as well as prediction systems. For instance, they can be used to automatically label information obtained from climate simulations (Chattopadhyay et al. 2020) and distinguish across indicators and noise in the assessment of climate change (Barnes et al. 2019). Both developed and emerging nations' GDPs are greatly impacted by the monetary sector (Haseeb et al., 2018; Shium et al.2024b). An efficient financial system draws in investors, strengthens the stock market, and increases the productivity of economic activity (Sadorsky, 2011). Furthermore, a substantial amount of empirical research suggests that growth in finances is influencing the quality of the natural ecosystem (Khan et al., 2018; Charfeddine and Kahia, 2019). Our research contributed to several distinctive perspectives. First off, the United States' huge population has accelerated economic growth and exacerbated ecological concerns. Second, the environmental effects of these factors will fluctuate considerably depending on different levels of financial development and AI technology in the USA. Therefore, goals related to sustainability might shift as development moves forward. Thirdly, this research contrasts with other studies like Dahmani et al. (2023), which emphasized multiple environmental variables in that it examines the expected advantages of ICT, AI innovation, and financial development on LCF. Furthermore, compared to the Ecological Footprint (EF), LCF offers an advanced approach to accounting for biodiversity loss. The combined effect of ICT use and AI innovation is significant in the context of ensuring ecological viability in the USA, and its implementation of the LCC hypothesis offers an exceptional contribution. In conclusion, the ARDL method is adopted in this study to explore the implications of several indicators and to assure robustness. FMOLS, DOLS, and CCR techniques are also utilized. Depending on the outcomes, we discuss the policy implications for enhancing environmental sustainability.

This investigation is structured into several key sections. The "Literature Review" provides an overview of relevant studies. The "Data and Methodology" section details the data sources and empirical techniques used for analysis. Findings and their interpretations are presented in the "Results and Discussion" section. Finally, the "Conclusion and Policy Implications" section offers concluding insights and recommendations for further research on green ecosystems.

Literature Review

Numerous experiments looked at how the usage of ICT, financial development, and GDP expansion affect the LCF. While multiple studies have used the ARDL framework, most of the studies have focused on how population density and advances in technology affect environmental quality. Other studies examined the link between the globalization of finance, ICT usage, and LCF; however, the variable innovation in AI has received less attention in those studies. Thorough research remains inadequate in the US literature on AI innovation and environmental sustainability. Nonetheless, a few previous investigations have offered insight into the factors and techniques of investigation applied. The next part goes over a few of those queries.

Substantial monetary growth and resource wealth are related to higher ecological degradation (Hunjra et al., 2024). Achieving sustainable development goals, addressing environmental problems, and ensuring financial stability are all possible with a green growth approach (Ridwan et al.,2023, Urbee et al.2024). By utilizing the ARDL approach, Raihan et al. (2023) demonstrated that Mexico's LCF decreases when economic expansion occurs. Adebayo and Samour (2024) employed the PNARDL method and showed that economic development is a major reason for environmental damage in BRICS countries. Moreover, several investigations, for example, Nathaniel et al.(2019), Nathaniel et al.(2020), Ahmed et al.(2020a), Ahmed et al.(2020b); Raihan et al.(2022a), Raihan et al.(2022b)

Raihan et al.(2024b) and Sun et al.(2024) concluded that expansion of economy degrades ecosystem quality. In response to this, Solarin et al. (2021), who utilized the ARDL approach for Nigeria, discovered that although growth in the economy first degrades the environment, it eventually improves it. Additionally, the link between GDP growth and CO_2 emissions in India from 1965 to 2022 was investigated by Raihan et al. (2024a). The ARDL long-run elasticity's findings suggest that economic expansion helped to mitigate some emissions. Several works by Hassan et al. (2019) and, Baloch et al.(2021) in Pakistan and Bento and Moutinho (2016) in Italy show that economic expansion causes environmental unsustainability. Moreover, Balcilar et al. (2018) asserted that ecological quality in Germany and the UK is unaffected negatively by monetary expansion.

There is a substantial deficiency in achieving the SDG goals due to the absence of research on the use of AI for environmental concerns. AI is crucial in mitigating the urgent problems of global warming, biodiversity loss, and ecological loss, which are becoming increasingly evident as humanity struggles to solve these issues (Akter, 2024). AI, in its simplest form, comprises computers or other devices that imitate the cognitive functions regarding intelligence in humans, like learning and solving problems (Khanzode and Sarode, 2020). Four primary domains broadly define the intersection of AI and green environment: pollution and waste administration, preservation of natural assets, agricultural sustainability, and monitoring of pollution and treatment (Qian et al., 2018; Granata and Nunno, 2021). Leveraging artificial intelligence (AI) technological advances is an appropriate strategy to promote systemic modifications and advance sustainable development (Jarrahi, 2018; Jeste et al., 2020). According to Ray et al. (2024), pollution, especially contamination with heavy metals, can be detected, examined, and regulated by integrating environmental research with technological advances in AI, particularly machine learning, forecasting, and advanced algorithms. Similarly, Yadav and Singh (2023) demonstrated that artificial intelligence (AI) may improve ecological sustainability by mitigating global warming and enhancing agriculture, water availability, marine ecosystems, prediction of weather, and resilience to disasters.

Financial development (FD) has the potential to adversely affect the ecosystem and either raise or lower the need for energy (Usman et al.,2024). In addition, by expanding the financing facilities to projects in R&D, enlarging techno-financial support to businesses, and encouraging environmentally friendly innovations, the financial development intends to lower emissions of carbon and sustain the environment (Abid et al., 2021; Yao et al., 2021). The dynamic consequence of expansion in finances on ecological sustainability in China was investigated by Fu et al. (2022), who determined that monetary expansion is favorable to long-term environmental sustainability. Using yearly data from 1990 to 2020, Solaymani and Montes (2024) employ the ARDL approach. The empirical study reveals that New Zealand's FD considerably lowers carbon emissions and ensures a green ecosystem. In the same way, Ahmad et al. (2022) established that by raising the EFP, financial development causes environmental damage. Moreover, advancement in finance can promote environmental preservation in South Asia countries (Ozturk et al.,2024). Furthermore, Ramzan et al. (2022) investigated how financial development affected Pakistan's increased pollution levels. The financial sector's encouragement of the widespread industrial processes increases the environmental hazards (Yuxiang and Chen, 2010; Usman et al., 2022). Multiple researchers also indicated that development in finances degrades the level of natural health (Saqib et al.,2024; Petrović and Lobanov,2022; Khan et al.,2019).

Numerous investigations into the connection between ICT and harm to the environment have produced conflicting findings. According to certain research, using ICTs greatly reduces environmental pollution, improving the natural environment (Park et al. 2018). ICT expenditure, however, has a minimal effect, mostly on ecological sustainability, as Ziemba and Grabara (2024) discovered. Qayyum et al. (2024) illustrate how ICT protects the atmosphere by lessening its ecological effect by using CS-ARDL estimators. The results of the investigation show that ICT invention is required to achieve the goal of a green environment in the long run. Similarly, Mensah et al. (2024) found that IQ and ICT collaborate to improve the environment and reduce footprint by 0.0748%. The majority of research indicates that using ICT facilities helps lower pollution (Ozcan and Apergis 2018). Moreover, Coroama et al. (2012) state that ICT might mitigate GHG emissions by promoting energy-efficient production and consumption practices. Similar findings also concluded by Lu (2018) in 12 Asian countries, Ahmad et al.(2023) in OECD countries, N'dri et al.(2021) in developing countries, Sahoo et al.(2021) in India and Chien et al.(2024) in Indonesia. However, a small number of additional studies suggest that using ICT leads to increased environmental contamination and environmental degradation (Asongu et al. 2018). By adopting the ARDL approach, Lin and Ullah (2023) observed that ICT hinders environmental sustainability in Pakistan. Ulucak and Khan (2020) concluded that ICT has a detrimental implication on GHG pollution in the BRICS nations. Additionally, Salahuddin et al. (2016) indicated that a 1% expansion in internet use generates a spike in carbon emissions in the OECD nations of 0.16%.

Growing populations are considered to have an unfavorable impact on the environment as individuals need more places to live, healthcare, schooling, and transportation options (Isik et al., 2019; Wu et al., 2022b, Raihan, 2023). However, since it lessens carbon emissions, population growth (POP) which is planned leads to environmental sustainability (Katircioglu et al., 2018; Dogan et al., 2020, Oje, 2024). Voumik et al. (2023c) used the ARDL approach to evaluate the impact of the population on Kenya's carbon emissions. They proved that the country's CO_2 emissions may climb in tandem with its growing population. Similarly, using data from 1990 to 2019 in Malaysia, Raihan (2024) adopted the ARDL approach and concluded that population growth has an encouraging association with long-term carbon pollution. By using the recently developed LCC hypothesis, Erdogan (2023) observed that an ecosystem is diminished by a high population in Africa. Additionally, Adebayo (2023) used the BDS test to investigate Turkey's ecological impact. They found that high population density is the major cause of ecological destruction in the majority of quantiles. Using a geographic semi-parametric panel technique, Xie et al. (2023) found similar results in China's environment, demonstrating that the country's population growth exacerbates damage to the environment. Additionally, Bangladesh's ecology suffers from high population density (Rahman and Alam, 2021, Datta, 2024). Conversely, Wu et al. (2021a) noted that China's increasing population might also have a short- and long-term beneficial impact on the reduction in biodiversity loss.

Ultimately, our literature assessment has proven that a few studies explicitly examine the LLC hypothesis for the USA while considering the consequences of financial development, ICT use, economic expansion, population, and AI innovation. Many studies examined the LLC hypothesis in emerging economies, but their study has been specific and fails to take other economic sectors into account. It seems reasonable to investigate the LLC hypothesis as the USA is an expanding nation with distinctive ecological variables. The literature that is currently available on AI for environmental sustainability addresses several topics, including power, transport, water, and biological diversity. On the other hand, relatively no research is being done on the real-world uses of AI innovation on load capacity factor, especially when it comes to solving sustainability problems. Even though certain useful applications, such as the disposal of trash using sophisticated navigation strategies and protecting animals for increased biodiversity, have been seen in developed nations, additional studies and research are still required. The absence of knowledge on how AI might be used to effectively safeguard the environmental sustainability of the United States creates a research gap. Additional research is required to discover and develop innovative applications of AI that can help the chosen area achieve the Sustainable Development Goals (SDGs). By bridging the knowledge and implementation gaps, closing this research gap would make it possible to apply AI and ICT effectively to address ecological sustainability concerns across different regions.

Methodology

Data

Table 1 is an essential feature of the study as it offers a comprehensive overview of all the variables examined. It offers insightful details on their descriptions, units of measurement, and sources. The LCF information for the US is obtained from the Global Footprint Network (GFN, 2022). A higher LCF is representative of a better ecosystem as it incorporates EF and biocapacity in the denominator (Pata and Kartal, 2023). Numerous independent factors were also included in this research, all of which depended on meticulously gathered data. World Development Indicators (WDI, 2022) offered statistics on GDP, GDP squares, and population; trustworthy Our World in Data (2022) was implemented to gather information on other significant elements such as Artificial Intelligence innovation and ICT usage. However, data regarding financial development is collected from the IMF. Therefore, by improving the accessibility and reliability of the study's methodology, the thorough documentation guarantees a clear and coherent analysis.

Table 1: Source and Description of Variables

Variables	Description	Logarithmic Form	Unit of Measurement	Source
LCF	Load Capacity Factor	LLCF	Gha per person	GFN (2022)
GDP	Gross Domestic Product	LGDP	GDP per capita (current US$)	WDI (2022)
GDP^2	Square of Gross Domestic Product	$LGDP^2$	GDP per capita (current US$)	WDI (2022)
AI	Artificial Intelligence Innovation	LAI	Annual patent applications related to artificial intelligence	Our World in Data (2022)
FD	Financial Development	LFD	Financial Development Index	IMF (2022)
ICT	ICT use	LICT	ICT goods imports (% of total imports)	Our World in Data (2022)
POP	Population	LPOP	Population, total	WDI (2022)

Theoretical Framework

The LCC theory depends on the LCF statistic, which takes prospects for ecological provision and human-made demand for resources into consideration (Pata et al.,2023). Through a contrast of ecological footprint and biocapacity, the LCF offers an additional assessment of the environment (Dogan and Pata, 2022). By comparing EFP and biocapacity, the LCF examines a specific ecological threshold; an upward trend in the LCF indicates a better ecosystem and a fall in the LCF suggests a surge in environmental deterioration (Alola et al.,2023). Moreover, the LCC emphasizes the interdependence of sustainability problems, such as resource scarcity, destruction of natural assets, and temperature rise (Wu et al.,2024). Ulucak et al. (2020) revealed that manufacturing pollution and waste are exacerbated by economic expansion, and production procedures and emissions are influenced by sectoral composition. Countries all around the world use a variety of petroleum-based products, including natural gas, coal, and fuel, to encourage growth in GDP, growth in population, and industrialization, all of which harm the planet (Chen et al.,2022). Similarly, financial development can also degrade biodiversity.

Now, we have created the following equation (1) for LCC theory:

$$Load\ Capacity\ Factor = f(GDP, GDP^2, K_t) \quad (1)$$

In this case, the variables for wealth in equation (1) are GDP and GDP squared, while the parameter for other factors affecting the LCF is K_t. The purpose of equation (2) is to provide an expanded view of the factors changing the LCF by consisting of several relevant factors such as population, development in finances, ICT use, and AI innovation.

$$LCF = f(GDP, GDP^2, AI, FD, ICT, POP) \quad (2)$$

In equation (2), the load capacity factor is represented by LCF, GDP stands for economic growth, AI represents artificial intelligence innovation, FD refers to financial development, and POP indicates population. The econometric justification of equation (3) is given above.

$$LCF_{it} = \delta_0 + \delta_1 GDP_{it} + \delta_2 GDP_{it}^2 + \delta_3 AI_{it} + \delta_4 FD_{it} + \delta_5 ICT_{it} + \delta_6 POP_{it} \quad (3)$$

In scientific and financial research, logarithmic scaling is a particularly helpful adjustment for consolidating broad ranges as it efficiently stabilizes fluctuation. It improves perception and facilitates the formulation of conclusions based on statistics by bringing down complex connections into simpler linear forms. Equation (4) illustrates the variables' logarithmic values.

$$LLCF_{it} = \delta_0 + \delta_1 LGDP_{it} + \delta_2 LGDP_{it}^2 + \delta_3 LAI_{it} + \delta_4 LFD_{it} + \delta_5 LICT_{it} + \delta_6 LPOP_{it} \quad (4)$$

Here, within the parameter range of δ_0 to δ_6, the coefficients of the research variables are listed.

Econometric Framework

This research uses multiple stages in its estimate technique to address frequent problems. The ADF, P-P, and DF-GLS examinations are utilized to check stationarity and confirm independence among the variables. Next, the ARDL method is used to discover both immediate and long-term relationships. The research then makes use of the FMOLS, DOLS, and CCR to confirm the accuracy of the long-run estimation. The associated relationships between GDP, financial development, ICT use, AI innovation, population, and LCF in the USA were then examined using the Pairwise Granger causality test. Finally, we performed three diagnostic tests to check autocorrelation, heteroscedasticity, and multicollinearity.

Stationarity test

In order to provide accurate statistical modeling, non-stationary data must be used as non-stationary regressions might produce deceptive findings. A series with a unit root suggests that systemic shocks have a lasting impact on the series' long-term behavior (Ridwan, 2023). In order to attain stationarity and guarantee precise forecasting and inference, researchers can distinguish between stationary and non-stationary processes by identifying unit roots. This distinction helps researchers select the right models and transformations, such as differencing (Ridzuan et al.2023). Three stationarity tests were performed in this research: the Augmented Dickey-Fuller (ADF) test, which Dickey and Fuller (1981) introduced, the Phillips and Perron (1988), and the DF-GLS examination, which Elliot et al. (1996) suggested. When variables are stationary but have a root close to a non-stationary frontier, the ADF and Phillips-Perron tests have drawn criticism for their inadequate efficiency (Brooks, 2014). When serial correlation is present in the residuals, the Phillip-Perron test was designed to remove the asymptotic bias that was present in the original ADF test (Davidson and MacKinnon, 1993). According to Elliot et al. (1996), the DF-GLS assessment is more robust compared to the ADF and Phillips-Perron tests when there is an uncertain mean or trend. The Monte Carlo evidence given by Stock (1994) also demonstrates the improved performance of the DF-GLS evaluation.

Autoregressive Distributive Lag model

The cointegrating link between the variables is further captured in the research with the help of the ARDL bounds assessment. For series with a small sample size, this test is trustworthy. When the factors are only partially integrated, it is also advantageous (Akadiri, 2022). Examining the link between the aforementioned sustainable ecosystem indicators and the GDP, FA, AI, ICT, and POP using the ARDL model highlights the relevance of LCF. Pesaran et al. (2001) proposed the ARDL approach, an extensive dynamic regression model that combines the characteristics of autoregressive as well as distributed lag models. In comparison to conventional cointegration techniques, it has several benefits. First of all, variables can be integrated into various orders; variables integrated of order one, order zero, or even fractionally integrated, except for 1(2), can be supported. Second, this framework may be used for data analysis in situations when sample sizes are limited and small due to its efficiency (Kumar et al., 2024). Thirdly, Harris and Sollis (2003) have shown that the model yields unbiased estimates over an extended period. Finally, this model captures both short-term dynamics and long-run linkages by integrating short-run adjustments with long-run equilibrium through the derivation of the Error Correction Term (ECT) via a straightforward linear transformation (Ali et al., 2017). Equation (5) can be used to represent the ARDL Bound test:

$$\begin{aligned}\Delta LLCF_t = {} & \omega_0 + \vartheta_1 LCF_{\mathrm{t-1}} + \vartheta_2 LGDP_{t-1} + \vartheta_3 \mathrm{LGDP^2}_{t-1} + \vartheta_4 LAI_{t=1} + \vartheta_5 LFD_{t-1} + \vartheta_6 LICT_{t-1} + \vartheta_7 LPOP_{t-1} \\ & + \sum_{i=1}^{k} \omega_1 \, \Delta LLCF_{2_{\mathrm{t-i}}} + \sum_{i=1}^{k} \omega_2 \, \Delta \mathrm{LGDP_{t-i}} + \sum_{i=1}^{k} \omega_3 \Delta \mathrm{lnGDP^2}_{\mathrm{t-i}} + \sum_{i=1}^{k} \omega_4 \Delta LAI_{t=1} \\ & + \sum_{i=1}^{k} \omega_5 \, \Delta \, LFD_{t-i} + \sum_{i=1}^{k} \omega_6 \Delta \mathrm{LICT_{t-i}} + \sum_{i=1}^{k} \omega_7 \Delta \mathrm{LPOP_{t-i}} + \varepsilon_t \qquad (5)\end{aligned}$$

The alternative hypothesis (H1) and the null hypothesis (H0) are represented by equations 6 and 7.The evidence supporting cointegration (the alternative hypothesis) is contrasted with the null hypothesis, which claims that there exit no cointegration. If the F-statistic exceeds both the lower and upper limit values, the null hypothesis cannot be accepted.

$$H_0 = \omega_1 = \omega_2 = \omega_3 = \omega_4 = \omega_5 = \omega_6 \neq \omega_7 \quad (6)$$

$$H_1 = \omega_1 \neq \omega_2 \neq \omega_3 \neq \omega_4 \neq \omega_5 \neq \omega_6 \neq \omega_7 \quad (7)$$

After confirming cointegration among the parameters, the short-run coefficient and the ECT are assessed using the Engle and Granger (1987) ECM. The ECM is included in the ARDL framework in the following ways to accomplish this:

$$\Delta LLCF_t = \omega_0 + \sum_{i=1}^{k} \vartheta_1 \Delta \mathrm{LCF}_{\mathrm{t-i}} + \sum_{i=1}^{k} \vartheta_2 \Delta \mathrm{LGDP}_{\mathrm{t-i}} + \sum_{i=1}^{k} \vartheta_3 \Delta \mathrm{lnGDP^2}_{\mathrm{t-i}} + \sum_{i=1}^{k} \vartheta_4 \Delta LAI_{t=1} + \sum_{i=1}^{k} \vartheta_5 \Delta\, LFD_{t-i} + \sum_{i=1}^{k} \vartheta_6\, \Delta \mathrm{LICT}_{\mathrm{t-i}} + \sum_{i=1}^{k} \vartheta_7 \Delta \mathrm{POP}_{\mathrm{t-i}} + \aleph ECT_{t-i} + \varepsilon_t \quad (8)$$

Here, the sign ℵ is used to denote the rate of adjustment.

Robustness Check

To assess the feasibility of ARDL results, we employed the FMOLS, DOLS, and CCR methodologies. When examining a single cointegrating link with a mixture of integrated orders of I(1) variables, the FMOLS approach is applied (Ahmad et al., 2019). The FMOLS analysis, a nonparametric method, has the benefit of simultaneously accounting for sequence correlation, endoplasmic error, and simultaneous bias (Hamit-Haggar.,2012). It also considers the possibility of heterogeneity in the long-run parameters (Phillips and Hansen, 1990). In the meanwhile, DOLS successfully combats potential endogeneity and sample bias difficulties and minimizes feedback in the cointegrating equation with its enhanced regression technique, which incorporates leads and lags of the initial differences of regressors (Idores et al., 2024). Kao and Chiang (1999) provided the DOLS as an alternative (parametric) estimator for predicting the long-run interaction of variables using first differenced regressor leads and lags. Additionally, the CCR approach established by Park (1992) could be utilized for testing for cointegrating vectors in a model with an integrated process of order I(1). Consistent estimates are produced by this approach in a variety of situations, including those involving extremely persistent time series. According to Kinnunen et al. (2024), CCR is particularly recognized for its flexibility in handling a wide range of difficulties that can be created with cointegrated regression analysis.

Granger Causality test

Our methodology is based on Granger (1969), who suggested using time-series data to establish the association between financial variables. Whether one factor may aid in the forecasting of another parameter is a usual inquiry in time series analysis (Kumo,2012). Granger causality has two main implications: either x must Granger cause Y or vice versa if two variables say x and y, are co-integrated (Awe,2012). Two variables are cointegrated if they have a shared stochastic trend (Engle and Granger, 1987). A pair of elements are considered cointegrated in a broader sense if their linear combinations are stationary (I(0)) and if they are not stationary in and of themselves but are stationary in their initial differences (Yousefi, 2015). It was possible to get a more complete and nuanced view of the links and linkages that occur in our analysis by incorporating pairwise Granger causality tests within our research.

Diagnostic test

To assess the accuracy of the information utilized for the factors selected in this work, we make use of the Breusch-Godfrey Lagrange Multiplier test to identify serial correlation issues, the Breusch-Pagan-Godfrey test is used to examine heteroskedasticity, and the Jarque-Bera test is used to confirm residual normality (Gupta and Singh, 2016). The sample skewness S and kurtosis K from the observed time series data are measured by the Jarque-Bera test statistics. According to the normality concept, S and K have values of 0 and 3, respectively (Thadewald & Büning 2007). Mokhtar (1994) argues that autocorrelation typically happens in both time-series and cross-sectional data. However, we know that time is the factor that causes autocorrelation in time series data. Unreliable research findings will emerge from a model with a heteroscedasticity issue, and the estimated model will not be appropriate for application (Lun and Samsudin, 2022).

Results and Discussion

Summary Statistics

Using the different results of many normality assessments (skewness, probability, kurtosis, and Jarque-Bera), Table 2 showcases the outcomes of the summary measurements among the variables. Additionally, it offers basic descriptive statistics for factors in the actual and logarithmic forms, including mean, standard error, median, standard deviation, and lowest and highest figures. Time series data for the USA from 1990 to 2019 is included in each parameter, with 32 observations. All of the elements appear to follow normality based on the negative values of skewness by the variables. In addition, the research used kurtosis to determine if the series exhibited a strong or weak tail compared to a normal distribution. Furthermore, the Jarque-Bera probability calculations demonstrate that every parameter is normal. We moved further with the component correlation assessment based on this information.

Table 2. Summary Statistics of the Variables

Statistic	LCLF	LGDP	$LGDP^2$	LAI	LFD	LICT	LPOP
Mean	-0.835416	10.64393	113.3917	2.625053	-0.167379	19.4995	7.505506
Median	-0.822656	10.71885	114.8942	7.157725	-0.096679	2.63119	19.50906
Maximum	-0.63269	11.15938	124.5318	9.724421	-0.081949	2.871059	19.62074
Minimum	-0.970971	10.08116	101.6297	6.320768	-0.520773	2.267549	19.33546
Std. Dev.	0.093945	0.318778	6.76113	1.035853	0.137067	0.132527	0.086792
Skewness	0.065531	-0.255693	-0.219087	1.155679	-1.662635	-0.270512	-0.311181
Kurtosis	1.965479	1.888894	1.876795	2.992345	4.273768	3.783686	1.894819
Jarque-Bera	1.449882	1.994763	1.938117	7.123243	16.90654	1.209162	2.14501
Probability	0.484353	0.368844	0.37944	0.128393	0.332213	0.546303	0.34215
Sum	-26.73331	340.6058	3628.534	240.1762	-5.356143	84.00168	623.984
Sum Sq. Dev.	0.273596	3.150205	1417.099	33.26275	0.582405	0.544463	0.233521
Observations	32	32	32	32	32	32	32

Stationarity test

The Table 03 below presents the findings of stationarity testing with the ADF, DF-GLS, and P-P procedures. The ADF test observations illustrated that after taking the first difference, LLCF, LGDP, $LGDP^2$, and LAI became stationary from their non-stationary values. On the other hand, LFD, LICT, and LPOP stayed stationary at their levels after first differencing. For each factor, the findings of the P-P and DF-GLS assessments were identical to those of the ADF test. Interestingly, at first differencing, every variable in the ADF, P-P, and DF-GLS tests is significant at the 1% level. After first differencing, the $LGDP^2$ variable in the DF-GLS analysis, however, is only significant at the 5% level. The stationarity examination findings reveal that the series is stationary at mixed levels of either level or first-order integration, I(0) or I(1), meaning that the ARDL bounds cointegration method might be applied to this study.

Table 3. Results of unit root tests

Variables	ADF		P-P		DF-GLS		Decision
	I(0)	I(1)	I(0)	I(1)	I(0)	I(1)	
LLCF	-0.799	-5.347***	-0.826	-5.345***	-1.475	-4.302***	I(1)
LGDP	-0.878	-4.841***	-0.953	-4.829***	-1.771	-3.137***	I(1)
$LGDP^2$	-0.614	-5.001***	-0.650	-4.968***	-1.142	-3.343**	I(1)
LAI	-2.014	-4.881***	-1.181	-3.676***	-2.047	-4.121***	I(1)
LFD	-3.071**	-4.381***	-3.108**	-4.551***	-3.184**	-4.221***	I(0)
LICT	-3.052**	-4.585***	-3.010**	-4.574***	-3.435**	-3.836***	I(0)
LPOP	-4.520***	-7.341***	-7.550***	-8.112***	-3.229**	-4.549***	I(0)

ARDL Bound test

We first determine the stationarity characteristics of the series and then perform the ARDL bounds technique for cointegration evaluation. The F-statistic was computed with suitable lag duration according to the lowest values of the Akaike Information Criterion in this investigation. The cointegration relationship between the variables was investigated using the ARDL bounds test, and the findings are displayed in Table 4. The outcomes are organized so that the existence of a long-term link between the variables is demonstrated if the estimated value of the F-test is greater than the values of both limits (upper and lower bound). Our findings support the rejection of the null hypothesis by indicating that the variables have a long-term connection. The approximate F-statistic value (9.129832) is greater than 10%, 5%, 2.5%, and 1% of the critical upper limit in the order zero and one, accordingly. Therefore, we conclude that variations in each of these factors have a consequence on the LCF in the USA.

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Table 4. Results of ARDL bound test

Test Statistic	Value	Signif.	I(0)	I(1)
F-statistic	9.129832	10%	Asymptotic: n=1000	1.99
		6%	2.27	3.28
		2.50%	2.55	3.61
		1%	2.88	3.99

ARDL short-run and Long-run

The ARDL results for each variable can be seen in Table 5. The short and long-term dynamics' findings revealed that GDP has an adverse effect on the LCF; that is, for every 1% rise in LGD, the ecosystem's quality will decline by 0.899% and 0.360%, respectively. This suggests that when economies evolve, they correspondingly increase the need for goods, power, and natural assets, which leads to greater production of pollutants, which worsen environmental conditions. According to the expected outcomes, economic expansion is not an indication of a sustainable US atmosphere. Conversely, the coefficient $LGDP^2$ is positively and significantly correlated with LLCF. A 1% increase in $LGDP^2$ leads to corresponding increases of 0.652% and 0.969% in LCF. This finding suggests that the United States environmental quality will benefit from a short- and long-term increase in LGDP squared. According to He et al. (2024), increased economic activity deteriorates ecological conditions in OECD nations. Numerous studies by Ali et al. (2024), Ullah et al. (2024), Mughal et al. (2022), and Rahman et al. (2022) concurred that a rise in economic growth led to a heightened rate of destruction of the environment. However, GDP expansion may also enhance the ecosystem (Jabeen et al.,2024; Mohammed et al.,2024).

Likewise, there exists an encouraging correlation between the LAI coefficient and the LCF over both terms. An increase of 1% in AI innovation will result in an expansion of 0.030% and 0.036% of LCF. This result illustrates how AI innovation can benefit the natural world by reducing CO_2 emissions, improving the efficiency of resources, and cutting garbage creation. According to Hoang et al. (2022), AI has demonstrated its potential for usage in preventing pollution and managing the environment in the future. In a similar vein, Habila et al. (2023) agreed that (AI) improves human capacity to manage global warming to achieve sustainability while utilizing renewable resources. Furthermore, AI has a great deal of promise for tackling severe environmental issues (Bibri et al.,2024, Rasheed, 2024). However, over both short and long terms, there is a detrimental and significant relationship between the LFD and LLCF, suggesting that financial development does not help guarantee a sustainable environment. In particular, 1% more financial development will end up in 0.343% and 0.295% of LCF in response. According to (Katircioğlu and Taşpinar, 2017 Xu et al., 2018 Imamoglu, 2019 Kayani et al.,2020; Yang et al.,2023, Xulu, 2024), expansion in finance harms the environment. Furthermore, several empirical studies (Cheng et al., 2019; Omri et al., 2019; Seetanah et al., 2019) suggested no discernible correlation between the growth of the financial industry and ecosystem health. On the other hand, several researches provide evidence that mitigating the harm to the environment can be achieved through the creation of a robust and well-planned financial sector (Dar and Asif, 2018; Fakher, 2019; Zaidi et al., 2019; Saud et al., 2018; Baloch et al., 2019; Khan et al., 2019; Akadiri et al.,2022; Annor et al.,2024).

In the same way, population density has a destructive but significant link to the LCF, which is detrimental to the ecological condition of the United States. The LCF will drop by 0.836% and 0.335%, respectively, with a 1% rise in LPOP. One explanation might be that when the population grows, there is a greater demand for materials, resulting in the exploitation and depletion of assets; this, in turn, causes environmental damage such as loss of wildlife, deforestation, and boosting contamination. According to Yeh and Liao (2017), Taiwan's population increase was the main contributor to carbon emissions, and a 16–29% reduction in population growth would result in lower emissions of carbon. Wu et al. (2021), however, dispute this claim and conclude that China's population growth can both slow down the short- and long-term boost to emissions and enhance the environment. Finally, there is a significant and beneficial association between ICT use and LCF. If LICT expands by 1% in a shorter time, LCF increases by 0.279% on average. Similarly, over time, a 1% increase in ICT will allow the LCF to boost by 0.106%. This conclusion is observed by (Asongu et al.,2017 Ahmed and Le,2021 Lahouel et al. 2024, Zhang and Liu,2015 Chen et al.,2019; Danish, 2019 and, Megbetor and Boateng, 2023), who concluded that ICT might be utilized to lessen the negative consequences of CO_2 emissions and enhance the environmental quality.

Conversely, Appiah-Otoo and Chen (2024), Raheem et al.(2020), and Haseeb et al.(2019) claimed that the elevation in GHG pollution is caused by ICT use and hampers environmental sustainability.

Table 5. Results of ARDL short-run and long-run

Long-run Estimation				
Variable	Coefficient	Std. Error	t-Statistic	Prob.
LGDP	-0.360	3.177805	-6.72179	0.0000
$LGDP^2$	0.969	0.151067	6.416285	0.0000
LAI	0.036	0.012913	-2.81781	0.0130
LFD	-0.295	0.132515	-2.2324	0.0413
LICT	0.106	0.040101	2.64342	0.0184
LPOP	-0.335	0.518045	7.76546	0.0000
C	8.14243	2.36632	1.785167	0.0945
Short-run Estimation				
Variable	Coefficient	Std. Error	t-Statistic	Prob
D(LLCF(-1))	0.172	0.072349	2.384869	0.0307
D(LGDP)	-0.899	2.906232	-5.12658	0.0001
D($LGDP^2$)	0.652	0.133748	4.881989	0.0002
D(LAI)	0.030	0.013241	-2.32651	0.0344
D(LFD)	-0.343	0.067581	-5.07745	0.0001
D(LICT)	0.279	0.032765	8.538319	0
D(LPOP)	-0.836	0.733377	1.140186	0.2721
CointEq(-1)*	-1.44956	0.140053	-10.35	0
R^2=0.9687				
Adjusted R^2 =0.9588				

Robustness Check

To confirm the consistency of the ARDL estimation, we implemented the FMOLS, DOLS, and CCR approaches. The outcomes for these models are shown in Table 6. The LCF is typically reduced by 0.708%, 0.467%, and 0.716% in the FMOLS, DOLS, and CCR models for each 1% improvement in the LGDP. This coefficient agrees with the results of the ARDL calculation and is significant in each case at the 1% level. In a similar vein, the notable and encouraging outcomes for $LGDP^2$ support the ARDL findings. The robustness of the ARDL estimation for the LAI and LICT variables is further demonstrated by the FMOLS, DOLS, and CCR conclusions. These factors are also significant at the 1% level and have a positive correlation with LCF.

However, the data shows that there is a detrimental and substantial link between LCF and financial development (LFD). To be more precise, under the FMOLS, DOLS, and CCR models, a 1% spike in LFD yields a 0.542%, 0.535%, and 0.510% drop in LCF, respectively. The variable is significant at the 1% level of significance in all cases. Finally, in the scenario of LPOP, the FMOLS, DOLS, and CCR results demonstrate an advantageous relationship. A 1% boost in LPOP in each model creates an average jump in LCF of 1.223%, 1.759%, and 1.148%, in that order. For FMOLS and CCR, the coefficient is significant at the 1% level; for DOLS, it is only significant at the 10% level of significance. However, this result is not aligned with the conclusions of the ARDL estimation.

So overall, the abovementioned information indicates the robustness of the outcomes of the ARDL short and long-run methodology.

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Table 6. Results of Robustness check

Variables	FMOLS	DOLS	CCR
LGDP	-0.708***(0.2708)	-0.467***(0.2045)	-0.716***(0.7166)
$LGDP^2$	0.693***(0.1049)	1.805***(0.9846)	0.689***(0.1312)
LAI	0.016***(0.0382)	0.089***(0.0687)	0.013***(0.0121)
LFD	-0.542***(0.1026)	-0.535***(0.9805)	-0.510***(0.1048)
LICT	0.132***(0.0345)	0.036***(0.2609)	0.101***(0.0367)
LPOP	1.223***(0.3095)	1.759*(0.4805)	1.148***(0.3775)
C	-9.261***(1.059)	-7.055*(1.432)	-9.359***(1.8912)

Pairwise Granger Causality test

Table 7 presents the findings of the causal links across different chosen variables. It is evident from an F-statistic of 3.38826 and a p-value of 0.0399 that LGDP doesn't Granger cause of LLCF. This implies that, at the 5% significance level, the null hypothesis that there exists no link between these variables is rejected. Furthermore, the presence of one-way causation from $LGDP^2$, LAI, LFD, and LICT to LLCF is confirmed by the p-values that are less than the conventional significance threshold. Thus, we rule out the null hypothesis that there is no causal connection under these circumstances. Nonetheless, a significant bidirectional causal association emerged between LPOP and LLCF. On the other hand, p-values greater than the traditional significance criterion for each case show that there is no meaningful causal association between LLCF and LGDP, $LGDP^2$, LAI, LFD, and LICT. These results imply that changes in LCF do not influence ICT usage, financial development, artificial intelligence, or economic growth. So, it is not possible to rule out the null hypothesis that there is no causality in these interactions.

Table 7. Results of Granger Causality test

Null Hypothesis	Obs	F-Statistic	Prob.
LGDP $\neq$ LLCF	30	3.38826	0.0399
LLCF $\neq$ LGDP		0.44313	0.647
$LGDP^2 \neq$ LLCF	30	3.4843	0.0463
LLCF $\neq LGDP^2$		0.44696	0.6446
LAI $\neq$ LLCF	30	2.38966	0.0123
LLCF $\neq$ LAI		1.48366	0.2461
LFD $\neq$ LLCF	30	6.00742	0.0074
LLCF $\neq$ LFD		0.25365	0.7779
LICT $\neq$ LLCF	30	13.581	0.0001
LLCF $\neq$ LICT		0.02088	0.9794
LPOP $\neq$ LLCF	30	4.3606	0.0237
LLCF $\neq$ LPOP		0.50808	0.0177

Diagnostic Test

The findings from three separate diagnostic examinations are displayed in Table 8. The results show that no diagnostic approach can rule out the null hypothesis since they are all contradictory. A p-value of 0.5621 from the Jarque-Bera test illustrates that the residuals have a normal distribution. Then, with a corresponding p-value of 0.2412, over the traditional threshold for significance, the Lagrange Multiplier analysis shows no serial correlation in the residuals. The Breusch-Pagan-Godfrey test, which yields a p-value of 0.4658, ultimately verifies that the residuals do not exhibit a heteroscedasticity problem.

Table 8. The results of diagnostic tests

Diagnostic tests	Coefficient	p-value	Decision
Jarque-Bera test	2.3412	0.5621	Residuals are normally distributed
Lagrange Multiplier test	1.5136	0.2412	No serial correlation exits
Breusch-Pagan-Godfrey test	0.9695	0.4658	No heteroscedasticity exists

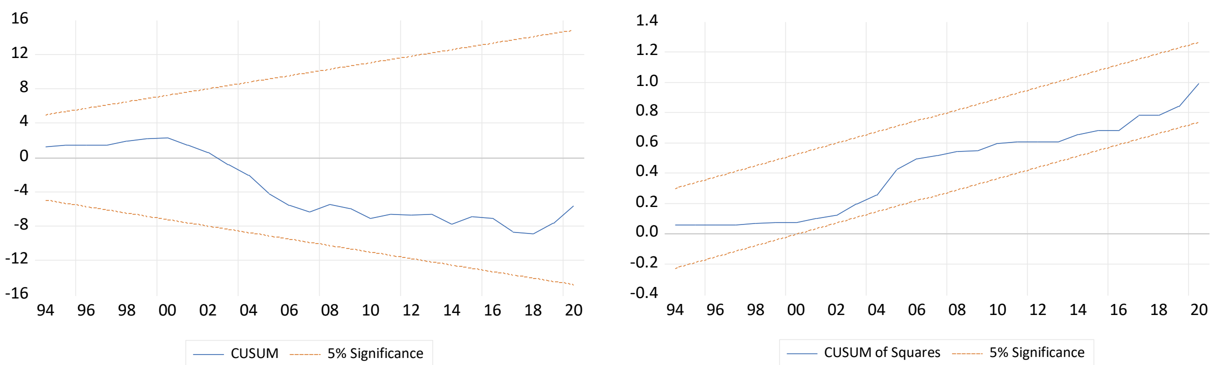

Figure 1. The plots of the CUSUM and CUSUMQ tests (critical bounds at a 5% significance level)

Moreover, CUSUM and CUSUM-SQ statistics are utilized to perform the stability assessment. For residuals of functions that show structural stability over the long and short terms, use the CUSUM and CUSUM-SQ testing. The statistical findings in this case fall between the upper and lower limits. The plot of the CUSUM-SQ test is located within the crucial line, as shown in Figure 1, which indicates that the parameters are stable and well-specified at a 5% percent significance threshold.

Conclusion and Policy Recommendation

Our investigation seeks to understand the long- and short-term implications of population growth, financial development, economic expansion, AI innovation, and ICT use on load capacity factor (LCF) in the United States using data from 1990 to 2019. This investigation used the ADF, DF-GLS, and P–P unit root tests to determine the dataset's integration order. The variables in question showed long-term cointegration, as demonstrated by the ARDL bounds examination. While population growth, financial development, and short-term economic expansion would increase environment degradation in the chosen location, the ARDL long-run relationship showed that $LGDP^2$, innovations in artificial intelligence (AI), and utilization of ICT improve the environment over time by lowering GHG emissions. Based on the CCR, FMOLS, and DOLS estimators, the projected findings are robust and validated. The LLCF of the USA may be granser caused by $LGDP^2$, LAI, LFD, LIT, and LPOP, owing to the Granger causality test. Additionally, the diagnostic test indicates that there is no autocorrelation or heteroscedasticity issue and that the analysis residuals are distributed correctly. This article makes further policy recommendations for reducing pollution while encouraging sustainable development through the funding of green ICT, equitable progress, and more application of AI innovation. Lastly, to prevent resource depletion, reduce the generation of waste, and ensure a sustainable environment and growth, the government should offer incentives to individuals for integrating green AI innovation and the latest information technologies.

To enhance environmental sustainability while promoting economic growth in the United States, policies should capitalize on the link between GDP and the environment. Key actions include adopting renewable energy, enforcing strict emissions standards, and supporting sustainable agriculture. As GDP grows, focus on sustainable development by investing in eco-friendly infrastructure, promoting energy efficiency, and improving public transportation. Foster innovation through research grants for clean technologies and assist industries in adopting greener practices. Additionally, invest in environmental education to cultivate a culture of sustainability, ensuring economic growth aligns with environmental goals.

Policymakers should leverage artificial intelligence (AI) and information and communication technologies (ICT) to boost environmental sustainability. These technologies can reduce emissions, optimize resource use, and monitor environmental impacts in real-time. Encourage AI and ICT adoption in sectors like industry, energy, and agriculture through tax incentives and subsidies. Support the development of smart grids and AI-driven energy management to enhance energy efficiency and integrate renewables. Invest in R&D for ICT and AI applications in environmental monitoring and precision agriculture. Establish legal frameworks for data sharing and public-private cooperation to maximize environmental benefits. Promote AI in urban planning to design sustainable cities with green infrastructure and efficient waste management. Ensure AI and ICT growth adheres to ethical standards, addressing concerns like data privacy and job displacement through comprehensive policies and worker transition programs.

Addressing the environmental impacts of population growth and financial development in the U.S. requires targeted measures. Regulate financial markets to encourage green investments and discourage environmentally harmful projects. Introduce green bonds and incentives for sustainable investment, and promote ESG standards in financial institutions. Implement laws to manage population growth by developing sustainable cities, improving resource efficiency, and reducing environmental impacts. Enhance public awareness through family planning and education initiatives. Improve public transportation and enforce strict land use laws to curb urban sprawl and protect natural areas. Invest in energy efficiency and renewable to meet the rising energy demand. Strengthen waste management and recycling systems to handle increased waste. These strategies will balance economic and demographic growth with environmental sustainability.

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Consent to participate: Informed consent was obtained from all individual participants included in the study. Participants were fully informed of the study's purpose, procedures, and their rights, including the right to withdraw at any time without penalty.

Consent for publication: All participants provided consent for the publication of data and findings derived from their participation in the study. The consent forms are available upon request from the corresponding author.

Data availability statement: The corresponding author can provide the datasets created and/or analyzed during the current work upon reasonable request.

Authors' contributions: Mohammad Ridwan contributed to the study's conception and design. Material preparation, data collection, and analysis were performed by Shewly Bala, Sarder Abdulla Al Shiam, Afsana Akhter, Md Asrafuzzaman, Sarmin Akter Shochona, Shake Ibna Abir, Shaharina Shoha. All authors read and approved the final manuscript.

References

Abid, A., Majeed, M. T., & Luni, T. (2021). Analyzing ecological footprint through the lens of globalization, financial development, natural resources, human capital, and urbanization. Pakistan Journal of Commerce and Social Sciences (PJCSS), 15(4), 765-795.

Adebayo, T.S. Assessing the environmental sustainability corridor: linking oil consumption, hydro energy consumption, and ecological footprint in Turkey. Environ Sci Pollut Res 30, 18890–18900 (2023). https://doi.org/10.1007/s11356-022-23455-1

Adebayo, T.S., Samour, A. Renewable energy, fiscal policy and load capacity factor in BRICS countries: novel findings from panel nonlinear ARDL model. Environ Dev Sustain 26, 4365–4389 (2024). https://doi.org/10.1007/s10668-022-02888-1

Adisa, M. O., Oyedeji, S., & Porras, J. (2024). The nexus between ICT, top-down and bottom-up approaches for sustainability activities: A systematic mapping study. Journal of Cleaner Production, 141768. https://doi.org/10.1016/j.jclepro.2024.141768

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 Research, 105, 299–310. https://doi.org/10.1016/J.GR.2021.09.012

Ahmad, M., Kuldasheva, Z., Nasriddinov, F., Balbaa, M. E., & Fahlevi, M. (2023). Is achieving environmental sustainability dependent on information communication technology and globalization? Evidence from selected OECD countries. Environmental Technology & Innovation, 31, 103178. https://doi.org/10.1016/j.eti.2023.103178

Ahmad, S., Raihan, A., & Ridwan, M. (2024). Role of economy, technology, and renewable energy toward carbon neutrality in China. Journal of Economy and Technology. https://doi.org/10.1016/j.ject.2024.04.008

Ahmed Z, Asghar MM, Malik MN, Nawaz K (2020b) Moving towards a sustainable environment: the dynamic linkage between natural resources, human capital, urbanization, economic growth, and ecological footprint in China. Res Policy 67:101677

Ahmed Z, Zafar MW, Ali S (2020a) Linking urbanization, human capital, and the ecological footprint in G7 countries: an empirical analysis. Sustain Cities Soc 55:102064

Ahmed, Z., Le, H.P. Linking Information Communication Technology, trade globalization index, and CO2 emissions: evidence from advanced panel techniques. Environ Sci Pollut Res 28, 8770–8781 (2021). https://doi.org/10.1007/s11356-020-11205-0

Akadiri, S.S., Adebayo, T.S., Riti, J.S. et al. The effect of financial globalization and natural resource rent on load capacity factor in India: an analysis using the dual adjustment approach. Environ Sci Pollut Res 29, 89045–89062 (2022). https://doi.org/10.1007/s11356-022-22012-0

Akter, M. S. (2024). Harnessing technology for environmental sustainability: utilizing AI to tackle global ecological challenge. Journal of Artificial Intelligence General science (JAIGS) ISSN: 3006-4023, 2(1), 61-70.

Al Shiam, S. A., Hasan, M. M., Nayeem, M. B., Choudhury, M. T. H., Bhowmik, P. K., Shochona, S. A., ... & Islam, M. R. (2024b). Deep Learning for Enterprise Decision-Making: A Comprehensive Study in Stock Market Analytics. Journal of Business and Management Studies, 6(2), 153-160.

Al Shiam, S. A., Hasan, M. M., Pantho, M. J., Shochona, S. A., Nayeem, M. B., Choudhury, M. T. H., & Nguyen, T. N. (2024a). Credit Risk Prediction Using Explainable AI. Journal of Business and Management Studies, 6(2), 61-66.

Ali, M., Kirikkaleli, D. & Altuntaş, M. The nexus between CO2 intensity of GDP and environmental degradation in South European countries. Environ Dev Sustain 26, 11089–11100 (2024). https://doi.org/10.1007/s10668-023-03217-w

Ali, W., Abdullah, A., & Azam, M. (2017). Re-visiting the environmental Kuznets curve hypothesis for Malaysia: Fresh evidence from ARDL bounds testing approach. Renewable and sustainable energy reviews, 77, 990-1000. https://doi.org/10.1016/j.rser.2016.11.236

Alola AA, Saint Akadiri S, Akadiri AC, Alola UV, Fatigun AS (2019a) Cooling and heating degree days in the US: the role of macroeconomic variables and its impact on environmental sustainability. Sci Total Environ 695:133832 https://doi.org/10.1016/j.scitotenv.2019.133832

Alola, A. A., Bekun, F. V., & Sarkodie, S. A. (2019b). The dynamic impact of trade policy, economic growth, fertility rate, renewable and non-renewable energy consumption on the ecological footprint in Europe. Science of the Total Environment, 685, 702-709. https://doi.org/10.1016/j.scitotenv.2019.05.139

Alola, A.A., Arikewuyo, A.O., Ozad, B. et al. A drain or drench on biocapacity? Environmental account of fertility, marriage, and ICT in the USA and Canada. Environ Sci Pollut Res 27, 4032–4043 (2020). https://doi.org/10.1007/s11356-019-06719-1

Annor, L.D.J., Robaina, M. & Vieira, E. Climbing the green ladder in Sub-Saharan Africa: dynamics of financial development, green energy, and load capacity factor. Environ Syst Decis (2024). https://doi.org/10.1007/s10669-023-09959-2

Appiah-Otoo, I., Chen, X. Exploring the Environmental Impact of Information and Communication Technologies, Population, Economic Growth, and Energy Consumption in MENA Countries. Environ Model Assess (2024). https://doi.org/10.1007/s10666-024-09979-5

Arif, M., Hasan, M., Al Shiam, S. A., Ahmed, M. P., Tusher, M. I., Hossan, M. Z., ... & Imam, T. (2024). Predicting Customer Sentiment in Social Media Interactions: Analyzing Amazon Help Twitter Conversations Using Machine Learning. International Journal of Advanced Science Computing and Engineering, 6(2), 52-56.

Asongu SA, Le Roux S, Biekpe N (2018) Enhancing ICT for environmental sustainability in sub-Saharan Africa. Technol Forecast Soc Chang 127:209–216. https://doi.org/10.1016/j.techfore.2017.09.022

Asongu, S. A., Le Roux, S., & Biekpe, N. (2017). Environmental degradation, ICT and inclusive development in Sub-Saharan Africa. Energy Policy, 111, 353-361. https://doi.org/10.1016/j.enpol.2017.09.049

Asongu, S. A., Le Roux, S., & Biekpe, N. (2018). Enhancing ICT for environmental sustainability in sub-Saharan Africa. Technological Forecasting and Social Change, 127, 209-216. https://doi.org/10.1016/j.techfore.2017.09.022

Awe, O. O. (2012). On pairwise granger causality modelling and econometric analysis of selected economic indicators. Interstatt journals. net/YEAR/2012/articles/1208002. pdf.

Bahroun, Z., Anane, C., Ahmed, V., & Zacca, A. (2023). Transforming education: A comprehensive review of generative artificial intelligence in educational settings through bibliometric and content analysis. Sustainability, 15(17), 12983. https://doi.org/10.3390/su151712983

Balcilar, M., Ozdemir, Z. A., Ozdemir, H., & Shahbaz, M. (2018). Carbon dioxide emissions, energy consumption and economic growth: The historical decomposition evidence from G-7 countries. Work Pap.

Baloch, A., Shah, S.Z., Habibullah, M.S. et al. Towards connecting carbon emissions with asymmetric changes in economic growth: evidence from linear and nonlinear ARDL approaches. Environ Sci Pollut Res 28, 15320–15338 (2021). https://doi.org/10.1007/s11356-020-11672-5

Baloch, M. A., Zhang, J., Iqbal, K., & Iqbal, Z. (2019). The effect of financial development on ecological footprint in BRI countries: Evidence from panel data estimation. Environmental Science and Pollution Research, 26(6), 6199–6208. https://doi.org/10.1007/s11356-018-3992-9

Baloch, M.A., Zhang, J., Iqbal, K. et al. The effect of financial development on ecological footprint in BRI countries: evidence from panel data estimation. Environ Sci Pollut Res 26, 6199–6208 (2019). https://doi.org/10.1007/s11356-018-3992-9

Barnes EA, Hurrell JW, Ebert-Uphoff I, Anderson C, Anderson D (2019) Viewing forced climate patterns through an AI lens. Geophys Res Lett 46(22):13389–13398. https://doi.org/10.1029/2019GL084944

Ben Lahouel, B., Taleb, L., Managi, S. et al. The threshold effects of ICT on CO2 emissions: evidence from the MENA countries. Environ Econ Policy Stud 26, 285–305 (2024). https://doi.org/10.1007/s10018-022-00346-w

Bento, J. P. C., & Moutinho, V. (2016). CO2 emissions, non-renewable and renewable electricity production, economic growth, and international trade in Italy. Renewable and sustainable energy reviews, 55, 142-155.

Bibri, S. E., Krogstie, J., Kaboli, A., & Alahi, A. (2024). Smarter eco-cities and their leading-edge artificial intelligence of things solutions for environmental sustainability: A comprehensive systematic review. Environmental Science and Ecotechnology, 19, 100330. https://doi.org/10.1016/j.ese.2023.100330

Bilgili F, Kocak E, Bulut U, Kuskaya S (2017) Can biomass energy be an efficient policy tool for sustainable development? Renew Sustain Energy Rev 71:830–845

BP (2019) BP statistical review of world energy. https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2019-full-report.pdf. Accessed 14 Feb 2020.

Charfeddine, L., & Kahia, M. (2019). Impact of renewable energy consumption and financial development on CO2 emissions and economic growth in the MENA region: a panel vector autoregressive (PVAR) analysis. Renewable energy, 139, 198-213. https://doi.org/10.1016/j.renene.2019.01.010

Chattopadhyay A, Hassanzadeh P, Pasha S (2020) Predicting clustered weather patterns: a test case for applications of convolutional neural networks to spatio-temporal climate data. Sci Rep 10(1):1317. https://doi.org/10.1038/s41598-020-57897-9

Chen X, Gong X, Li D, Zhang J (2019) Can information and communication technology reduce CO2 emission? A quantile regression analysis. Environ Sci Pollut Res 26:32977–32992. https://doi.org/10.1007/s11356-019-06380-8

Chen, H., Tackie, E.A., Ahakwa, I. et al. RETRACTED ARTICLE: Does energy consumption, economic growth, urbanization, and population growth influence carbon emissions in the BRICS? Evidence from panel models robust to cross-sectional dependence and slope heterogeneity. Environ Sci Pollut Res 29, 37598–37616 (2022). https://doi.org/10.1007/s11356-021-17671-4

Cheng, Z., Li, L., & Liu, J. (2019). The effect of information technology on environmental pollution in China. Environmental Science and Pollution Research, 26(32), 33109-33124. https://doi.org/10.1007/s11356-019-06454-7

Chien, F., Hsu, CC., Moslehpour, M. et al. A step toward sustainable development: the nexus of environmental sustainability, technological advancement and green finance: evidence from Indonesia. Environ Dev Sustain 26, 11581–11602 (2024). https://doi.org/10.1007/s10668-023-03424-5

Choi C, Kim J, Kim J, Kim D, Bae Y, Kim HS (2018) Development of heavy rain damage prediction model using machine learning based on big data. In: Research article. Advances in meteorology. Hindawi. https://doi.org/10.1155/2018/5024930

Coroama VC, Hilty LM, Birtel M (2012) Effects of Internet-based multiple-site conferences on greenhouse gas emissions. Telemat Informatics 29:362–374. https://doi.org/10.1016/j.tele.2011.11.006

Dahmani, M., Mabrouki, M., & Ben Youssef, A. (2023). The ICT, financial development, energy consumption and economic growth nexus in MENA countries: dynamic panel CS-ARDL evidence. Applied Economics, 55(10), 1114-1128. https://doi.org/10.1080/00036846.2022.2096861

Dam, M. M., Durmaz, A., Bekun, F. V., & Tiwari, A. K. (2024). The role of green growth and institutional quality on environmental sustainability: A comparison of CO2 emissions, ecological footprint and inverted load capacity factor for OECD countries. Journal of Environmental Management, 365, 121551. https://doi.org/10.1016/j.jenvman.2024.121551

Danish (2019) Effects of information and communication technology and real income on CO2 emissions: The experience of countries along Belt and Road. Telemat Informatics 45:101300. https://doi.org/10.1016/j.tele.2019.101300

Danish, Ulucak R (2020) The pathway toward pollution mitigation: does institutional quality make a difference? Bus Strategy Environ 29:3571-3583

Danish, Ulucak R (2021) A revisit to the relationship between financial development and energy consumption? Is globalization paramount? Energy 227:1-8

Dar, J. A., & Asif, M. (2018). Does financial development improve environmental quality in Turkey? An application of endogenous structural breaks based cointegration approach. Management of Environmental Quality: An International Journal, 29(2), 368-384. https://doi.org/10.1108/MEQ-02-2017-0021

Datta, R. K. (2024). Bangladesh towards green growth: a review of environmental sustainability indicators. Journal of Environmental Science and Economics, 3(2), 17–40. https://doi.org/10.56556/jescae.v3i2.889

Davidson, R., & MacKinnon, J. G. (1993). Estimation and inference in econometrics (Vol. 63). New York: Oxford.

Dickey, D. A., & Fuller, W. A. (1981). Likelihood ratio statistics for autoregressive time series with a unit root. Econometrica: journal of the Econometric Society, 1057-1072. https://doi.org/10.2307/1912517

Dogan, A., & Pata, U. K. (2022). The role of ICT, R&D spending and renewable energy consumption on environmental quality: Testing the LCC hypothesis for G7 countries. Journal of Cleaner Production, 380, 135038. https://doi.org/10.1016/j.jclepro.2022.135038

Dogan, E., Ulucak, R., Kocak, E., & Isik, C. (2020). The use of ecological footprint in estimating the environmental Kuznets curve hypothesis for BRICS by considering cross-section dependence and heterogeneity. Science of the Total Environment, 723, 138063. https://doi.org/10.1016/j.scitotenv.2020.138063

Economic Commission for Latin America and the Caribbean (ECLAC), United States economic outlook: 2022 year-in-review and early 2023 developments (LC/WAS/TS.2023/2), Santiago, 2023. https://repositorio.cepal.org/server/api/core/bitstreams/4fc6db6a-0f7a-452f-ae3f-0f5b3ee16cae/content

Elias Megbetor, & Boateng, S. (2023). Examining the Implications of Climate Change and Adaptation Technologies on the Livelihood of Cocoa Farmers in Offinso Municipalities, Ghanas. Journal of Environmental Science and Economics, 2(3), 86–108. https://doi.org/10.56556/jescae.v2i3.641

Elliott, G., Rothenberg, T. J., & Stock, J. H. (1992). Efficient tests for an autoregressive unit root.

Engle RF, Granger CW (1987) Co-integration and error correction: representation, estimation, and testing. Econometrica: Journal of the Econometric Society 251–276

Engle, R. F., & Granger, C. W. (1987). Co-integration and error correction: representation, estimation, and testing. Econometrica: journal of the Econometric Society, 251-276. https://doi.org/10.2307/1913236

Erdogan, S. (2023). Linking natural resources and environmental sustainability: a panel data approach based on the load capacity curve hypothesis. Sustainable Development. https://doi.org/10.1002/sd.2836

Evans, S. Analysis: Coronavirus Set to Cause Largest Ever Annual Fall in CO2 Emissions. Carbon Brief. 2020. Available online: https://www.carbonbrief.org/analysis-coronavirus-set-to-cause-largest-ever-annual-fall-in-CO2-emissions/ (accessed on 13 March 2021).

Fakher, HA. Investigating the determinant factors of environmental quality (based on ecological carbon footprint index). Environ Sci Pollut Res 26, 10276–10291 (2019). https://doi.org/10.1007/s11356-019-04452-3

Fu, H., Huang, P., Xu, Y., & Zhang, Z. (2022). Digital trade and environmental sustainability: The role of financial development and ecological innovation for a greener revolution in China. Economic Research-Ekonomska Istrazivanja. https://doi.org/10.1080/1331677X.2022.2125889

Germanwatch (2019). Largest producers of territorial fossil fuel CO2 emissions worldwide in 2018, based on their share of global CO2 emissions [Graph]. In Statista. Retrieved December 23, 2019, from https://www.statista.com/statistics/271748/the-largest-emitters-of-co2-in-the-world

Global Footprint Network (GFN, 2022). Accessed on 20th March 2024. Available at: https://www.footprintnetwork.org/

Granata, F., Di Nunno, F. Artificial Intelligence models for prediction of the tide level in Venice. Stoch Environ Res Risk Assess 35, 2537–2548 (2021). https://doi.org/10.1007/s00477-021-02018-9

Granger, C. W. (1969). Investigating causal relations by econometric models and cross-spectral methods. Econometrica: journal of the Econometric Society, 424-438. https://doi.org/10.2307/1912791

Gupta, P. and Singh, A. (2016), "Causal nexus between foreign direct investment and economic growth: A study of BRICS nations using VECM and Granger causality test", Journal of Advances in Management Research, Vol. 13 No. 2, pp. 179-202. https://doi.org/10.1108/JAMR-04-2015-0028

Hamit-Haggar, M. (2012). Greenhouse gas emissions, energy consumption and economic growth: A panel cointegration analysis from Canadian industrial sector perspective. Energy Economics, 34(1), 358-364.

Harris, R., & Sollis, R. (2003). Applied Time Series Modelling and Forecasting.

Haseeb A, Xia E, Saud S, Ahmad A, Khurshid H (2019) Does information and communication technologies improve environmental quality in the era of globalization? An empirical analysis. Environ Sci Pollut Res 26:8594–8608. https://doi.org/10.1007/s11356-019-04296-x

Haseeb, A., Xia, E., Danish et al. Financial development, globalization, and CO2 emission in the presence of EKC: evidence from BRICS countries. Environ Sci Pollut Res 25, 31283–31296 (2018). https://doi.org/10.1007/s11356-018-3034-7

Hassan ST, Baloch MA, Mahmood N, Zhang J (2019) Linking economic growth and ecological footprint through human capital and biocapacity. Sustain Cities Soc 47:101516

He, B., Jie, W., He, H., Alsubih, M., Arnone, G., & Makhmudov, S. (2024). From resources to resilience: How green innovation, fintech and natural resources shape sustainability in OECD countries. Resources Policy, 91, 104856. https://doi.org/10.1016/j.resourpol.2024.104856

Hoang, TD., Ky, N.M., Thuong, N.T.N., Nhan, H.Q., Ngan, N.V.C. (2022). Artificial Intelligence in Pollution Control and Management: Status and Future Prospects. In: Ong, H.L., Doong, Ra., Naguib, R., Lim, C.P., Nagar, A.K. (eds) Artificial Intelligence and Environmental Sustainability. Algorithms for Intelligent Systems. Springer, Singapore. https://doi.org/10.1007/978-981-19-1434-8_2

https://www.worldometers.info/world-population/us-population/. Accessed 1 July 2024.

Hunjra, A. I., Bouri, E., Azam, M., Azam, R. I., & Dai, J. (2024). Economic growth and environmental sustainability in developing economies. Research in International Business and Finance, 70, 102341. https://doi.org/10.1016/j.ribaf.2024.102341

Idroes, G.M., Hardi, I., Rahman, M.H. et al. The dynamic impact of non-renewable and renewable energy on carbon dioxide emissions and ecological footprint in Indonesia. Carbon Res. 3, 35 (2024). https://doi.org/10.1007/s44246-024-00117-0

Imamoglu, H. The role of financial sector in energy demand and climate changes: evidence from the developed and developing countries. Environ Sci Pollut Res 26, 22794–22811 (2019). https://doi.org/10.1007/s11356-019-05499-y

International Monetary Fund (IMF, 2022). Accessed on 20th March 2024. Available at: https://data.imf.org/?sk=4c514d48-b6ba-49ed-8ab9-52b0c1a0179b&sId=-1

IPCC. Summary for Policymakers. In Global Warming of 1.5 °C; IPCC: Geneva, Switzerland, 2018.

Isfat, M., & Raihan, A. (2022). Current practices, challenges, and future directions of climate change adaptation in Bangladesh. Journal homepage: www. ijrpr. com ISSN, 2582, 7421.

Isik, C., Ongan, S., & Özdemir, D. (2019). The economic growth/development and environmental degradation: Evidence from the US state-level EKC hypothesis. Environmental Science and Pollution Research, 26(30), 30772–30781. https://doi.org/10.1007/s11356-019-06276-7

Jaafari A, Zenner EK, Panahi M, Shahabi H (2019) Hybrid artificial intelligence models based on a neuro-fuzzy system and metaheuristic optimization algorithms for spatial prediction of wildfire probability. Agric for Meteorol 266–267(March):198–207. https://doi.org/10.1016/j.agrformet.2018.12.015

Jabeen, Gul, Dong Wang, Cem Işık, Rafael Alvarado, and Serdar Ongan. "Role of energy utilization intensity, technical development, economic openness, and foreign tourism in environmental sustainability." Gondwana Research 127 (2024): 100-115. https://doi.org/10.1016/j.gr.2023.03.001

Jarrahi, M. H. (2018). Artificial intelligence and the future of work: Human-AI symbiosis in organizational decision making. Business horizons, 61(4), 577-586. https://doi.org/10.1016/j.bushor.2018.03.007

Jeste, D. V., Graham, S. A., Nguyen, T. T., Depp, C. A., Lee, E. E., & Kim, H. C. (2020). Beyond artificial intelligence: exploring artificial wisdom. International Psychogeriatrics, 32(8), 993-1001. https://doi.org/10.1017/S1041610220000927

Kao, C., & Chiang, M. H. (2001). On the estimation and inference of a cointegrated regression in panel data. In Nonstationary panels, panel cointegration, and dynamic panels (pp. 179-222). Emerald Group Publishing Limited. https://doi.org/10.1016/S0731-9053(00)15007-8

Katircioğlu, S. T., & Taşpinar, N. (2017). Testing the moderating role of financial development in an environmental Kuznets curve: empirical evidence from Turkey. Renewable and Sustainable Energy Reviews, 68, 572-586. https://doi.org/10.1016/j.rser.2016.09.127

Katircioglu, S., Katircioglu, S., & Kilinc, C. C. (2018). Investigating the role of urban development in the conventional environmental Kuznets curve: Evidence from the globe. Environmental Science and Pollution Research, 25(15), 15029–15035. https://doi.org/10.1007/s11356-018-1651-9

Kayani, G. M., Ashfaq, S., & Siddique, A. (2020). Assessment of financial development on environmental effect: implications for sustainable development. Journal of Cleaner Production, 261, 120984. https://doi.org/10.1016/j.jclepro.2020.120984

Khan, A.Q., Saleem, N. & Fatima, S.T. Financial development, income inequality, and CO2 emissions in Asian countries using STIRPAT model. Environ Sci Pollut Res 25, 6308–6319 (2018). https://doi.org/10.1007/s11356-017-0719-2

Khan, M. K., Teng, J. Z., Khan, M. I., & Khan, M. O. (2019). Impact of globalization, economic factors and energy consumption on CO2 emissions in Pakistan. Science of the total environment, 688, 424-436. https://doi.org/10.1016/j.scitotenv.2019.06.065

Khan, M. T. I., Yaseen, M. R., & Ali, Q. (2019). Nexus between financial development, tourism, renewable energy, and greenhouse gas emission in high-income countries: A continent-wise analysis. Energy Economics, 83, 293-310.

Khanzode, K. C. A., & Sarode, R. D. (2020). Advantages and disadvantages of artificial intelligence and machine learning: A literature review. International Journal of Library & Information Science (IJLIS), 9(1), 3.

Kinnunen, J., Georgescu, I., & Nica, I. (2024). Evaluating the Environmental Phillips Curve Hypothesis in the STIRPAT Framework for Finland. Sustainability, 16(11), 4381. https://doi.org/10.3390/su16114381

Kumo, W. L. (2012). Infrastructure investment and economic growth in South Africa: A granger causality analysis. African development bank group working paper series, 160.

Kunduru, A. R. (2023). Artificial intelligence usage in cloud application performance improvement. Central Asian Journal of Mathematical Theory and Computer Sciences, 4(8), 42-47.

Lashkarizadeh, M., & Salatin, P. (2012). The effects of information and communications technology (ICT) on air pollution. Elixir Pollut, 46, 8058-8064.

Lin, B., & Ullah, S. (2023). Towards the goal of going green: Do green growth and innovation matter for environmental sustainability in Pakistan. Energy, 285, 129263. https://doi.org/10.1016/j.energy.2023.129263

Lu W (2018) The impacts of information and communication technology, energy consumption, financial development, and economic growth on carbon dioxide emissions in 12 Asian countries

Magazzino, C., Mele, M., Schneider, N., & Sarkodie, S. (2021). Waste generation, wealth and ghg emissions from the waste sector: is denmark on the path towards circular economy?. The Science of the Total Environment, 755, 142510. https://doi.org/10.1016/j.scitotenv.2020.142510

Microsoft (2018) The carbon benefits of cloud computing: a study on the Microsoft Cloud

Mohammed, S., Gill, A. R., Ghosal, K., Al-Dalahmeh, M., Alsafadi, K., Szabó, S., ... & Harsanyi, E. (2024). Assessment of the environmental kuznets curve within EU-27: Steps toward environmental sustainability (1990–2019). Environmental Science and Ecotechnology, 18, 100312. https://doi.org/10.1016/j.ese.2023.100312

Mokhtar A. 1994. Regression Analysis. Kuala Lumpur: Dewan Bahasa dan Pusaka.

Mughal, N., Wen, J., Zhang, Q., Pekergin, Z. B., Ramos-Meza, C. S., & Pelaez-Diaz, G. (2024). Economic, social, and political determinants of environmental sustainability: Panel data evidence from NEXT eleven economies. Energy & Environment, 35(1), 64-87. https://doi.org/10.1177/0958305X221124224

N’dri, L. M., Islam, M., & Kakinaka, M. (2021). ICT and environmental sustainability: any differences in developing countries?. Journal of Cleaner Production, 297, 126642. https://doi.org/10.1016/j.jclepro.2021.126642

Nathaniel S, Anyanwu O, Shah M (2020) Renewable energy, urbanization, and ecological footprint in the Middle East and North Africa region. Environ Sci Pollut Res 27:14601–14613 1-13. https://doi.org/10.1007/s11356-020-08017-7

Nathaniel S, Nwodo O, Adediran A, Sharma G, Shah M, Adeleye N (2019) Ecological footprint, urbanization, and energy consumption in South Africa: including the excluded. Environ Sci Pollut Res 26:27168–27179 1-12

Oje, G. (2024). The Threshold level of Institutional Quality in the Nexus between Financial Development and Environmental Sustainability in Nigeria. Journal of Environmental Science and Economics, 3(1), 42-64.

Omri, A., Euchi, J., Hasaballah, A. H., & Al-Tit, A. (2019). Determinants of environmental sustainability: evidence from Saudi Arabia. Science of the Total Environment, 657, 1592-1601. https://doi.org/10.1016/j.scitotenv.2018.12.111

Opoku-Mensah, E., Chun, W., Ofori, E. K., Ampofo, S. A., Chen, W., & Appiah-Otoo, I. (2024). Revisiting the role of ICT and green institutional governance in environmental sustainability and proposing an ecological footprint mitigation pathway using a volatility-driven model. Journal of Cleaner Production, 434, 139824. https://doi.org/10.1016/j.jclepro.2023.139824

Our World in Data (2022). Accessed on 20th March 2024. Available at: https://ourworldindata.org/

Ozcan B, Apergis N (2018) The impact of internet use on air pollution: evidence from emerging countries. Environ Sci Pollut Res 25(5):4174–4189. https://doi.org/10.1007/s11356-017-0825-1

Ozturk, I., Farooq, S., Majeed, M. T., & Skare, M. (2024). An empirical investigation of financial development and ecological footprint in South Asia: Bridging the EKC and pollution haven hypotheses. Geoscience Frontiers, 15(4), 101588. https://doi.org/10.1016/j.gsf.2023.101588

Park Y, Meng F, Baloch MA (2018) The effect of ICT, financial development, growth, and trade openness on CO2 emissions: an empirical analysis. Environ Sci Pollut Res 25(30):30708–30719. https://doi.org/10.1007/s11356-018-3108-6

Park, J. Y. (1992). Canonical cointegrating regressions. Econometrica: Journal of the Econometric Society, 119-143. https://doi.org/10.2307/2951679

Pata, U. K. (2021). Do renewable energy and health expenditures improve load capacity factor in the USA and Japan? A new approach to environmental issues. The European Journal of Health Economics, 22(9), 1427–1439. https://doi.org/10.1007/s10198-021-01321-0

Pata, U. K., & Kartal, M. T. (2023). Impact of nuclear and renewable energy sources on environment quality: Testing the EKC and LCC hypotheses for South Korea. Nuclear Engineering and Technology, 55(2), 587-594. https://doi.org/10.1016/j.net.2022.10.027

Pata, U. K., Kartal, M. T., Erdogan, S., & Sarkodie, S. A. (2023). The role of renewable and nuclear energy R&D expenditures and income on environmental quality in Germany: Scrutinizing the EKC and LCC hypotheses with smooth structural changes. Applied Energy, 342, 121138. https://doi.org/10.1016/j.apenergy.2023.121138

Pattak, D. C., Tahrim, F., Salehi, M., Voumik, L. C., Akter, S., Ridwan, M., ... & Zimon, G. (2023). The driving factors of Italy’s CO2 emissions based on the STIRPAT model: ARDL, FMOLS, DOLS, and CCR approaches. Energies, 16(15), 5845. https://doi.org/10.3390/en16155845

Pesaran, M. H., Shin, Y., & Smith, R. J. (2001). Bounds testing approaches to the analysis of level relationships. Journal of applied econometrics, 16(3), 289-326. https://doi.org/10.1002/jae.616

Petrović, P., Lobanov, M.M. Impact of financial development on CO2 emissions: improved empirical results. Environ Dev Sustain 24, 6655–6675 (2022). https://doi.org/10.1007/s10668-021-01721-5

Phillips, P. C., & Perron, P. (1988). Testing for a unit root in time series regression. biometrika, 75(2), 335-346. https://doi.org/10.1093/biomet/75.2.335

Plepys, A. (2002). The grey side of ICT. Environmental impact assessment review, 22(5), 509-523. https://doi.org/10.1016/S0195-9255(02)00025-2

Polcyn, J., Voumik, L. C., Ridwan, M., Ray, S., & Vovk, V. (2023). Evaluating the influences of health expenditure, energy consumption, and environmental pollution on life expectancy in Asia. International Journal of Environmental Research and Public Health, 20(5), 4000. https://doi.org/10.3390/ijerph20054000

Qayyum, M., Zhang, Y., Ali, M., & Kirikkaleli, D. (2024). Towards environmental sustainability: The role of information and communication technology and institutional quality on ecological footprint in MERCOSUR nations. Environmental Technology & Innovation, 34, 103523. https://doi.org/10.1016/j.eti.2023.103523

Qian, Y., Song, K., Hu, T., & Ying, T. (2018). Environmental status of livestock and poultry sectors in China under current transformation stage. Science of the Total Environment, 622, 702-709. https://doi.org/10.1016/j.scitotenv.2017.12.045

Rafindadi AA, Muye IM, Kaita RA (2018) The effects of FDI and energy consumption on environmental pollution in predominantly resource-based economies of the GCC. Sustainable Energy Technologies and Assessments 25:126–137 https://doi.org/10.1016/j.seta.2017.12.008

Raheem ID, Tiwari AK, Balsalobre-Lorente D (2020) The role of ICT and financial development in CO2 emissions and economic growth. Environ Sci Pollut Res 27:1912–1922. https://doi.org/10.1007/s11356-019-06590-0

Rahman, M. M., & Alam, K. (2021). Clean energy, population density, urbanization and environmental pollution nexus: Evidence from Bangladesh. Renewable Energy, 172, 1063-1072. https://doi.org/10.1016/j.renene.2021.03.103

Rahman, M. M., & Halim, M. A. (2024). Does the export-to-import ratio affect environmental sustainability? Evidence from BRICS countries. Energy & Environment, 35(2), 904-926. https://doi.org/10.1177/0958305X221134946

Raihan, A. (2023). A review of the global climate change impacts, adaptation strategies, and mitigation options in the socio-economic and environmental sectors. Journal of Environmental Science and Economics, 2(3), 36-58.

Raihan, A. (2024). The influence of tourism on the road to achieving carbon neutrality and environmental sustainability in Malaysia: The role of renewable energy. Sustainability Analytics and Modeling, 4, 100028. https://doi.org/10.1016/j.samod.2023.100028

Raihan, A., & Tuspekova, A. (2022). Dynamic impacts of economic growth, energy use, urbanization, agricultural productivity, and forested area on carbon emissions: New insights from Kazakhstan. World Development Sustainability, 1, 100019. https://doi.org/10.1016/j.wds.2022.100019

Raihan, A., Atasoy, F. G., Atasoy, M., Ridwan, M., & Paul, A. (2022). The role of green energy, globalization, urbanization, and economic growth toward environmental sustainability in the United States. Journal of Environmental and Energy Economics, 1(2), 8-17. https://doi.org/10.56946/jeee.v1i2.377

Raihan, A., Bala, S., Akther, A., Ridwan, M., Eleais, M., & Chakma, P. (2024b). Advancing environmental sustainability in the G-7: The impact of the digital economy, technological innovation, and financial accessibility using panel ARDL approach. Journal of Economy and Technology. https://doi.org/10.1016/j.ject.2024.06.001

Raihan, A., Rashid, M., Voumik, L. C., Akter, S., & Esquivias, M. A. (2023). The dynamic impacts of economic growth, financial globalization, fossil fuel, renewable energy, and urbanization on load capacity factor in Mexico. Sustainability, 15(18), 13462. https://doi.org/10.3390/su151813462

Raihan, A., Tanchangya, T., Rahman, J., & Ridwan, M. (2024a). The Influence of Agriculture, Renewable Energy, International Trade, and Economic Growth on India's Environmental Sustainability. Journal of Environmental and Energy Economics, 37-53. https://doi.org/10.56946/jeee.v3i1.324

Raihan, A., Tanchangya, T., Rahman, J., Ridwan, M., & Ahmad, S. (2022). The influence of Information and Communication Technologies, Renewable Energies and Urbanization toward Environmental Sustainability in China. Journal of Environmental and Energy Economics, 1(1), 11-23. https://doi.org/10.56946/jeee.v1i1.351

Raihan, A., Voumik, L. C., Ridwan, M., Ridzuan, A. R., Jaaffar, A. H., & Yusoff, N. Y. M. (2023). From growth to green: navigating the complexities of economic development, energy sources, health spending, and carbon emissions in Malaysia. Energy Reports, 10, 4318-4331. https://doi.org/10.1016/j.egyr.2023.10.084

Ramzan, M., Raza, S. A., Usman, M., Sharma, G. D., & Iqbal, H. A. (2022). Environmental cost of non-renewable energy and economic progress: do ICT and financial development mitigate some burden?. Journal of Cleaner Production, 333, 130066.

Rana, M. N. U., Al Shiam, S. A., Shochona, S. A., Islam, M. R., Asrafuzzaman, M., Bhowmik, P. K., ... & Asaduzzaman, M. (2024). Revolutionizing Banking Decision-Making: A Deep Learning Approach to Predicting Customer Behavior. Journal of Business and Management Studies, 6(3), 21-27.

Rane, N. (2023). ChatGPT and Similar Generative Artificial Intelligence (AI) for Smart Industry: role, challenges and opportunities for industry 4.0, industry 5.0 and society 5.0. Challenges and Opportunities for Industry, 4. https://dx.doi.org/10.2139/ssrn.4603234

Rasheed, M. (2024). Renewable energy adoption and CO2 emissions in G7 economies: In-depth analysis of economic prosperity and trade relations. Journal of Environmental Science and Economics, 3(2), 41–66. https://doi.org/10.56556/jescae.v3i2.839

Ravi Kumar, K. N., Reddy, K. G., Mohan Reddy, M. J., & Shafiwu, A. B. (2024). Unveiling the interplay between climate variability and economic growth in India: an auto regressive distributed lag (ARDL) framework. Cogent Social Sciences, 10(1), 2352507. https://doi.org/10.1080/23311886.2024.2352507

Ray, R. K., Chowdhury, F. R., & Hasan, M. R. (2024). Blockchain Applications in Retail Cybersecurity: Enhancing Supply Chain Integrity, Secure Transactions, and Data Protection. Journal of Business and Management Studies, 6(1), 206-214. Doi: https://doi.org/10.32996/jbms.2024.6.1.13

Ridwan, M. (2023). Unveiling the powerhouse: Exploring the dynamic relationship between globalization, urbanization, and economic growth in Bangladesh through an innovative ARDL approach.

Ridwan, M., Raihan, A., Ahmad, S., Karmakar, S., & Paul, P. (2023). Environmental sustainability in France: The role of alternative and nuclear energy, natural resources, and government spending. Journal of Environmental and Energy Economics, 2(2), 1-16. https://doi.org/10.56946/jeee.v2i2.343

Ridwan, M., Urbee, A. J., Voumik, L. C., Das, M. K., Rashid, M., & Esquivias, M. A. (2024). Investigating the environmental Kuznets curve hypothesis with urbanization, industrialization, and service sector for six South Asian Countries: Fresh evidence from Driscoll Kraay standard error. Research in Globalization, 8, 100223.

Ridzuan, A. R., Rahman, N. H. A., Singh, K. S. J., Borhan, H., Ridwan, M., Voumik, L. C., & Ali, M. (2023, May). Assessing the Impact of Technology Advancement and Foreign Direct Investment on Energy Utilization in Malaysia: An Empirical Exploration with Boundary Estimation. In International Conference on Business and Technology (pp. 1-12). Cham: Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-55911-2_1

Robinson C, Dilkina B (2018) A machine learning approach to modeling human migration. In: Proceedings of the 1st ACM SIGCAS conference on computing and sustainable societies. COMPASS '18. Association for Computing Machinery, Menlo Park and San Jose, pp 1–8. https://doi.org/10.1145/3209811.3209868

Sadorsky P (2011) Financial development and energy consumption in central and eastern European frontier economies. Energy Policy 39:999–1006. https://doi.org/10.1016/j.enpol.2010.11.034

Sahoo, M., Gupta, M., & Srivastava, P. (2021). Does information and communication technology and financial development lead to environmental sustainability in India? An Empirical Insight. Telematics and Informatics, 60, 101598.

Salahuddin M, Alam K, Ozturk I (2016) The effects of Internet usage and economic growth on CO2 emissions in OECD countries: a panel investigation. Renew Sustain Energy Rev 62:1226–1235

Saqib, N., Usman, M., Ozturk, I., & Sharif, A. (2024). Harnessing the synergistic impacts of environmental innovations, financial development, green growth, and ecological footprint through the lens of SDGs policies for countries exhibiting high ecological footprints. Energy Policy, 184, 113863. https://doi.org/10.1016/j.enpol.2023.113863

Saud, S., Chen, S., Danish et al. Impact of financial development and economic growth on environmental quality: an empirical analysis from Belt and Road Initiative (BRI) countries. Environ Sci Pollut Res 26, 2253–2269 (2019). https://doi.org/10.1007/s11356-018-3688-1

Seetanah, B., Sannassee, R. V., Fauzel, S., Soobaruth, Y., Giudici, G., & Nguyen, A. P. H. (2019). Impact of economic and financial development on environmental degradation: evidence from small island developing states (SIDS). Emerging Markets Finance and Trade, 55(2), 308-322. https://doi.org/10.1080/1540496X.2018.1519696

Shang, Y., Razzaq, A., Chupradit, S., Binh An, N., & Abdul-Samad, Z. (2022). The role of renewable energy consumption and health expenditures in improving load capacity factor in ASEAN countries: Exploring new paradigm using advance panel models. Renewable Energy, 191, 715–722. https://doi.org/10.1016/j.renene.2022.04.013

Siche R, Pereira L, Agostinho F, Ortega E (2010) Convergence of ecological footprint and energy analysis as a sustainability indicator of countries: Peru as case study. Commun Nonlinear Sci Numer Simul 15(10):3182–3192

Solarin, S.A., Nathaniel, S.P., Bekun, F.V. et al. Towards achieving environmental sustainability: environmental quality versus economic growth in a developing economy on ecological footprint via dynamic simulations of ARDL. Environ Sci Pollut Res 28, 17942–17959 (2021). https://doi.org/10.1007/s11356-020-11637-8

Solaymani, S., & Montes, O. (2024). The role of financial development and good governance in economic growth and environmental sustainability. Energy Nexus, 13, 100268. https://doi.org/10.1016/j.nexus.2023.100268

Stock, J. H. (1994). Unit roots, structural breaks and trends. Handbook of econometrics, 4, 2739-2841. https://doi.org/10.1016/S1573-4412(05)80015-7

Sun, Y., Usman, M., Radulescu, M., Pata, U. K., & Balsalobre-Lorente, D. (2024). New insights from the STIPART model on how environmental-related technologies, natural resources and the use of the renewable energy influence load capacity factor. Gondwana Research, 129, 398-411. https://doi.org/10.1016/j.gr.2023.05.018

Tan, K. L., & Samsudin, H. B. (2022). Relationship between foreign direct investment (FDI) of the service sector and GDP in Malaysia. Journal of Quality Measurement and Analysis, 18(3), 95-109.

Thadewald, T., & Büning, H. (2007). Jarque–Bera test and its competitors for testing normality–a power comparison. Journal of applied statistics, 34(1), 87-105.

Tian, J., Yu, L., Xue, R., Zhuang, S., & Shan, Y. (2022). Global low-carbon energy transition in the post-COVID-19 era. Applied energy, 307, 118205. https://doi.org/10.1016/j.apenergy.2021.118205

Ukoba, K., Fadare, O., & Jen, T. C. (2019, December). Powering Africa using an off-grid, stand-alone, solar photovoltaic model. In Journal of Physics: Conference Series (Vol. 1378, No. 2, p. 022031). IOP Publishing. https://doi.org/10.1088/1742-6596/1378/2/022031

Ullah, A., Dogan, M., Pervaiz, A., Bukhari, A. A. A., Akkus, H. T., & Dogan, H. (2024). The impact of digitalization, technological and financial innovation on environmental quality in OECD countries: Investigation of N-shaped EKC hypothesis. Technology in Society, 77, 102484. https://doi.org/10.1016/j.techsoc.2024.102484

Ulucak ZŞ, İlkay SÇ, Burcu Özcan AG (2020) Financial globalization and environmental degradation nexus: evidence from emerging economies. Resour Policy. https://doi.org/10.1016/j.resourpol.2020.101698

Ulucak, R., & Khan, S. U. D. (2020). Does information and communication technology affect CO2 mitigation under the pathway of sustainable development during the mode of globalization? Sustainable Development, 28(4), 857–867. https://doi.org/10.1002/sd.2041

UNEP. Emissions Gap Report 2019. United Nations Environment Programme, Nairobi. 2019. Available online: http://www.unenvironment.org/emissionsgap (accessed on 26 October 2021).

Urbee, A. J., Ridwan, M., & Raihan, A. (2024). Exploring Educational Attainment among Individuals with Physical Disabilities: A Case Study in Bangladesh. Journal of Integrated Social Sciences and Humanities. https://doi.org/10.62836/jissh.v1i1.181

Usman, M., Chughtai, S., Rashid, A. et al. Disaggregated financial development and ecological sustainability: the critical role of urbanization, energy utilization, and economic growth in next 11 economies. Environ Dev Sustain 26, 11455–11474 (2024). https://doi.org/10.1007/s10668-023-03368-w

Usman, M., Jahanger, A., Makhdum, M. S. A., Balsalobre-Lorente, D., & Bashir, A. (2022). How do financial development, energy consumption, natural resources, and globalization affect Arctic countries' economic growth and environmental quality? An advanced panel data simulation. Energy, 241, 122515. https://doi.org/10.1016/j.energy.2021.122515

Usman, O., Akadiri, S.S. & Adeshola, I. Role of renewable energy and globalization on ecological footprint in the USA: implications for environmental sustainability. Environ Sci Pollut Res 27, 30681–30693 (2020). https://doi.org/10.1007/s11356-020-09170-9

Verma, D., Okhawilai, M., Dalapati, G., Ramakrishna, S., Sharma, A., Sonar, P., … & Sharma, M. (2022). Blockchain technology and ai-facilitated polymers recycling: utilization, realities, and sustainability. Polymer Composites, 43(12), 8587-8601. https://doi.org/10.1002/pc.27054

Voumik, L. C., & Ridwan, M. (2023). Impact of FDI, industrialization, and education on the environment in Argentina: ARDL approach. Heliyon, 9(1). https://doi.org/10.1016/j.heliyon.2023.e12872

Voumik, L. C., Akter, S., Ridwan, M., Ridzuan, A. R., Pujiati, A., Handayani, B. D., ... & Razak, M. I. M. (2023a). Exploring the factors behind renewable energy consumption in Indonesia: Analyzing the impact of corruption and innovation using ARDL model. International Journal of Energy Economics and Policy, 13(5), 115-125. https://doi.org/10.32479/ijeep.14530

Voumik, L. C., Rahman, M. H., Rahman, M. M., Ridwan, M., Akter, S., & Raihan, A. (2023b). Toward a sustainable future: Examining the interconnectedness among Foreign Direct Investment (FDI), urbanization, trade openness, economic growth, and energy usage in Australia. Regional Sustainability, 4(4), 405-415. https://doi.org/10.1016/j.regsus.2023.11.003

Voumik, L. C., Ridwan, M., Rahman, M. H., & Raihan, A. (2023c). An investigation into the primary causes of carbon dioxide releases in Kenya: Does renewable energy matter to reduce carbon emission?. Renewable Energy Focus, 47, 100491. https://doi.org/10.1016/j.ref.2023.100491

World Bank (2020) World Bank open data. https://data.worldbank.org/. Accessed 24 Mar 2020.

World Development Indicator (WDI, 2022). Accessed on 20th March 2024. Available at: https://databank.worldbank.org/source/world-development-indicators

Worldometer (2024) worldometer (United States Population open data).

Wu L, Jia X, Gao L, Zhou Y (2021a) Effects of population flow on regional carbon emissions: evidence from China. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-021-15131-7

Wu, R., Wang, J., Wang, S., & Feng, K. (2021b). The drivers of declining CO2 emissions trends in developed nations using an extended STIRPAT model: A historical and prospective analysis. Renewable and Sustainable Energy Reviews, 149, 111328. https://doi.org/10.1016/j.rser.2021.111328

Wu, Y., Anwar, A., Quynh, N.N. et al. Impact of economic policy uncertainty and renewable energy on environmental quality: testing the LCC hypothesis for fast growing economies. Environ Sci Pollut Res 31, 36405–36416 (2024). https://doi.org/10.1007/s11356-023-30109-3

Xie, Q., Yan, Y. & Wang, X. Assessing the role of foreign direct investment in environmental sustainability: a spatial semiparametric panel approach. Econ Change Restruct 56, 1263–1295 (2023). https://doi.org/10.1007/s10644-022-09470-9

Xu, D., Salem, S., Awosusi, A. A., Abdurakhmanova, G., Altuntaş, M., Oluwajana, D., Kirikkaleli, D., & Ojekemi, O. (2022). Load Capacity Factor and Financial Globalization in Brazil: The Role of Renewable Energy and Urbanization. Frontiers in Environmental Science. https://doi.org/10.3389/fenvs.2021.823185

Xu, Z., Baloch, M.A., Danish et al. Nexus between financial development and CO2 emissions in Saudi Arabia: analyzing the role of globalization. Environ Sci Pollut Res 25, 28378–28390 (2018). https://doi.org/10.1007/s11356-018-2876-3

Xulu. (2024). Digital transformation and enterprise dual innovation: Evidence from China's A-share listed companies. Journal of Environmental Science and Economics, 3(2), 67–89. https://doi.org/10.56556/jescae.v3i2.897

Yadav, M., & Singh, G. (2023). Environmental sustainability with artificial intelligence. EPRA International Journal of Multidisciplinary Research (IJMR), 9(5), 213-217. https://doi.org/10.36713/epra13325

Yang, M., She, D., Abbas, S., Ai, F., & Adebayo, T. S. (2023). Environmental cost of financial development within the framework of the load capacity curve hypothesis in the BRICS economies: Do renewable energy consumption and natural resources mitigate some burden?. Geological Journal, 58(10), 3915-3927. https://doi.org/10.1002/gj.4817

Yao, X., Yasmeen, R., Hussain, J., & Shah, W. U. H. (2021). The repercussions of financial development and corruption on energy efficiency and ecological footprint: evidence from BRICS and next 11 countries. Energy, 223, 120063. https://doi.org/10.1016/j.energy.2021.120063

Yeh, J. C., & Liao, C. H. (2017). Impact of population and economic growth on carbon emissions in Taiwan using an analytic tool STIRPAT. Sustainable Environment Research, 27(1), 41-48. https://doi.org/10.1016/j.serj.2016.10.001

Yousefi, A. (2015). A Panel Granger causality test of investment in ICT capital and economic growth: Evidence from developed and developing countries. Economics World, 3(5-6), 109-127. https://doi.org/10.17265/23287144/2015.0506.001

Yuxiang, K., & Chen, Z. (2010). Financial development and environmental performance: evidence from China.

Zaidi, S. A. H., Zafar, M. W., Shahbaz, M., & Hou, F. (2019). Dynamic linkages between globalization, financial development and carbon emissions: evidence from Asia Pacific Economic Cooperation countries. Journal of cleaner production, 228, 533-543. https://doi.org/10.1016/j.jclepro.2019.04.210

Zhang C, Liu C (2015) The impact of ICT industry on CO2 emissions: a regional analysis in China. Renew Sust Energ Rev 44:12–19. https://doi.org/10.1016/j.rser.2014.12.011

Ziemba, E. W., & Grabara, D. (2024). Sustainability affected by ICT adoption in enterprises. Journal of Computer Information Systems, 1-19. https://doi.org/10.1080/08874417.2024.2321529

RESEARCH ARTICLE

Climate Change Intersecting Socio-economic Vulnerabilities of Kalash Indigenous Community in Nothern Pakistan

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Abstract
Climate Change has a significant effect on all walks of life or human activities across the world. However, indigenous communities in different parts of the world are more susceptible to the worst effects of climate change due to their dependency on natural resources. Climate change directly affects natural resources such as forests, water, grazing land, bio-diversity and traditional foods of indigenous communities. This study explores how climate change overlaps or intersects the socio-economic, and bio-cultural marginality of the Kalash indigenous community, living in northern Pakistan. The qualitative research paradigm was used to explore how climate change overlaps or intersects the socio-economic marginality of the Kalash Indigenous community. It reveals that climate change has significantly affected natural resources such as water, biodiversity, forests and crops of Kalash's indigenous community. Climate-induced natural disasters affected their livelihood resources and compelled them to migrate or be displaced from their native town. It reveals that climate change also affects women's marginality in Kalash's indigenous community. It also reveals that climate change overlaps and intersects with the socio-economic marginality of Indigenous communities and policymakers should give priority to indigenous communities who have a dependency on natural resources to protect them from the worst effect of climate change across the world.

Keywords: Climate Change; Kalash Indigenous Community; Natural Resources; Intersectionality; Socio-economic Marginality

Introduction

Changes in temperature, greenhouse gas concentration and variations in weather patterns significantly affect human activities across the world (Forster, Smith, Walsh, Lamb, Palmer, von Schuckmann, & Zhai, 2023). However, variation in weather patterns or climate change has a direct impact on rural or indigenous communities because they have a dependency on natural resources. For their livelihood, they are dependent on forest, rainwater and traditional food. However, Indigenous communities face the worst effects of climate change in different parts of the world and their dependency on natural resources, traumatic colonial history and worst post-colonial policies make them more susceptible to its worst effects (Lansbury Hall & Crosby, 2022). Hence, climate change intersects or overlaps with their socio-economic marginality.

It is believed that Indigenous communities comprise six per cent of the global population. However, they care about eighty per cent of the world's biodiversity or natural resources (Brubacher, Chen, Longboat, Dodd, Peach, Elliott, & Neufeld, 2024). Indigenous communities lost medicinal plants that badly affected their health and they used different medicinal plants for the treatment of various types of diseases (Redvers, Aubrey, Celidwen, & Hill 2023). Moreover, climate change disturbs the rain cycle, causes flooding, and affects the biodiversity and livestock of the indigenous communities and these effects overlap or intersect indigenous communities' marginalities. Moreover, climate-induced disasters affect crops, livestock and agricultural and grazing land of indigenous communities. Briefly, climate change has disturbed all walks of life and livelihood resources. Climate change like other indigenous communities affects the livelihood resources of Kalash indigenous people. The Kalash Indigenous community live in the mountainous region of north-west, Khyber Pakhtunkhwa) Pakistan. The population is 3000 thousand to 4000 thousand of the Kalash indigenous community (Ishaq & Ghilzai, 2020). They live in a hostile (both social and physical) environment that poses numerous threats to their survival including climate-induced disasters. Bio-diversity loss, disasters, and displacement threaten their physical and cultural survival. It is observed, that the Kaslash indigenous community population has been decreasing and facing the worst kind of socio-political and economic problems. Pakistan as a state has failed to protect the rights of this small ethnic and religious indigenous community (Siddiqui, 2023).They uphold polytheistic beliefs, distinctive culture, and social setup within a predominated Muslim state. They have been facing various socio-economic problems in Pakistan.

The majority of the Kalash indigenous community lives under the poverty line.The government of Pakistan in the post-colonial period has failed to address the socio-economic and survival issues in their native places. Kalash's indigenous community has been facing the worst of discrimination in socio-economic, and political matters in Pakistan. The British colonial regime in the colonial era and Pakistan in the post-colonial era did not initiate any program to address their socio-economic vulnerabilities (Kalash, 2022).Kalash's indigenous community's colonial history and post-colonial suppression further intersect their marginality. The injustices they faced in the past, and also the post-colonial period make them more vulnerable to climate change (Bicker, Ellen,& Parkes, 2003). It is argued that climate change further intersects their marginality (Karrar & Mostowlansky, 2018). It intensifies pre-existing vulnerabilities of the Kalash community. Moreover, climate-induced disasters increase the ratio of displacement from their native town. They have lost their cultural values and traditions due to climate-induced displacement. Hence, this research article focuses on how climate change overlaps or intersects with the Kalash indigenous community's volunerbalities. This research article also explores the climate change impact on their limited livelihood resources such as forests, domesticated animals, agricultural land, grazing land and crops. Intersectionality theory is applied to understand climate change's intersecting impact on the Kalash indigenous community.

Kalash Indigenous Community and Their Ways of Life

As mentioned above, the Kalash indigenous community lives in district Chitral, Khyber Pakhtunkhwa, Pakistan. They live in mountainous and difficult geographical terrain. Their geographical region is prone to land sliding especially in monsoon season (Choudhry, Golden, & Sang-Ah Park, 2024). Kalash people speak the Kalasha language (it is known as Kalasha-mun) and belong to Indo-Aryan stock. They have unique religions, customs, traditions and food. The Kalash people are the followers of the traditional Kalasha religion which is a form of animism and ancestor worship mixed with ancient Hinduism. They have a distinctive socio-cultural and religious identity. Moreover, in their native town, they are dependent on natural resources such as timber, crops, fruits and domesticated animals (Uddin, 2019). Agriculture is a main source of livelihood but they have limited low land and mainly live in mountainous regions. Variations in weather patterns or rain cycles create problems for them to find pasture for domesticated animals. Variation in the rain cycle has a direct impact on the grazing land. Moreover, they cultivate wheat, maize, vegetables and different types of fruits. These are the cash crops of Kalash's indigenous community. They purchase agricultural products in the local market (Fentz, 1996). However, climate change has significantly affected their productivity and it barely fulfils their family needs now. They have no cash crops now. They face problems in fulfilling other needs after the worst effect of climate change on their agricultural products. They used trees for heat or domestic use and purchased timber in the local market. Many Kalasha community members are doing timber or fruit business However, the scarcity of trees or forests often causes conflict among the Kalasha community. They are leaving the timber business and this business is not enough to fulfil their family expenditure (Zeb, Hamann, Armstrong, & Acuna-Castellanos, 2019). Moreover, the family is the basic unit and performs economic and security functions Family institutions perform socio-economic, caring and caring of children functions. The majority of them live in joint families but some of Kalash's indigenous community members live in nuclear families as well (Ali & Chawla, 2019). They have a patriarchal structure, where men make major decisions. However, it is not a strict type of patriarchy and women are allowed to take part in all walks of life. They have strong family ties and social networks. Moreover, in religious or wedding ceremonies, traditionally they knock goat and sheep meat or any other traditional food. Moreover, they used different plants as a traditional medicine and they live in remote areas and have no easy access to medical facilities in their native places. They cannot afford health expenditures and also cannot afford the educational expenses of their children (Parkes, 1987). In short, they have been facing socio-economic and political problems. The following line explains the theoretical framework of this study, and how climate change overlaps or intersects with the existing socio-economic problems of the Kalash indigenous community.

Theoretical Framework

Indigenous communities are dependent on natural resources as mentioned above. However, climate change directly affects the natural resources that intersect the socio-economic vulnerability of indigenous communities. Hence, the intersectional theory presented by Kimberlé Williams Crenshaw in 1989 provides theoretical insight to this study (Carastathis, 2014). The intersectional theory refers to socio-cultural or environmental factors that overlap or intersect with associated oppressive, dominating, or discriminatory systems (Kaijser, & Kronsell, 2014).This theory provides theoretical insight to understand the climate change effect on the already marginalized position of the Kalash indigenous community living in the periphery of Pakistan. Kalash's indigenous community remained oppressed in the colonial and post-colonial eras. They have also been facing discriminating policies in the post-colonial times after the emergence of Pakistan. They live under the poverty line and do not have access to health and educational facilities in their native region. Climate change further intersects with their already marginalized position. Therefore, the theory of intersectionality provides theoretical insight into this study of how climate change overlaps or intersects with the oppressed or marginalized position of the Kalash indigenous community.

Methodology of the Study

A qualitative research paradigm was used to understand the climate change effect on the Kalash indigenous community. The data was collected through participant observation and in-depth interviews with both men and women. Climate change differently affects men and women, therefore, the primary data was collected from both men and women of Kalash indigenous communities. Moreover, the primary data was thematically analysed to understand the climate change effect on the Kalash indigenous community living in northern Pakistan. The primary data juxtaposed with the secondary data to understand the climate change interaction with the socio-economic marginality of Indigenous people living in the peripheries in the different parts of the world.

Theorizing Effects of Climate Change on Indigenous Communities

Indigenous communities are more vulnerable to climate change (Datta, & Kairy, 2024).They lose their traditional knowledge due to rapidly changing ecological conditions. Climate change increases the risk of food insecurity and also significantly affects the traditional foods of indigenous communities in different parts of the world (Reyes-García, Álvarez-Fernández, Benyei, P., Calvet-Mir, Chambon, M., García-del-Amo, and Tofighi-Niaki, 2023). Moreover, climate change creates scarcity of water and also causes climate-induced disasters which significantly affect indigenous communities. Climate-induced disasters relocate them from their historical homelands (Ngcamu, 2023).As a result of relocation, they lose their traditions, customs and traditional knowledge.

Displacement from the native town also affects their indigenous resilience to climate change. It is believed that Indigenous resilience is entrenched in the culture and environmental heritage of Indigenous communities. Indigenous resilience to climate change is also embedded in their social and geographical history, spiritual values, traditional ecological knowledge, and worldview (O'Rourke, J. 2023). Climate-induced displacement affects not only their food, and livelihood but affect their resilience to climate change (Balbi, 2024). The socioeconomic marginality of the indigenous communities further intersects with their vulnerabilities of indigenous communities. Moreover, the majority of Indigenous people live under the poverty line due to their traumatic colonial history. It is important before assessing climate change to understand the colonial history of indigenous communities. They faced the worst colonial policy; and discriminatory policies in the post-colonial period (Datta, Chapola, Waucaush-Warn, Subroto, & Hurlbert, 2024). Indigenous communities across the world face extreme poverty; substandard and inadequate housing; a lack of health and community services, food, infrastructure, transportation, and education as well as historical and current institutional and policy issues related to Native resources (Howitt, 2020). The Kalasha indigenous community has no access to their indigenous resources and Pakistan as a state does not recognize their rights to their indigenous resources. Climate change further intersects their vulnerabilities. Moreover, indigenous communities are also vulnerable because their physical, mental, intellectual, social, and cultural well-being is traditionally tied to their natural environment and native land. Hence, they depend on the land and resources for basic needs such as medicine, shelter, and food (Parsons & Fisher, 2022). As a result of the change, they lose their bio-diversity which significantly affects their health. Therefore, climate changes exacerbate many barriers to providing for these human needs. Climate change also makes it difficult for them to give an adaptative response to the worst effects of climate change. The following line specifically explains the socioeconomic vulnerabilities of the Kalasha community living in the northern part of Pakistan.

Kalash Indigenous Community Socio-economic Conditions in Colonial and Post-colonial Periods

Kalash indigenous people like other indigenous groups such as Pashtun also faced discrimination in the British colonial period (Ishaq, & Ghilzai, 2020). Moreover, their culture and religion were stigmatized both in the colonial and also in the post-colonial period. The British colonial regime completely ignored development in this region and colonial policy in this region was security-oriented rather than development. Kalash indigenous people were completely ignored in the colonial era and colonial injustices reinforced socioeconomic vulnerabilities in this region. Pakistan as a state in the post-colonial era continued the British security-oriented policy (Sengar, & Adjoumani (Eds.), 2023). In this regard, Kalash Indigenous community members stated that

> “the British completely ignored this region and the post-colonial era, Pakistan as a state also deliberately ignored this region Javeed (Individual Interview, 21 March 2024)"

The British imposed the worst policies for peripheries or in the name of settled or unsettled regions (Khter, and Ghalib, 2015). However, in the post-colonial era, Pakistan also continued the same policy in this region and did not initiate any developmental program for the Kalash's indigenous people. Moreover, in the post-colonial era, Pakistan as a state failed to protect the rights of Kalash's indigenous community, minority ethnic and religious groups they are facing various socio-economic problems in their native places (Zeb, Armstrong, & Hamann, 2019). Therefore, the majority of the Kalash indigenous community is living under the poverty line because of the indifferent attitude of the state towards the solution to their socio-economic problems (Khan, 2023). Kalash indigenous community has limited economic opportunities, and livelihood resources and climate change further creates socio-economic issues for them. The Kalash people also face problems preserving their religious and cultural heritage amidst the influence of the majority and a changing world. In the post-colonial period, Pakistan as a state failed to protect this indigenous community from religious extremism, and socio-economic exploitation. The majority of them are dissatisfied with development projects in the region. Hence, in the post-colonial times, the Kalash people face many challenges that increase their socioeconomic vulnerabilities. However, climate change further jeopardizes their future in their native region. The following lines explain the climate change impact on the existing livelihood resources of the Kalash indigenous community.

Climate Change Impact on the Kalsha Indigenous Community

As mentioned above, the Kalash indigenous people live in difficult geographical terrain in the north-west of Khyber Pakhtunkhwa, Pakistan. They are dependent on natural resources such as forests, rain, domesticated animals, agriculture, and fruits (Abdul Aziz, Ullah & Pieroni, 2020). Climate change has directly affected their natural resources and threatens their bio-cultural heritage. Climate change increases their socioeconomic vulnerabilities because for livelihood they are dependent on the natural resources in Kalash Valley. For instance, plants or bio-diversity in this region are badly affected by climate change. Climate change also affects medicinal plants which affects the health care, income and culture of the Kalash indigenous community. Climate change affects the natural forests and jeopardizes Kalash's Indigenous community's future because they have no other option to protect themselves from extreme winter. They are using trees for heating. Climate change affects their livelihood resources. In this regard, Kalash community member stated that

> “I saw snowfall and unexpected rain in our native town in April for the first time. This variation in the weather pattern and rain cycle affected our ways of life. Climate change affected the livelihood resources of both men and women in our native town” Zarmeena, (Individual Interview, 25, March 2024).

Variation in the rain cycle creates the possibility of extreme weather, flood and drought. Agriculture is the main source of their livelihood and variation in the rain cycle badly affected their crops. They have no irrigation land (Sher, Al-Yemeni, & Sher, 2010). Moreover, domesticated animals are the basic sources of their livelihood. Climate change has a significant effect on grazing land, it is difficult now for them to manage pasture for domesticated animals. Extreme weather not only affects their houses but also affects their animals Moreover, natural disasters such as flooding due to climate change also cause soil erosion which badly affects the plants, crops and grazing land of the Kalash indigenous community. It also disturbs the traditional biodiversity in this region (Bellard, Bertelsmeier, Leadley, Thuiller, & Courchamp, 2012). Climate change affected the plants they were using for the different types of diseases of humans and animals (Weiskopf, Rubenstein, Crozier, Gaichas, Griffis, Halofsky & Whyte, 2020). In this regard, one community member stated that;

> "Climate change affected our livelihood resources and we are dependent on our natural environment and variations in weather patterns, rain cycle affects our means of livelihood in our native places, Sujeel (Individual interview, 24 March 2024).

Moreover, as mentioned above, they are not only dependent on forests for domestic use but timber is the main business of the Kalash indigenous community.Their dependency on forests for domestic use causes deforestation in Kalash Valley. It is believed that deforestation is also one of the reasons for climate change (Zeb, Hamann, Armstrong, & Acuna-Castellanos, 2019). Moreover, they are living under the poverty line as mentioned, they cannot afford climate-resilient seeds. Therefore, climate change has badly affected their crops (Aich, Dey, & Roy, 2022). It is important to provide them with climate-resilient seeds and increase the adaptive capacity and resilience of Kalash's indigenous community formers. However, the Kalash indigenous community cannot afford climate-resilient seeds (Shilomboleni, Recha, Radeny, & Osumba, 2023). In this regard, one of the community members stated that;

> “climate change has a significant effect on our crops, especially wheat. Formers of our community need climate resilient seeds and informal training of the local farmers to educate them about climate resilient forming Roshmina (Individual interview, 24, March 2024).

Moreover, extreme weather causes health problems in domesticated animals. Climate change reduces grazing land and pasture but also affects the health of animals, especially goats and sheep. The Kalasha community who are dependent on domesticated animals, changed their profession (Ingold, 2002). Moreover, the mining industry also affects the grazing land (Haq, Kontakiotis, Janjuhah, Rahman, Tabassum, IKhan, & Jamal, 2022). More often than not mining sites create landsliding hazards for the local community, especially for pastoral communities and also for animals. Kalash indigenous people face multifaceted issues due to climate change in their native places. They are uneducated and do not have the modern skills to search for new livelihood resources. Therefore, climate change overlaps or intersects with their socio-economic marginality. The following line explains how the climate change effect intersects their marginality.

Climate Change Intersectiong Socio-economic Marginality of Kalasha Community

Various socio-economic, and political factors make Indigenous communities more susceptible to the worst effects of climate change (Abate, & Kronk, 2013). Indigenous communities are dependent on natural resources and do not have the modern technology and institutions to face the worst effects of climate change. They rely on their indigenous institutions and resilience to cope with climate change. It is believed that indigenous communities are already socio-economically marginalized due to their colonial history and exploitation and climate change further intersects their marginality (Nightingale & Rankin, 2014). The colonial injustices and post-colonial exploitative policies reinforced poverty in this region and they have limited resources in their native town. Forceful conversion, political instability, and religious extremism have brought demographic changes and displaced many Kalash indigenous people from their native places. Climate change further intersects or overlaps with their existing socio-economic vulnerabilities. In this regard, Indigenous community members stated that;

> “the colonial regime and in the post-colonial period our community has not been supporting and these states failed to initiate any developmental program for our people. Therefore, we are facing a multifaceted socio-economic problem. However, climate change further makes us socio-economically vulnerable"Akhtar Wali (Individual Interview, 21 March 2024).

Climate change further affected their local livelihood resources especially their natural resources (Sperber, 2014). Climate-induced disasters displaced Kalash's indigenous people and they have limited land and faced the problem of resettlement. Along with the climate-induced displacement, scarcity of resources, and forceful conversion are considered reinforcing factors of their displacement from their native places. Almost in every monsoon season, flash flood affects their crops, animals and houses. Heavy rain and flash floods damage their homes. They have limited land to build their houses in safe places. In this regard, one Kalash Indigenous woman stated;

> "Climate change affected our resources and we women face problems even though we do not have safe places to wash our clothes and it is also difficult for us to bring pasture for our domesticated animal" Aleena (Individual Interview, 19 March 2024).

Climate change also intersects or overlaps with women's marginality. As compared to men, women of the Kalash indigenous community face multifaceted issues. Climate change-induced disasters also differently affected women because during displacement they are more exposed to physical and sexual violence. Along with women, men cannot afford the expenditure of their families. Climate change affects their local resources and now they are compelled to leave their native place in search of livelihood resources. Therefore, climate change intersects with Kalash's Indigenous community's socio-economic problems. They were already deprived and lived under the poverty line. Climate change further intersects their socio-economic vulnerabilities and jeopardizes their future in their native places.

Conclusion

This study focuses on the socio-economic vulnerabilities of the Kalash indigenous community. It is revealed that Kalasha's indigenous community has faced numerous socio-economic challenges in their native town. It reveals that climate change further intersection their socio-economic vulnerabilities. Kalasha's indigenous community already live under the poverty line. The climate further overlaps or intersects with the vulnerabilities in their native town. The theory of intersectionality provided theoretical insight to this study. Climate change intersects the vulnerability of the Kalash indigenous community. The colonial policy in this region was security-oriented and ignored socio-economic development. Pakistan also has failed to initiate a developmental program for the Kalash indigenous community. Their historical, as well as post-colonial policies reinforce socio-economic marginality. However, climate change intersects or overlaps the socio-economic marginality of the Kalash indigenous people who live in the northwest of Pakistan.

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References

Abdul Aziz, M., Ullah, Z., & Pieroni, A. (2020). Wild food plant gathering among Kalasha, Yidgha, Nuristani and Khowar speakers in Chitral, NW Pakistan. Sustainability, 12(21), 9176.

Aich, A., Dey, D., & Roy, A. (2022). Climate change resilient agricultural practices: A learning Experience from indigenous communities all over India. PLOS Sustainability and Transformation, 1(7), e0000022.

Abate, R. S., & Kronk, E. A. (2013). The commonality among unique Indigenous communities: An introduction to climate change and its impacts on indigenous peoples. In Climate change and indigenous peoples (pp. 3-18). Edward Elgar Publishing.

Ali, M. K., & Chawla, M. I. (2019). Socio-cultural life of the Kalasha people of Chitral: A study of their festivals. Pakistan Vision, 20(2), 42-57.

AKHTER, S. T., & GHALIB, M. (2015). INTER-JURISDICTIONAL GOVERNANCE COORDINATION, COMMUNITY SUPPORT AND COMPLIANCE WITH THE ILO 169 CONVENTION ON INDIGENOUS RIGHTS: FINDINGS OF A CROSS-SECTIONAL STUDY OF THE INDIGENOUS PEOPLE OF THE KALASH VALLEY IN PAKISTAN. International Journal of Interdisciplinary Social Science Studies, 4.

Brubacher, L. J., Chen, T. T. W., Longboat, S., Dodd, W., Peach, L., Elliott, S. J., ... & Neufeld, H. (2024). Climate change, biodiversity loss, and Indigenous Peoples' health and wellbeing: a systematic umbrella review protocol. Systematic Reviews, 13(1), 8.

Bellard, C., Bertelsmeier, C., Leadley, P., Thuiller, W., & Courchamp, F. (2012). Impacts of Climate change on the future of biodiversity. Ecology Letters, 15(4), 365-377.

Bicker, A., Ellen, R., & Parkes, P. (2003). Indigenous environmental knowledge and its Transformations: Critical anthropological perspectives. Routledge.

Balbi, A. A. J. (2024). LEAVE NO ONE BEHIND: WE NEED A RIGHTS-BASED APPROACH TO CLIMATE DISPLACEMENT. Indigenous Policy Journal, 34(2).

Carastathis, A. (2014). The concept of intersectionality in feminist theory. Philosophy compass, 9(5), 304-314.

Choudhry, F. R., Golden, K. J., & Sang-Ah Park, M. (2024). " It's always an admixture of so many identities": Interpretative Phenomenological Analysis of Indigenous Kalasha Cultural Identity. Qualitative Report, 29(3).

Datta, R., & Kairy, B. (2024). Decolonizing climate change adaptations from Indigenous perspectives: Learning reflections from Munda Indigenous communities, coastal areas in Bangladesh. Sustainability, 16(2), 769.

Datta, R., Chapola, J., Waucaush-Warn, J., Subroto, S., & Hurlbert, M. (2024, May). Decolonizing meanings climate crisis and land-based adaptions: From Indigenous women's perspectives in Western Canada. In Women's Studies International Forum (Vol. 104, p. 102913). Pergamon.

Fentz, M. (1996). Natural resources and cosmology in changing Kalasha society (Vol. 30). NIAS Press

Forster, P. M., Smith, C. J., Walsh, T., Lamb, W. F., Palmer, M. D., von Schuckmann, K., ... & Zhai, P. (2023). Indicators of Global Climate Change 2022: Annual update of large-scale Indicators of the state of the climate system and human influence. Earth System Science Data Discussions, 2023, 1-82.

Haq, N. U., Kontakiotis, G., Janjuhah, H. T., Rahman, F., Tabassum, I., Khan, U., ... & Jamal, N. (2022). Environmental Risk Assessment in the Hindu Kush Himalayan Mountains of Northern Pakistan: Palas Valley, Kohistan. Sustainability, 14(24), 16679.

Howitt, R. (2020). Decolonizing people, place and country: Nurturing resilience across time and space. Sustainability, 12(15), 5882.

Ishaq, M., & Ghilzai, S. A. (2020). Indigenous knowledge and disaster mitigation: the case of Kalash community of northern Pakistan. PalArch's Journal of Archaeology of Egypt/Egyptology, 17(3), 2396-2415.

Ingold, T. (2002). From trust to domination: an alternative history of human-animal relations. In Animals and human society (pp. 13-34). Routledge.

Kaijser, A., & Kronsell, A. (2014). Climate change through the lens of Intersectionality. Environmental Politics, 23(3), 417-433.

Khan, W. A. (2023). Establishing the Contemporary Issues of Kalash: Challenges and Way Forward. Pakistan Perspectives, 28(2).

Karrar, H. H., & Mostowlansky, T. (2018). Assembling marginality in northern Pakistan. Political Geography, 63, 65-74.

Kalash, S. G. (2022). Indigenous archaeology and heritage in Pakistan: Supporting Kalash Cultural preservation through education and awareness. Journal of Community Archaeology & Heritage, 9(1), 33-43.

Lansbury Hall, N., & Crosby, L. (2022). Climate change impacts health in remote Indigenous Communities in Australia. International Journal of Environmental Health Research, 32(3), 487-502.

Nightingale, A., & Rankin, K. N. (2014). Politics of Social Marginalization and Inclusion: The Challenge of Adaptation to Climate Change. In Inclusive Urbanization (pp. 53-63).

Routledge.

Ngcamu, B. S. (2023). Climate change effects on vulnerable populations in the Global South: a systematic review. Natural Hazards, 118(2), 977-991.

O'Rourke, J. (2023). The Overlooked Communities of Forced Displacement in the United States: Humanizing the Relocation of Indigenous Tribes in the Face of Climate Change. U. Cin. L. Rev., 92, 850.

Parkes, P. (1987). Livestock symbolism and pastoral ideology among the Kafirs of the Hindu Kush. Man, 637-660

Parsons, M., & Fisher, K. (2022). Decolonising flooding and risk management: Indigenous Peoples, settler colonialism, and memories of environmental injustices. Sustainability, 14(18), 11127.

Redvers, N., Aubrey, P., Celidwen, Y., & Hill, K. (2023). Indigenous Peoples: Traditional Knowledge, climate change, and health. PLOS Global Public Health, 3(10), e0002474.

Reyes-García, V., Álvarez-Fernández, S., Benyei, P., Calvet-Mir, L., Chambon, M., García-del- Amo, D., ... & Tofighi-Niaki, A. (2023). Introduction: Understanding climate change Impacts on Indigenous Peoples and local communities: A global perspective from local studies. In Routledge Handbook of Climate Change Impacts on Indigenous Peoples and Local Communities (pp. 1-18). Routledge.

Sperber, B. G. (2014). Nature in the Kalasha Perception of life. In Asian Perceptions of Nature (pp. 126-147). Routledge Shilomboleni, H., Recha, J., Radeny, M., & Osumba, J. (2023). Scaling climate-resilient seed Systems through SMEs in Eastern and Southern Africa: challenges and opportunities. Climate and Development, 15(3), 177-187.

Siddiqui, S. (2023). Kalasha People in Pakistan: A Mountain Indigenous Tribe's Struggles to Protect Identity, Culture, Ancestral Lands, and Survival. In Indigenous Societies in the Post-colonial World: Responses and Resilience Through Global Perspectives (pp. 285-299). Singapore: Springer Nature Singapore.

Sher, H., Al-Yemeni, M. N., & Sher, H. (2010). Forest Resource Utilization Assessment for Economic development of rural communities in northern parts of Pakistan. J. Med. PlantsRes, 4(12), 1197-1208.

Sengar, B., & Adjoumani, A. M. E. (Eds.). (2023). Indigenous Societies in the Post-colonial World: Responses and Resilience Through Global Perspectives. Springer Nature.

Uddin, S. (2019). Cultural Commodification in Kalash Valley: A Case Study of Bumburet Village, District Chitral (Doctoral dissertation, Pakistan Institute of Development Economics).

Weiskopf, S. R., Rubenstein, M. A., Crozier, L. G., Gaichas, S., Griffis, R., Halofsky, J. E., ... & Whyte, K. P. (2020). Climate change affects biodiversity, ecosystems, ecosystem services, and natural resource management in the United States. Science of the Total Environment, 733, 137782

Zeb, A., Hamann, A., Armstrong, G. W., & Acuna-Castellanos, D. (2019). Identifying local Actors of deforestation and forest degradation in the Kalasha valleys of Pakistan. Forest Policy and Economics, 104, 56-64.

Zeb, A., Armstrong, G. W., & Hamann, A. (2019). Forest conversion by the Indigenous Kalasha Of Pakistan: A household level analysis of socioeconomic drivers. Global environmental change, 59, 102004.

Zeb, A., Hamann, A., Armstrong, G. W., & Acuna-Castellanos, D. (2019). Identifying local Actors of deforestation and forest degradation in the Kalasha valleys of Pakistan. Forest Policy and Economics, 104, 56-64.

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RESEARCH ARTICLE

Analyzing the Nexus between AI Innovation and Ecological Footprint in Nordic Region: Impact of Banking Development and Stock Market Capitalization using Panel ARDL method

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Abstract
This study investigates the impact of Artificial Intelligence (AI) innovation on the ecological footprint in the Nordic region from 1990 to 2020, alongside the effects of banking development, stock market capitalization, economic growth, and urbanization. Utilizing the STIRPAT model, the study incorporates cross-sectional dependence and slope homogeneity tests, revealing issues of heterogeneity and cross-sectional dependence. The analysis employs both first and second-generation panel unit root tests, confirming that the variables are free from unit root problems. Panel cointegration tests demonstrate that the variables are cointegrated in the long run. To explore the short- and long-term relationships, the study utilizes the Panel Autoregressive Distributed Lag (ARDL) model. The Panel ARDL results indicate that economic growth, stock market capitalization, and urbanization positively correlate with the ecological footprint in both the short and long run. Conversely, AI innovation and banking development negatively correlate with the ecological footprint. To validate the Panel ARDL estimations, robustness checks are performed using Fully Modified OLS, Dynamic OLS, and Fixed Effects with OLS, all of which support the initial findings. Furthermore, the study employs the D-H causality test to identify causal relationships. The results show a unidirectional causal relationship between AI innovation, stock market capitalization, urbanization, and the ecological footprint. In contrast, a bidirectional causal relationship exists between economic growth and the ecological footprint, as well as between banking development and the ecological footprint.

Keywords: Artificial Intelligence; Banking Development; Stock Market Capitalization; Ecological Footprint; Nordics Region

Introduction

Because of rising modernization, worldwide population growth, shifting lifestyles, and greater energy consumption, the threat of climate change has worsened in recent years (Voumik et al.,2022; Ahmed et al.2024). Based on data from Global Footprint Network (GFN 2018), over 80% of people on Earth reside in nations experiencing a serious environmental catastrophe. For developed as well as developing nations, combating global warming and environmental damage has been a top concern (Apergis et al., 2023; Raihan et al., 2023a). The Nordic countries (Denmark, Finland, Iceland, Norway, and Sweden) are regarded as worldwide examples of converting to green energy. They are among the most developed in the World, consistently ranking highly on the Human Development Index (HDI) of the United Nations, with Norway leading among them (Urban et al., 2018). They were also effective in splitting their economy from carbon emissions, which is obviously highly desirable but challenging to do. The Nordic nations have forward aggressive climate change and energy policies to eliminate fossil fuels by 2050 (Sovacool, 2017). Moreover, this region is widely considered to be a pioneer in climate environmental sustainability and home to affluent countries that are contributing significantly to climate change beyond their national borders by absorbing a significant portion of the resources and energy used by their citizens (Maczionsek et al., 2023; Ridwan et al.2023). These areas are included in the study to provide an intriguing figure with motivating common characteristics; they have similar socioeconomic circumstances. Furthermore, they are commonly recognized as leaders in the worldwide effort to combat climate change (Jokinen et al., 2020). To address concerns about ecological sustainability in the chosen area, this analysis focused on the relationships across stock market capitalization, banking development, AI, and economic growth. Using panel data analysis techniques, the project seeks to uncover empirical evidence and guide research-based policy recommendations for an improved future that is greener both globally and in the Nordic region.

In the real world, the Nordic area provides a model of how nations, businesses, and individuals have successfully reduced their GHG emissions and fostered clean energy (Raihan et al.2022a). The academic literature continues to endorse it as an example of advances in technology and the implementation of clean energy sources (Borup et al., 2008; Sovacool, 2013). Moreover, Finland, Iceland, Norway, and Sweden (except Denmark) have relatively substantial levels of sustainability disclosure (94%, 91%, 91%, and 98%, respectively) (KPMG, 2022). Numerous global problems, including escalating demands for energy, waste creation, shortages of water, and increasing EFP, are contributing to environmental damage (He et al. 2018; Quan et al. 2021). Researchers are linking several EFP-related elements to reveal potential mitigation strategies that could aid in achieving sustainable development. Ecological footprint (EFP) can effectively handle and analyze natural resources and is a substitute that is heavily used to evaluate ecosystem conditions (Khan et al. 2021; Ridzuan et al.2023). When the population's needs are met outside of the limits of the environment, an ecological deficit results (Dogan et al., 2022; Sahoo and Sethi, 2021). This is known as an ecological footprint exceeding biocapacity. Nordic European countries, including all members of the European Environmental Agency Countries (EEA-32), might evaluate the outcomes of their "Green Deal" initiative and Environmental Action Plans, which represent their primary environmental policy (Apergis et al.,2023; Raihan et al.2024a). In fact, by utilizing 15 indicators, the Nordic community established collaboration in 2019 to make the Nordic European Area the most integrated, competitive, and sustainable region in the World by 2030 (Nordic Statistic Database, 2022). By influencing consumption and manufacturing habits, innovation in technology, utilization of resources, environmental laws, and social welfare of both the business growth and society, the development of stock markets can have a consequence on the EFP (Younis et al., 2021; Sharma et al., 2021; Tsagkanos et al., 2019). Depending on some factors, including the extent, framework, effectiveness fluctuation, and expansion of the financial system; the level of GDP growth; the quality of the institutions; ecological consciousness global context; and advances in the energy field, the rise of stock markets can have both positive and destructive implications on EFP (Paramati et al., 2017; Topcu et al., 2020; Raihan et al.2023b). Furthermore, it has been proven that modern technology fosters sustainable development over time in all countries, and the Nordic region is no exception. By addressing environmental challenges, innovation contributes to the improvement of the natural World (Alola et al.,2024). In 2018, there was a 1.7% increase in emissions of carbon in Sweden, with a peak of almost 33.1 billion metric tons (Khanal, 2021; Raihan et al., 2022b). On the other hand, pollution levels in Norway have

been rising continuously since the 1960s, except for a brief drop that occurred between 1990 and 1995. To stop this growing trend, which was brought on by uncertain macroeconomic conditions, innovative energy technology initiatives, and limitations on greenhouse gas emissions, both nations adopted carbon pricing (Jagers & Hammar, 2009). In our analysis, we investigate the impact of economic growth, urbanization, stock market capitalization, artificial intelligence, and banking development on the Nordic countries' ecological footprint. The following is how the article advances earlier research: (i) some researchers have spoken on the connection between the environment, development, and energy in panel discussions and individual studies. The present research is the first empirical analysis to look at the Nordic countries' advancement in banking, stock market capitalization, AI innovation, and ecological footprint—all encouraging indicators through this work. Nonetheless, the majority of earlier research (Akram et al., 2020; Ali et al., 2019; Salahuddin et al., 2019; Raihan and Voumik, 2022; Voumik et al. 2023a, 2023b) took CO2 emission as a measure of ecological condition. However, the study utilized the EFP as a substitute for environmental sustainability. The EFP calculates an individual's or a community's demand for accessible natural resources (Omojolaibi and Nathaniel 2020). EFP has, therefore, been employed in numerous research to explore the green environment (Pata et al., 2021; Nuta et al.,2024; Idroes et al., 2024) to some extent. (ii) The study also contributed to the body of literature on the use of second-generation panel estimation approaches as more advanced than conventional panel estimation methods. To investigate both the short- and long-term consequences within the chosen variables, we used the Novel ARDL methodology and the STIRPAT framework.
The remaining content is given below: the existing literature is organized in the second part. Data collection and the methodological framework are covered in the next part. The discussion and empirical results are reported in the fourth portion. In the fifth subsection, a conclusion and policy implications are developed.

Literature Review

Multiple studies have measured the condition of the environment utilizing different indicators, like ecological footprint and CO2 emissions. To identify discrepancies in the literature, we conduct a thorough assessment of the current condition of academic work in this part. As a result, we will address previous studies on the effects of EFP on economic development, urbanization, artificial intelligence (AI), banking development, and stock market capitalization, which will support the parameters of our study. The intricate link between GDP and ecological footprint (EFP) can be affected by geographic differences as well as additional pertinent factors. The contemporary economic boom has had an enormous effect on the increase in carbon emissions globally (Longsheng et al., 2022). Sahoo and Sethi (2021) have discovered a similar result in emerging economies using the FMOLS and DOLS approaches, and they propose the need for legislative actions to lessen ecological challenges. Using the panel dynamic Generalized Method of Moments (GMM) in conjunction with Fully Modified Ordinary Least Square (FMOLS), Zhang et al. (2022) conducted research to explore the long-term connection among the chosen factors in five emerging countries between 1990 and 2019. They added that the EFP increased as a result of GDP development. Moreover, Shahbaz et al. (2023) used annual data from 1992 to 2017 for the ten countries with the biggest ecological footprint. They concluded that through a spike in EFP, monetary expansion has a detrimental implication on environmental quality. Similar conclusions were reached by Ahmad et al. (2020), Destek (2020), and Sharif et al. (2020) about the long-term positive link between EFP and economic growth. Conversely, the rise in GDP of the G-7 countries concerning greenhouse gas emissions was done by Balcilar et al. (2018). The results go counter to the EKC hypothesis, which holds that the condition of the ecosystem in Germany and the UK is not negatively impacted by economic growth. Ozturk et al. (2021) discovered that Saudi Arabia's environmental degradation is negatively impacted by economic growth. The findings of Li et al. (2022) showed that, in 120 nations, development in the economy was linked to a decrease in ecological footprint. This conclusion is facilitated by some research, including Ahmed et al. (2021) in the USA, Aslam et al. (2021) in China, and Ali et al. (2021) in Pakistan.

By helping with power administration, combating pollution, biodiversity preservation, and other areas, artificial intelligence plays a critical role in environmental sustainability and helps achieve sustainable development goals (Kumari and Pandey, 2023; Ridwan, 2023). According to Rasheed et al. (2024), artificial intelligence actively contributes to reducing emissions of carbon and sustaining the ecosystem of seven developing Asian nations. Chen et al. (2022) discovered that the consequences of artificial intelligence (AI) on mitigating CO2 emissions are more apparent in big cities, extremely large towns, better-developed facilities, and highly technological cities based on panel data collected for 270 Chinese cities. However, in small and medium-sized towns, as well as in cities with insufficient services and low levels of technology, it is not significant. Research has adopted AI innovation methods, including artificial neural networks (ANNs) and hybrid machine learning models, to examine the environmental effects of multiple operations, including the cultivation of soybeans (Kashka et al., 2022), consumption habits (Janković et al., 2021), and economic global indicators (Roumiani and Mofidi,2022; Roumiani and Mofidi, 2021). These AI models have yielded encouraging predictions of ecological parameters, with ANNs outperforming conventional regression methods in terms of ecological impact indices. In the same way, Arya et al. (2024) revealed that AI-based solutions for GHG emission monitoring, prediction, and reduction may contribute to a cleaner environment. From 2007 to 2020, Liu et al. (2024) illustrated the influences of industrial robots on the ecosystem in ten of the World's top manufacturing AI countries: Singapore, South Korea, Japan, Germany, Sweden, Denmark, USA, China, France, and Italy. The results imply that these robots enhance the ecological health in the selected countries by reducing EFP across different data quantiles.

The growth of banking can spur economic prosperity by allowing households to purchase vehicles, homes, and appliances. However, these activities put pressure on the environment by increasing the demand for and utilization of fossil fuels (Baloch et al., 2019, Al Shium et al.2024a). Yet, the growth of banking might encourage the creation of high-quality environments: vigorous investments in R&D and environmentally friendly projects could be encouraged and financed by a healthy financial system (Zhao et al.,2021; Shahbaz et al.,2016). Financial development includes the growth of the banking industry; generally speaking, current research has focused more on how financial growth contributes to ecological degradation (Samour et al., 2019). Using data from 1990 to 2018, Radulescu et al. (2022) investigate how banking development has affected the ecological impact of 27 OECD nations. The MMQR approach results displayed that an upsurge of 1% in banking expansion is expected to increase the EFP in all quantiles of the OECD countries. The findings thus confirm that the OECD countries' ecological sustainability is compromised by banking development. According to Zafar et al. (2019), the banking development index raises emissions of carbon in N-11 countries while lowering them in G-7 territory. Samour et al.(2022) acknowledge that banking sector development decreases the environmental level and extends the idea that South Africa must leverage the growth of the banking industry to reduce ecosystem damage. From one perspective, the growth of the banking industry could encourage modern innovations in the power sector to aid in the reduction of emissions and ensure environmental sustainability (Khan and Rehan, 2022). However, an investigation carried out in Malaysia between 1980 and 2018 by Altıntaş et al. (2024) found that the improvement of the banking industry has a favorable effect on the green environment. Furthermore, rising loan rates in developed economies, growing rates of deposits in emerging nations, and higher rates in countries that are developing all help decrease greenhouse gases overall (Obiora et al., 2020).

Numerous studies indicate that the size of the stock market can have a positive or inverse effect on EFP, considering several elements. Focusing on rapid financial achievements in the stock market can push companies to prioritize profits over biodiversity concerns, potentially leading to increased environmental damage (Taghizadeh-Hesary et al., 2022; Al Shium et al., 2024b). Incorporating the capitalization of stocks (SMC) into national and regional global warming mitigation efforts is essential, primarily to tackle the adverse impacts of environmental degradation (Azeem et al., 2023). These considerations serve as a basis for examining the connection between environmental damage and stock market capitalization (Ozturk and Acaravci 2013; Sadorsky 2010). When accounting for market shocks, Mhadhbi et al. (2021) demonstrated that the stock market growth measures of emerging market countries have a destructive influence on natural health quality. Li et al. (2022) demonstrated that the stock market had a detrimental effect on ecological sustainability in OECD countries that were undergoing rapid economic growth but that it was positively correlated with better environmental quality in nations that were experiencing slower economic expansion. According to Zafar et al. (2019), stock market activity caused CO_2 emissions to grow in G7 countries relative to N-11 countries, while it decreased in N-11 countries and improved the ecological condition. Su (2023) examines the intricate dynamics of stock market capitalization and CO_2 emissions. Utilizing the NARDL model demonstrates that China's stock market capitalization is responsible for short-term increases in environmental deterioration. Similarly, Nguyen et al.(2021) demonstrated that SMS is not good for the ecological condition of G-6 countries as it leads to a rise in carbon emissions. However, Zeqiraj et al. (2020) revealed that the stock market assisted EU nations in building economies with low emissions. Habiba et al. (2021) also agreed that environmental pollution decreased in industrialized economies and the G20 countries as stock markets developed but climbed in emerging economies. Moreover, Asiedu (2024) found that in rising countries, stock market capitalization reduces EFP. Since urbanization is thought to be one of the primary drivers of ecological decline, it has garnered much attention in empirical as well as theoretical studies (Adebayo and Kirikkaleli, 2021; Rana et al., 2024). Multiple scholars have empirically examined the adverse and beneficial correlation between urbanization and ecological conditions. Using FMOLS and DOLS long-run estimators, Ulucak et al. (2020) assessed the BRICS countries from 1992 to 2016. The evidence indicates urbanization reduces EFP, suggesting that it improves the ecology. Similarly, urbanization improves the ecosystem quality in Sri Lanka (Gasimli et al. 2019). Chien et al. (2023) analyzed the consequences of urbanization on the generation of GHGs in the G-7 nations using the innovative MMQR method. They found that an increasing population reduces pollution in high-emission economies. Conversely, Nathaniel et al. (2021) observed a negative correlation between URBA and ecological effects at the top 10 tourist locations. According to Ahmed et al. (2020a), from 1971 to 2014, urbanization boosted the EFP in the G7 areas. Similar findings were made by Nathaniel et al. (2020) within the MENA region, Zhang et al. (2021) in Malaysia, Ridwan et al. (2024) in six South Asian countries, Raihan et al. (2024b) in the G-7 region, Liu et al. (2024) in China, Voumik and Ridwan (2023) in Argentina, and others which showed that urbanization degrades the environment. Moreover, Addai et al. (2022) in Eastern Europe revealed that urbanization is not a uniform cause of ecological footprint. In Pakistan, negative trends in urbanization caused a decline in environmental degradation, while positive urbanization movements prompted an increase in it (Arif et al.,2023).

Regarding the link between the improvement in the banking sector, artificial intelligence (AI), stock market capitalization, and the ecological footprint, there is a deficiency in the literature currently in publication, especially when it comes to the Nordic region. Previous research has largely concentrated on greenhouse gas emissions, or CO_2 emissions, and has overlooked the important factor of ecological footprint (EFP). In particular, by encouraging funding for environmentally friendly projects and green technologies, banking growth, and stock market capitalization may improve the condition of the environment. Moreover, efforts in the application of Green AI might support green habits, reduce climate risk, promote clean energy, and create ecological practices, all of which would lessen the negative effects on the environment. Together, these elements constitute artificial intelligence, the growth of banks, and stock market capitalization, which is a whole new area of study from a Nordic standpoint. To address those drawbacks, the research assists academicians and stakeholders in developing strategies that are specific to the ecological and macroeconomic fields of the Nordic region by utilizing statistical techniques such as ARDL, FMOLS, DOLS, and FE-OLS processes.

Methodology

Data and Variables

This study used data from the Global Footprint Network (GFN), Global Financial Development (GFD), and World Development Indicators (WDI) from 1995 to 2021 to check out the consequences of GDP, banking development, stock market capitalization, artificial intelligence (AI), and urbanization on the EFP of the Nordic area. These countries were picked for consideration due to the value and accessibility of their statistical information for our ongoing research requirements. The ecological footprint is the dependent variable in our work. The GFN delivered the EFP statistics, and the WDI gave the GDP per capita in US dollars. Statistics on urbanization were also taken from WDI. Our research relies on data from the GFD to determine important elements such as banking development and stock market capitalization. Our World in Data is where the AI variable data came from. Table 1 straightforwardly illustrates the factors.

In this study logarithmic variables is used to handle non-linear connections and stabilize variance. Logarithmic transformations facilitate the linearization of connections between variables, simplifying the application of linear regression techniques and enabling the interpretation of coefficients as percentage changes. In addition, they tackle heteroscedasticity problems by reducing the range of data, which can enhance the accuracy of the model and the statistical significance. Furthermore, log transformations can mitigate the influence of extreme values or outliers, resulting in more resilient and dependable outcomes in empirical investigations.

Table 1. Description and Source of Variables

Variables	Description	Logarithmic Form	Unit of Measurement	Source
EFP	Ecological Footprint	LEFP	Gha per person	GFN
LGDP	Gross Domestic Product	LGDP	GDP per capita (Current US$)	WDI
LAI	AI Innovation	LAI	Annual patent applications related to AI	Our World in data
LBD	Banking Development	LBD	Deposit money banks assets to GDP (%)	Global Financial Development
LSMC	Stock Market Capitalization	LSMC	Stock market capitalization to GDP (%)	Global Financial Development
LURBA	Urbanization	LURBA	Urban Population (% of total population)	WDI

Theoretical Framework

According to Voumik and Ridwan (2023), the IPAT model can be utilized to evaluate how business activity impacts the environment as well as energy consumption. The environmental pressure resulting from prosperity, population trends, and innovations in technology is measured by the framework using a random effects regression (Ehrlich and Holdren, 1971). Through the selection of dependent and independent variables, we illustrate the use of the widely accepted IPAT/STIRPAT model. The term STIRPAT stands for population, wealth, and technology-related stochastic effects through regression. Many nations have acknowledged this approach as a legitimate choice, including Malaysia, Italy, the Nordic, China, and the OECD (Shahbaz et al.,2016; Pattak et al.,2023; Owusu et al.,2024; Amin & Dogan, 2021; Hashmi & Alam, 2019). This investigation is conducted considering some factors such as population dynamics, financial situations, and technological innovations:

$$I = \int PAT \qquad (1)$$

In this study, we employed EFP as an indication of ecosystem damage (I). Following the STIRPAT framework offered by Dietz and Rosa (1997), we utilized urbanization as a measure of population (P), economic growth, banking development, stock market capitalization as an indicator of affluence (A), and AI as a measure of technology (T). Equation (2) displays the updated form after the intercept term (C) and standard error term (ε) were included.

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

The empirical model used in this article is the outcome of a thorough review of the relevant research, and this review has informed the subsequent representations.

$$Environmental\ Impact = f(Population, Affluence, Technology) \qquad (3)$$

In addition to independent factors, we included environmental impact and used EFP as a proxy indicator. To obtain Equation (4), apply the following procedure:

$$EFP_{it} = \alpha_0 + \alpha_1 GDP_{it} + \alpha_2 AI_{it} + \alpha_3 BD_{it} + \alpha_4 SMC_{it} + \alpha_5 URBA_{it} \qquad (4)$$

Here, GDP means gross domestic product, AI stands for Artificial intelligence, BD indicates banking development, SMC for stock market capitalization, and URBA for urbanization. In equation (4), we adapted α_1 to α_5 for coefficients of the independent variables and α_0 denoted intercept term. The log forms of the variables are used in equation (5) to ensure normal distribution.

$$LEFP_{it} = \alpha_0 + \alpha_1 LGDP_{it} + \alpha_2 LAI_{it} + \alpha_3 LBD_{it} + \alpha_4 LSMC_{it} + \alpha_5 LURBA_{it} \quad (5)$$

Econometric Framework

The characteristics of the panel data in the Nordic nations might face stationary CSD, SH, or mixed-order stationary challenges. While all of these economies are growing, the rates of growth vary significantly. Here, the slope homogeneity test is employed for this reason. In this endeavor, the first and second-generation unit root assessments, along with the cointegration examination, are required to confirm the CSD and SH concerns. After the study had considered all of these criteria, the ARDL approach was adopted. The estimations of FMOLS, DOLS, and FE-OLS were featured in our analysis to determine the accuracy. The conclusions of the research, their interpretation, and potential implications for the study are all concisely and precisely described in this section, which may be subdivided by areas.

Cross-Sectional Dependence Test

In panel data, an increase in CSD is expected as monetary integration grows and additional barriers are eliminated (Ridwan et al.,2024). If researchers ignore the issue and handle the cross-sections as isolated, CSD may produce disorganized, misleading, and contradicting results (Hoyos et al., 2006). It is essential to explore the information for CSD because panel data are utilized in this study; this test can be seen by the following equation.

$$CSD = \sqrt{\frac{2T}{N(N-1)N}\left(\sum_{i=1}^{N-1}\sum_{K=i+1}^{N}\widehat{Corr_{\iota,t}}\right)} \dots\dots\dots\dots (6)$$

Slope Homogeneity Test

Slopes in panel data are often consistent because cross-sections usually share the same properties. For this reason, it is essential to handle slope homogeneity in panel data analysis (Ayad and Djedaiet, 2022). According to Pesaran and Yamagata (2008), the homogeneity of the slopes is confirmed using the SH test. This evaluation makes use of each individual's weighted slope dispersion. The slope heterogeneity is shown by Equation (7) as follows:

$$\breve{\Delta} = \sqrt{N}\left(\frac{N^{-1}S\%-k}{\sqrt{2k}}\right) \text{ and } \breve{\Delta}_{adj} = \sqrt{N}\left(\frac{N^{-1}S\%-k}{\sqrt{\frac{2k(T-k-1)}{T+1}}}\right) \dots\dots\dots\dots (7)$$

Panel Unit root test

To guarantee the correct cointegration order for panel data, Rauf (2018) advised utilizing both parametric and nonparametric approaches. The first generation of the panel unit root test fails to consider heterogeneity, CSD consequences, or over-rejection of null hypotheses into account (Choi, 2001). To solve this issue, the investigation leverages the first-generation unit root examination, known as the Levin, Lin, and Chu (LLC) test, which was developed by Levin et al. (2002), and the IPS test introduced by Im et al. (2003). Conversely, Pesaran (2007) established the CIPS and CADF, which are second-generation unit root methods that take CSD and slope variability into account. The following formula may be used to represent the IPS test:

$$\Delta y_{it} = \alpha_i + \beta_i t + \gamma y_{it-1} + \delta_i \Delta y_{it-1} + \varepsilon_{it} \dots\dots\dots\dots (8)$$

The following formulas were used for the LLC test statistics:

$$\Delta y_{it} = \beta_i y_{it-1} + \sum_{j=1}^{\vartheta i} d_{ij}\Delta y_{it-1} + G'_{it}\eta + \mu_{it} \quad \dots\dots\dots\dots (9)$$

Here, G'_{it} means the column vector of the independent variable, and in regression, η indicates the vector of parameters. The CIPS unit root analysis ensures unit roots in individual time series are checked and addresses CSD in panel data to prevent inaccurate inference if not adequately addressed (Polcyn et al.,2023). The CIPS test is conducted using Equation (10):

$$CIPS = \frac{1}{N}\sum_{t=1}^{N} t_1(N,T) \dots\dots\dots\dots (10)$$

Here, N denotes a cross-sectional dimension, and T indicates a time series dimension. The CADF test has a strong relationship with the CIPS test. Equation (11) provides the following method for computing the CADF:

$$\Delta Yi_t = \varphi_i + \rho i Yi_{t-1} + \varphi i \bar{Y}_{t-1} + \sum_{j=1}^{m} \varphi_{ij}\bar{Y}_{t-1} + \sum_{j=1}^{m} \gamma_{ij}\Delta Y_{i,t-1} + \varepsilon_{it} \dots\dots\dots (11)$$

Here, $\bar{Y}_{t-1}$ and $\Delta Y_{i,t-1}$ represent the mean values of the cross-sectional analysis for both the first difference and lag.

Panel Cointegration test

Our examination used a second-generation panel cointegration assessment to assess for long-term cointegration among the variables after data stationarity. This method provides more accurate and consistent cointegration estimates than first-generation panel cointegration techniques (Ridwan et al., 2024, Arif et al.2024). A stable, long-term correlation across two or more non-stationary factors is referred to as cointegration. In other words, cointegrated factors typically follow the same course throughout time despite periodic variations (Westerlund and Edgerton, 2008). This method was invented by Westerlund (2007), and the four equations below describe this test form.

$$G_a = \frac{1}{n}\sum_{i=1}^{N}\frac{\acute{a}_i}{SE(\acute{a}_i)} \text{……………………..} (12)$$

$$G_t = \frac{1}{n}\sum_{i=1}^{N}\frac{T\acute{a}_i}{a_i\acute{(}1)} \text{………………………} (13)$$

$$P_t = \frac{\acute{a}}{SE(\acute{a})} \text{…………………………….} (14)$$

$$P_a = T\acute{a} \text{………………………………} (15)$$

Moreover, panel means statistics (Pt and Pa), there are additional group means statistics (Gt and Ga), each with its own set of symbols. The same test results are expected if the model variables are assumed to be "null" or disconnected; otherwise, if the assumption is placed that "there exist cointegrating links."

Panel ARDL method

We used the panel ARDL technique, recommended by Pesaran et al. (2001), as the variables are a combination of the I(0) and I(1) procedures. Regardless of the specified variables' order of integration, the ARDL methodology can simultaneously and rigorously estimate the short- and long-term associations (Alsamara et al., 2024). Pesaran and Shin (1995) claimed that since the ARDL model has no residual correlation and removes both serial correlation and endogeneity, it provides less reason for concern over the endogeneity issue. Furthermore, it produces consistent findings even when endogeneity problems arise because the dynamic speciation of the model can be sufficiently enhanced to make serial mistakes uncorrelated and regressors purely exogenous (Loayza & Rancière, 2006). The following are some reasons why the ARDL approach is beneficial: In a mixed order of integration, such as I(0) and I(1), or strictly I(1) but not I(2), it can be used. (ii) It addresses the endogeneity and serial correlation challenges. (iii) Robust for a limited number of samples (Nathaniel et al., 2024).

The long-term relationship models for PMG are expressed as follows:

$$\Delta Y_{1,it} = \partial_{1i} + \alpha_{1i}Y_{1,it-1} + \sum_{l=2}^{k}\alpha_{1i}X_{1,it-1} + \sum_{j=1}^{p-1}\delta_{1ij}\Delta Y_{1,it-j} + \sum_{j=0}^{q-1}\sum_{l=2}^{k}\delta_{lij}\Delta X_{1,it-j} + \varepsilon_{1i,t} \qquad (16)$$

Here, Y_1 refers to the dependent variable, and X_1 is an independent variable where l=1,2,3,4. ε_{it} and Δ are residual & first difference operators, respectively.

Two steps are considered when applying the ARDL technique. The initial step is to employ the F test to assess whether there is a long-term link among the pertinent variables in the presence of an error correction. Estimating the coefficients of the long-run relations is the second stage of the ARDL, which comes after confirming that the F tests from the first step fall within acceptable limits (Hazmi et al.,2024). As a result, the long-term links between development in the economy, urbanization, banking development, stock market capitalization, AI, and ecological footprint of Nordic territory can be expressed using the ARDL models:

$$\Delta LEFP_{it} = \partial_{1i} + \alpha_{1i}LEFP_{i,t-1} + \alpha_{2i}LGDP_{i,t-1} + \alpha_{3i}LAI_{i,t-1} + \alpha_{4i}LBD_{i,t-1} + \alpha_{5i}LSMC_{i,t-1} + \alpha_{6i}LURBA_{i,t-1} + \sum_{j=1}^{p}\delta_{1i}\Delta LEFP_{i,t-j} + \sum_{i=0}^{q}\delta_{2i}\Delta LGDP_{i,t-j} + \sum_{i=0}^{q}\delta_{3i}\Delta LAI_{i,t-j} + \sum_{i=0}^{q}\delta_{4i}\Delta LBD_{i,t-j} + \sum_{i=0}^{q}\delta_{5i}\Delta LSMC_{i,t-j} + \sum_{i=0}^{q}\delta_{6i}\Delta LURBA_{i,t-j} + \varepsilon_{1i,t} \quad \ldots\ldots\ldots\ldots(17)$$

Furthermore, the following is the short-run association that takes ECM into account:

$$\Delta \mathrm{LEFP}_{\mathrm{it}} = \sum_{j=1}^{p-1}\beta_{1ij}\Delta \mathrm{LEFP}_{i,t-j} + \sum_{i=0}^{q-1}\beta_{2ij}\Delta \mathrm{LGDP}_{i,t-j} + \sum_{i=0}^{q-1}\beta_{3i}j\Delta \mathrm{LAI}_{i,t-j} + \sum_{i=0}^{q-1}\beta_{4i}j\Delta \mathrm{LBD}_{i,t-j} + \sum_{i=0}^{q-1}\beta_{5ij}\Delta \mathrm{LSMC}_{i,t-j} + \sum_{i=0}^{q-1}\beta_{6ij}\Delta \mathrm{LURBA}_{i,t-j} + \mu_{1i}\mathrm{ECT}_{1,it-1} + \varepsilon_{1i,t} \quad \ldots\ldots\ldots\ldots(18)$$

Robustness Check

We have used the robustness check estimators CCR, FMOLS, and DOLS. For a more accurate and comprehensive view of the effects over time, the researchers carried out FMOLS and DOLS calculations. For time-series modeling, FMOLS was initially proposed by Phillips and Perron as a method of regression for effective parameter estimation in cointegrated systems (Phillips and Perron, 1988). It is especially renowned for its dependability in small sample sizes and its capacity to deal with endogeneity and serial correlation, as noted by Hamit-Haggar (Hamit-Haggar, 2012). However, Kao and Chiang have proved that the DOLS estimation approach, which was developed by Stock and Watson, performs better than FMOLS in terms of estimating outcomes. This is because Kao and Chiang took into account correlations among regressors (Stock and Watson, 1993; Kao, 1999). Additionally, the FE-OLS approach is applied, which is a great tool for verifying that FMOLS and DOLS are legitimate. FE-OLS is robust with autocorrelation and CSD, and it is enhanced by DKSE (Driscoll and Kraay 1998). Also, this approach is robust to common forms of autocorrelation and CSD up to a predetermined lag (Adebayo et al., 2022).

D-H Causality test

Lastly, this study applies Dumitrescu and Hurlin's (2012) causality examination to confirm the short-term correlation across the variables, which is required for policymaking. For non-homogeneous panel data models with consistent coefficients, the D-H panel causality analysis is a straightforward variant of the Granger non-causality test (Ahmed et al., 2022). The DH causality test is a more appropriate and reliable method than the Granger non-causality test (Hashmi et al., 2021) and can be used in both short and long panels ($N > T$). Additionally, this method may address multiple significant issues with pooled data, like CSD and individual heterogeneity. It has been used in earlier research (Destiartono and Hartono, 2022; Ajanaku and Collins, 2021). The following can be used to write a general model:

$$P_{i,t} = \vartheta_i + \sum_{i=1}^{k}\lambda_i^n P_{i,t-i} + \sum_{i=1}^{k}\alpha_i^n \beta_{i,t-i} + \varepsilon_t \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (19)$$

In the D-H equation, the constant, regression parameter, and auto regressions are represented by ϑ_i, λ_i^n, and α_i^n.

Results and Discussion

Table 2 presents the descriptive information of GDP, AI, BD, SMC, URB, and EFP in logarithmic format for the study period (1980–2018). The data's standard deviation, median, minimum, mean, and maximum values were all displayed properly in the table. The calculated standard deviations of the majority of the variables are quite small, indicating that the data points are somewhat temporally variable and centered around the mean. The majority of the variables exhibit a negative skew, except LEFP and LURBA. Furthermore, the Jarque-Bera test and low kurtosis and skewness statistics support the normal distribution of the variables.

Table 2. Descriptive Statistics of Variables

Statistic	LEFP	LGDP	LAI	LBD	LSMC	LURBA
Mean	2.172568	10.86771	3.102615	4.804582	3.799236	4.452720
Median	1.897619	10.87999	3.135494	4.832309	3.922183	4.447006
Maximum	3.776661	11.54785	3.89182	5.72111	4.82769	4.542699
Minimum	1.587192	10.10012	1.791759	3.834337	2.332338	4.335695
Std. Dev.	0.641229	0.312364	0.502838	0.345983	0.535468	0.053723
Skewness	1.37579	-0.179975	-0.529248	-0.120022	-0.843834	0.045105
Kurtosis	3.348248	3.055801	2.47716	2.933702	2.949145	2.550493
Jarque-Bera	35.25716	0.608104	6.388144	0.284241	13.0662	0.963392
Probability	0	0.737823	0.041005	0.867517	0.001454	0.617735
Sum	238.9825	1195.448	341.2877	528.504	417.9160	489.7992
Sum Sq. Dev.	44.81805	10.63526	27.56027	13.04774	31.25316	0.314587
Observations	110	110	110	110	110	110

Table 3 illustrates the CSD test findings for the selected elements. Test statistics and p-values are available for all explanation variables. If the p-value is less than one of the three significant levels (1%, 5%, or 10%), the null hypothesis that there is no CSD is rejected. The p-values (0.000) for the tests performed on cross-sectional variables in Table 3 provide evidence of a CSD for each variable studied at the 1% level. It implies, then, that there may be a CSD issue with our data collection.

Table 3. Results of the CSD test

Variables	CD-Statistics	P-Value
LEFP	8.75***	0.000
LGDP	13.03***	0.000
LAI	6.11***	0.000
LBD	6.64***	0.000
LSMC	7.28***	0.000
LURBA	14.18***	0.000

Panel data analysis commonly uses the Slope Homogeneity assessment to ascertain whether the independent variable coefficients are constant across several cross-sectional units (in this case, country). With p-values of 0.000, the $\breve{\Delta}$ statistic of 4.654*** and the $\breve{\Delta}_{adj}$ test statistic of 5.637*** both from Table 4 suggest that there is a considerable degree of variance in the slopes across the parameters. The fact that the links among the model's elements change during the cross-sectional units suggests the existence of unique effects or coefficients for the explanatory variables.

Table 4. Results of Slope Homogeneity test

Slope homogeneity tests	Δ statistic	P-value
$\breve{\Delta}$ test	4.654***	0.000
$\breve{\Delta}_{adj}$ test	5.637***	0.000

Table 5 reveals the outcomes from three distinct unit root analyses. The IPS test shows that all other variables (LGDP, LAI, LBD, and LSMC) are level stationary at the 1% significance level, except for LEFP and LURBA. However, at their first difference, I(1), each factor becomes stationary. Second-generation tests, such as CIPS and CADF, provide more accurate findings than first-generation testing when dealing with panel data, which might exhibit cross-sectional interdependence. Such tests include cross-sectional means of lagged levels and initial differences. The results of the IPS tests accord with those of the CIPS and CADF examinations, as Table 5 demonstrates. According to the results, every component is primarily integrated at either level (I(0)) or first difference (I(1)). As a result, there is no unit root issue, and the elements have cointegrated over a long period.

Table 5. Results of Panel Unit root test

Variables	IPS		CIPS		CADF		Decision
	I(0)	I(1)	I(0)	I(1)	I(0)	I(1)	
LEFP	-1.939	-7.031***	-1.268	-5.874***	-2.131	-4.088***	I(1)
LGDP	-3.296***	-6.452***	-4.961***	-6.496***	-3.115***	-4.981***	I(0)
LAI	-3.270***	-8.991***	-3.630***	-5.352***	-3.853***	-5.778***	I(0)
LBD	-3.131***	-6.656***	-4.736***	-5.831***	-3.140***	-4.503***	I(0)
LSMC	-3.851***	-5.312***	-3.289***	-5.066***	-3.231***	-4.556***	I(0)
LURBA	-1.555	-3.495***	-1.444	-3.611***	-1.691	-4.632***	I(1)

After establishing that every parameter stays constant, the next step is to assess whether the variables are cointegrated within time. The results of Westerlund's (2007) cointegration assessment conducted for this investigation are displayed in Table 6. Given that the Gt, Ga, Pt, and Pa statistics all have statistically significant p-values (less than 0.05), therefore we can reject the null hypothesis. The results of this test indicate that long-run cointegration prevails between the factors under consideration.

Table 6. Results of Westerlund Panel Cointegration test

Statistics	Value	Z-Value	P-value
Gt	-2.956	-2.956	0.010
Ga	-5.829	1.717	0.021
Pt	-4.829	-1.560	0.034
Pa	-4.400	1.021	0.012

The Panel ARDL model's results, given in Table 07, demonstrate the intricate dynamics influencing the Nordic region's ecological footprint. In terms of LGDP, the short-term coefficient is 0.166 but statistically insignificant, with a p-value greater than the typical threshold, while the long-run coefficient is 0.095 and statistically significant at conventional levels. This suggests that economic expansion alone may notably contribute to environmental degradation in this setting, as GDP has an encouraging influence on the EFP. Nathaniel et al. (2020a) identified that in MENA nations, GDP growth raises the EFP and degrades the environment. Moreover, Ahmed et al.(2020a) in G-7 countries, Mikayilov et al. (2018) in oil-rich economies, Khan et al.(2021) in Malaysia, and Ahmed et al.(2020b) in China also align with these findings. However, in the long run, environmental quality in Europe is improved by 0.81% for every 1% growth in real GDP (Alola et al., 2019). Georgescu and Kinnunen (2024) in Finland reveal that GDP negatively influences ecological footprint. Surprisingly, economic expansion has no adverse effects on the ecosystems in CIVETS (Colombia, Indonesia, Vietnam, Egypt, Turkey, and South Africa) (Nathaniel et al.,2020b).

In the short and long terms, there is a negative link between LAI and LEFP; the short-term results are not significant, but the long-term coefficients are. This conclusion demonstrates that while AI technology has a short-term destructive implication on the environment, it has a long-term favorable advantage. LEFP drops by 0.057% in the near run and 0.097% in the long term for every 1% increase in LAI. This could be because while urgent green initiatives need assets, AI can improve energy efficiency across a range of industries, such as manufacturing, travel, and residence power. Dhar (2020) talked about AI's dual role in the fight against climate change, emphasizing that technology is a major carbon emitter as well as a tool for tackling the issue. Furthermore, Liang et al. (2022) made use of AI's ability to reduce emissions of carbon in China's industrial sector. The findings showed that China still has a long way to go in improving its performance in this area. Similarly, there is an obvious connection between banking sector activities and the environment, as evidenced by the inverse relationship observed between LBD and LEFP across both short and long periods. These results imply that banking development could boost ecological conditions in the long run but not in the short term, with p-values over the usual level in the short run and below 0.05 in the long run. Based on Sadorsky (2011), the established banking industry also increases consumer credit, which motivates people to purchase more appliances and cars, increasing energy demand and harming the natural environment. However, domestic bank lending to the private sector helps businesses create more cash assets and manufacturing inputs to create energy-efficient machinery and tools (Kareem et al.,2023). In contrast to our findings, Radulescu et al. (2022) contend that the OECD countries' ecological sustainability is negatively impacted by banking expansion.

In both the short and long term, the table demonstrates an encouraging relationship between LSMS and LEFP. The long-term statistical significance of the effect is supported by a slight short-term effect, indicating that stock market capitalization stimulates higher monetary and business transactions but may not have a positive short-term impact on the ecosystem. Asiedu (2024) disputes our results, stating that stock market capitalization ensures environmental sustainability in emerging nations and reduces the ecological footprint in those nations. However, Paramati et al. (2017) discovered that long-term environmental sustainability is guaranteed by stock market expansion in industrialized nations. Based on both short- and long-term assessments, urbanization (LURBA) and LEFP have an encouraging interaction. Over time, there is a small but statistically significant 0.0870% increase in LEFP with a p-value of less than 0.05 for every 1% increase in LURBA. A notable short-term spike in LEFP of 0.706% is associated with a 1% rise in LURBA. This could be because of the continual consequences of urban expansion, which lower ecological diversity and disrupt the natural World, such as the destruction of trees and the removal of natural ecosystems for redevelopment. According to Abid et al. (2022), there is a need for improved laws in the G-8 countries due to the substantial impact that urbanization has on environmental deterioration. Moreover, Nathaniel (2021) in South Africa, Salahuddin et al.(2019) in Sub-Saharan Africa (SSA) economies, and Alola et al.(2024) in the Nordic region also agree that urbanization increases the EFP and degrades the ecosystem. Conversely, Zhu et al. (2018) found that in the BRICS region, urbanization lowers carbon emissions and hence enhances environmental quality.

Table 7. Results of Panel ARDL method

Long-run Estimation				
Variable	Coefficient	Std. Error	t-Statistic	Prob.*
LGDP	0.095	0.047113	1.918186	0.0032
LAI	-0.097	0.04754	-2.055968	0.0435
LBD	-0.247	0.14441	-1.710938	0.0115
LSMC	0.233	0.04906	4.754246	0.0000
LURBA	0.870	0.79054	2.896378	0.0000
Short-run Estimation				
Variable	Coefficient	Std. Error	t-Stat	p-Value
COINTEQ01	-0.533	0.173518	-3.072053	0.0030
D(LGDP)	0.166	0.029231	5.700034	0.0000
D(LAI)	-0.057	0.041075	-1.396781	0.1669
D(LBD)	-0.129	0.090518	-1.427376	0.1579
D(LSMC)	0.067	0.046865	1.440284	0.1542
D(LURBA)	0.706	4.496835	1.713697	0.0911
C	10.068	3.226847	3.120119	0.0026

Multiple kinds of estimating methods, such as FMOLS, DOLS, and FE-OLS, were utilized to investigate the accuracy of the ARDL results in more detail in Table 8. For each of the three tests, the projected LGD values are 0.012, 0.285, and 0.082, accordingly. These outcomes indicate that the Nordic countries' ecological health has been harmed by economic expansion. The results are consistent with the ARDL model's short and long-term conclusions despite the fact that all estimators show significant coefficient values at the 1% level of thresholds. Conversely, based on the findings of all three tests, the LEFP variable exhibits a negative connection with both LAI and LBD. In the FMOLS test, the LAI coefficient values are significant at the 5% level; in the DOLS and FE-OLS tests, they are significant at the 1% level. In particular, EFP reduces by 0.023%, 0.089%, and 0.026%, respectively, for every 1% boost in AI innovation. This implies that the ecosystems in the Nordic nations might benefit from the application and adoption of AI technologies. These findings are consistent with statements drawn from the Panel ARDL calculation. In a similar vein, the three estimation procedures reveal a negative correlation between the LBD variable and LEFP. In particular, LEFP will fall by 0.088%, 0.287%, and 0.039%, respectively, for every 1% increase in banking development. The variable is statistically significant at the 1% level in each instance. This is parallel to the discoveries of the ARDL model and demonstrates the positive impact of banking development on the ecosystems of the Nordic nations. In contrast, the LEFP variable showed negative correlations with both LSMC and LURBA, indicating that increasing levels of urbanization and stock market capitalization are detrimental to the biodiversity in the chosen regions. At the 1% level, the LSMC variable is significant for each of the three estimation instances. Furthermore, an additional 1% in URBA will result in an elevated LEFP of 0.353% for FMOLS, 0.516% for DOLS, and 0.036% for FE-OLS. The variable is significant at the 5% level in the FMOLS estimation but at the 1% level in the other two scenarios. The ARDL model's conclusions are supported by the LSMC and LURBA data. These results thereby verify the ARDL model, which is the primary estimating approach used in this paper.

Table 8. Result of Robustness check

Variables	FMOLS	DOLS	FE-OLS
LGDP	0.012***(0.0702)	0.285***(0.0892)	0.082***(0.0597)
LAI	-0.023**(0.049)	-0.089***(0.0512)	-0.026***(0.0426)
LBD	-0.088***(0.0621)	-0.287***(0.2170)	-0.039***(0.0508)
LSMC	0.036***(0.073)	0.254***(0.2745)	0.005***(0.0572)
LURBA	0.353**(0.2340)	0.516***(0.0691)	0.036***(0.8967)

A panel causality assessment was performed using the Dumitrescu and Hurlin (2012) technique, which made it possible to determine if the associations were linear or nonlinear, as illustrated in Table 9. If the p-value is significant at the 1%, 5%, or 10% levels, the null hypothesis—which states that the variable under investigation does not consistently cause another variable—can be rejected. According to the study, at the 1% level, the p-value of 0.0223 denotes a statistically significant impact of LGDP on LEFP. Hence, it is possible to reject the null hypothesis and establish a unidirectional causal relationship between LGDP and LEFP. On the other hand, as the p-value exceeds the crucial levels, no meaningful association is seen between LEFP and LGDP. A greater examination reveals that LEFP and LAI have a comparable one-way relationship. The results imply that changes in LEFP have no effect on LAI, as the null hypothesis cannot be rejected in this instance. However, statistically significant p-values in all research point to a bidirectional link between LEFP and LAI. Furthermore, neither LEFP nor LURBA appear to be causally related to one another, according to the p-values. The p-value is below 0.05 and significant at the 1% level, indicating a substantial unidirectional causal link between LBD and LEFP. This result enables us to conclude that banking development has a detrimental effect on the ecosystem and to reject the null hypothesis. To summarize, out of all the regressors, the factors that affect LEFP are LGDP, LAI, LBD, LSMC, and LURBA.

Table 9. Results of the D-H causality test

Null Hypothesis	W-Stat.	Zbar-Stat.	Prob.
LGDP $\neq$ LEFP	5.06159	2.2851	0.0223
LEFP $\neq$ LGDP	4.66212	1.95363	0.0507
LAI $\neq$ LEFP	4.12222	1.50564	0.0322
LEFP $\neq$ LAI	7.0682	3.95013	0.2551
LBD $\neq$ LEFP	5.02193	2.25219	0.0243
LEFP $\neq$ LBD	4.71521	1.99769	0.0458
LSMC $\neq$ LEFP	6.41532	3.40838	0.0007
LEFP $\neq$ LSMC	3.63803	1.10387	0.2696
LURBA $\neq$ LEFP	7.69494	4.47018	0.0023
LEFP $\neq$ LURBA	3.52225	1.0078	0.3135

Conclusion and Policy Implications

In this paper, we investigated the factors influencing the EFP in Nordic countries from 1995 to 2021 using the ARDL framework and the STIRPAT model. Our study sought to determine the main drivers of environmental deterioration while making recommendations for future legislation about green practices. The ARDL technique makes a detailed examination of the intricate relationships between the dependent and explanatory variables possible. The study finds an unexpectedly strong positive correlation between ecological footprint, stock market value, and GDP per capita, which contradicts our assumptions. This suggests that financial activity and economic progress harm biodiversity.

The study also emphasizes the detrimental effects of urbanization on the ecological footprint, demonstrating a positive association between LEFP and LURBA and highlighting the necessity of sustainable urban planning in Nordic countries. Furthermore, the analysis indicates advantageous patterns that suggest a correlation between the advancement of banking, the integration of AI technology, and upgrades in environmental quality. These findings point to the possibility of incorporating environmental factors with the goals of sustainable development and eco-friendly behaviors into socio-economic strategies. Our analytical framework was rigorously tested using FMOLS, DOLS, and FE-OLS techniques. The Dumitrescu and Hurlin (D-H) causality tests were employed to examine the causal linkages among the variables. The findings indicated unidirectional causality between LGDP and LEFP, LAI and LEFP, LSMS and LEFP, and LEFP and LURBA. For stakeholders and legislators dedicated to advancing green policies and sustainable growth in these nations, this study offers insightful information about the evolving patterns of the ecological footprint in the Nordic region.

Based on the research that shows how economic growth, stock market capitalization, and urbanization contribute to the ecological footprint in the Nordic region, it is crucial to implement specific policy suggestions to reduce the environmental impact. Initiate sustainable economic growth by using green technologies and renewable energy sources to diminish carbon emissions and resource exhaustion. In addition, promotes ecologically conscious investment practices in the stock market by offering incentives to companies that embrace sustainable business strategies and disclose their environmental footprint. Moreover, stringent urban planning regulations should be enforced to manage the expansion of cities, improve the quality of green areas, and encourage the construction of environmentally sustainable infrastructure. Furthermore, it is crucial to enhance both public and private funding for research and development in order to promote sustainable technologies and ideas. Additionally, implement and uphold rigorous environmental regulations and standards for industries in order to minimize pollution and waste. In addition, public awareness and education initiatives should be implemented to promote sustainable consumption patterns and minimize the ecological impact. Engage in cooperative efforts with international organizations and neighboring countries to exchange successful methods and establish collective projects aimed at preserving the environment. Lastly, consistently oversee and assess the efficiency of these strategies and make essential modifications to guarantee ongoing advancement towards sustainability objectives.

In order to leverage the inverse relationship between AI advancement and environmental impact in the Nordic region, authorities should prioritize investing in eco-friendly AI technologies that encourage sustainability, such as those that improve energy efficiency and waste management. It is essential to create strong legislative frameworks that encourage the advancement and adoption of environmentally friendly AI technologies. One way to accomplish this is by providing tax incentives, grants, and subsidies to corporations and research institutes that prioritize the use of AI to minimize environmental harm. In addition, the success of these activities can be maximized by promoting public-private partnerships, which involve merging resources and expertise. By implementing these strategies, the Nordic area may enhance its AI capabilities while also promoting its dedication to ecological sustainability.

Policymakers have to concentrate on incorporating sustainable finance practices into the banking industry since the study indicates a negative correlation between the expansion of banking and the ecological footprint in the Nordic area. Promoting green banking efforts is one way to do this, such as giving loans intended for renewable energy projects or environmental projects better interest rates. To guarantee that their funding promotes low-impact and sustainable businesses, financial institutions should also be urged to implement strict environmental, social, and governance (ESG) standards in their investment portfolios. Regulators may improve this by giving banks explicit instructions and financial incentives to prioritize green investments and integrate sustainability into their lending procedures. Moreover, enforcing stricter reporting requirements and enhancing transparency about the environmental effect of projects financed by banks will encourage the adoption of more responsible banking practices and help hold institutions accountable. The Nordic area can maintain economic growth while drastically lowering its ecological imprint by coordinating banking expansion with ecological sustainability.

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Consent for publication: All participants provided consent for the publication of data and findings derived from their participation in the study. The consent forms are available upon request from the corresponding author.

Data availability statement: The corresponding author can provide the datasets created and/or analyzed during the current work upon reasonable request.

Authors' contributions: Mohammad Ridwan contributed to the study's conception and design. Material preparation, data collection, and analysis were performed by Sarder Abdulla Al Shiam, Afsana Akhter, Md Mahdi Hasan, S M Shamsul Arefeen, Md Sibbir Hossain, Shake Ibna Abir, Shaharina Shoha. All authors read and approved the final manuscript.

References

A Omojolaibi, J., & P Nathaniel, S. (2022). Assessing the potency of environmental regulation in maintaining environmental sustainability in MENA countries: An advanced panel data estimation. Journal of Public Affairs, 22(3), e2526. https://doi.org/10.1002/pa.2526

Abid, A., Mehmood, U., Tariq, S. et al. The effect of technological innovation, FDI, and financial development on CO2 emission: evidence from the G8 countries. Environ Sci Pollut Res 29, 11654–11662 (2022). https://doi.org/10.1007/s11356-021-15993-x

Addai, K., Serener, B. & Kirikkaleli, D. Empirical analysis of the relationship among urbanization, economic growth and ecological footprint: evidence from Eastern Europe. Environ Sci Pollut Res 29, 27749–27760 (2022). https://doi.org/10.1007/s11356-021-17311-x

Adebayo, T.S., Akadiri, S.S., Haouas, I. et al. Criticality of geothermal and coal energy consumption toward carbon neutrality: evidence from newly industrialized countries. Environ Sci Pollut Res 29, 74841–74850 (2022). https://doi.org/10.1007/s11356-022-21117-w

Adebayo, T.S., Kirikkaleli, D. Impact of renewable energy consumption, globalization, and technological innovation on environmental degradation in Japan: application of wavelet tools. Environ Dev Sustain 23, 16057–16082 (2021). https://doi.org/10.1007/s10668-021-01322-2

Ahmad M, Jiang P, Majeed A, Umar M, Khan Z, Muhammad S (2020) The dynamic impact of natural resources, technological innovations and economic growth on ecological footprint: an advanced panel data estimation. Resour Policy 69(September):101817. https://doi.org/10.1016/j.resourpol.2020.101817

Ahmad, S., Raihan, A., & Ridwan, M. (2024). Role of economy, technology, and renewable energy toward carbon neutrality in China. Journal of Economy and Technology. https://doi.org/10.1016/j.ject.2024.04.008

Ahmed Z, Cary M, Le HP (2021) Accounting asymmetries in the long-run nexus between globalization and environmental sustainability in the United States: an aggregated and disaggregated investigation. Environ Impact Assess Rev 86:106511 https://doi.org/10.1016/j.eiar.2020.106511

Ahmed Z, Zafar MW, Ali S (2020a) Linking urbanization, human capital, and the ecological footprint in G7 countries: an empirical analysis. Sustain Cities Soc 55:102064 https://doi.org/10.1016/j.scs.2020.102064

Ahmed, N., Sheikh, A. A., Hamid, Z., Senkus, P., Borda, R. C., Wysokińska-Senkus, A., & Glabiszewski, W. (2022). Exploring the causal relationship among green taxes, energy intensity, and energy consumption in Nordic countries: Dumitrescu and Hurlin causality approach. Energies, 15(14), 5199. https://doi.org/10.3390/en15145199

Ahmed, Z., Asghar, M. M., Malik, M. N., & Nawaz, K. (2020b). Moving towards a sustainable environment: the dynamic linkage between natural resources, human capital, urbanization, economic growth, and ecological footprint in China. Resources Policy, 67, 101677. https://doi.org/10.1016/j.resourpol.2020.101677

Ajanaku, B. A., & Collins, A. R. (2021). Economic growth and deforestation in African countries: Is the environmental Kuznets curve hypothesis applicable?. Forest Policy and Economics, 129, 102488.

Akram R, Chen F, Khalid F, Ye Z, Majeed MT (2020) Heterogeneous effects of energy efficiency and renewable energy on carbon emissions: evidence from developing countries. J Clean Prod 247:119122. https://doi.org/10.1016/j.jclepro.2019.119122

Al Shiam, S. A., Hasan, M. M., Nayeem, M. B., Choudhury, M. T. H., Bhowmik, P. K., Shochona, S. A., ... & Islam, M. R. (2024a). Deep Learning for Enterprise Decision-Making: A Comprehensive Study in Stock Market Analytics. Journal of Business and Management Studies, 6(2), 153-160.

Al Shiam, S. A., Hasan, M. M., Pantho, M. J., Shochona, S. A., Nayeem, M. B., Choudhury, M. T. H., & Nguyen, T. N. (2024b). Credit Risk Prediction Using Explainable AI. Journal of Business and Management Studies, 6(2), 61-66.

Ali R, Bakhsh K, Yasin MA (2019) Impact of urbanization on CO2 emissions in emerging economy: evidence from Pakistan. Sustain Cities Soc 48:101553. https://doi.org/10.1016/j.scs.2019.101553

Ali S, Ying L, Anjum R, Nazir A, Shalmani A, Shah T, Shah F (2021) Analysis on the nexus of CO2 emissions, energy use, net domestic credit, and GDP in Pakistan: an ARDL bound testing analysis. Environ Sci Pollut Res 28:4594–4614 https://doi.org/10.1007/s11356-020-10763-7

Alola, A. A., Bekun, F. V., Obekpa, H. O., & Adebayo, T. S. (2024). Explaining the environmental efficiency capability of energy mix innovation among the Nordic countries. Energy Reports, 11, 233-239. https://doi.org/10.1016/j.egyr.2023.11.051

Alola, A.A., Bekun, F.V., Sarkodie, S.A.: Dynamic impact of trade policy, economic growth, fertility rate, renewable and non-renewable energy consumption on ecological footprint in Europe. Sci. Total Environ. 685, 702–709 (2019) https://doi.org/10.1016/j.scitotenv.2019.05.139

Alsamara, M., Mimouni, K., Barkat, K., & Kayaly, D. (2024). Can exchange rate policies and trade partners' income enhance the trade balance in Algeria? Evidence from the nonlinear ARDL model. International Journal of Emerging Markets, 19(5), 1135-1156. https://doi.org/10.1108/IJOEM-02-2022-0341

Altıntaş, N., Açıkgöz, F., Okur, M., Öztürk, M., & Aydın, A. (2024). Renewable Energy and Banking Sector Development Impact on Load Capacity Factor in Malaysia. Journal of Cleaner Production, 434, 140143. https://doi.org/10.1016/j.jclepro.2023.140143

Amin, A., & Dogan, E. (2021). The role of economic policy uncertainty in the energy-environment nexus for China: evidence from the novel dynamic simulations method. Journal of Environmental Management, 292, 112865. https://doi.org/10.1016/J.JENVMAN.2021.112865

Apergis, N., Pinar, M. & Unlu, E. How do foreign direct investment flows affect carbon emissions in BRICS countries? Revisiting the pollution haven hypothesis using bilateral FDI flows from OECD to BRICS countries. Environ Sci Pollut Res 30, 14680–14692 (2023). https://doi.org/10.1007/s11356-022-23185-4

Arif, M., Gill, A.R. & Ali, M. Analyzing the non-linear association between urbanization and ecological footprint: an empirical analysis. Environ Sci Pollut Res 30, 109063–109076 (2023). https://doi.org/10.1007/s11356-023-30012-x

Arif, M., Hasan, M., Al Shiam, S. A., Ahmed, M. P., Tusher, M. I., Hossan, M. Z., ... & Imam, T. (2024). Predicting Customer Sentiment in Social Media Interactions: Analyzing Amazon Help Twitter Conversations Using Machine Learning. International Journal of Advanced Science Computing and Engineering, 6(2), 52-56.

Arya, A., Bachheti, A., Bachheti, R.K., Singh, M., Chandel, A.K. (2024). Role of Artificial Intelligence in Minimizing Carbon Footprint: A Systematic Review of Recent Insights. In: Chandel, A.K. (eds) Biorefinery and Industry 4.0: Empowering Sustainability. Green Energy and Technology. Springer, Cham. https://doi.org/10.1007/978-3-031-51601-6_14

Asiedu, B.A. (2024), "The combine impact of stock market, international investment and clean energy consumption on ecological footprint in emerging countries", International Journal of Energy Sector Management, Vol. ahead-of-print No. ahead-of-print. https://doi.org/10.1108/IJESM-12-2023-0027

Aslam B, Hu J, Shahab S, Ahmad A, Saleem M, Shah SSA, Javed MS, Aslam MK, Hussain S, Hassan M (2021) The nexus of industrialization, GDP per capita and CO2 emission in China. Environ Technol Innov 23:101674 https://doi.org/10.1016/j.eti.2021.101674

Ayad, H., Djedaiet, A. Does the unemployment rate matter for environmental issues in the G7 nations? New testing for the environmental Phillips curve using the load capacity factor. Environ Dev Sustain (2024). https://doi.org/10.1007/s10668-024-04956-0

Azam M, Khan AQ (2016) Urbanization and environmental degradation: evidence from four SAARC countries—Bangladesh, India, Pakistan, and Sri Lanka. Environ Prog Sustain Energy 35(3):823–832 https://doi.org/10.1002/ep.12282

Azeem, A., Naseem, M.A., Hassan, N.U. et al. A novel lens of stock market capitalization and environmental degradation. Environ Sci Pollut Res 30, 11431–11442 (2023). https://doi.org/10.1007/s11356-022-22885-1

Balcilar, M., Ozdemir, Z. A., Ozdemir, H., & Shahbaz, M. (2018). Carbon dioxide emissions, energy consumption and economic growth: The historical decomposition evidence from G-7 countries. Work Pap.

Baloch, M.A., Zhang, J., Iqbal, K. et al. The effect of financial development on ecological footprint in BRI countries: evidence from panel data estimation. Environ Sci Pollut Res 26, 6199–6208 (2019). https://doi.org/10.1007/s11356-018-3992-9

Borup, M. (2008). Nordic energy innovation systems-patterns of need integration and co-operation. In NORIA-Energy Policy Seminar. Sovacool, B. K. (2013). Energy policymaking in Denmark: Implications for global energy security and sustainability. Energy Policy, 61, 829-839.

Chen, P., Gao, J., Ji, Z., Liang, H., & Peng, Y. (2022). Do artificial intelligence applications affect carbon emission performance?—evidence from panel data analysis of Chinese cities. Energies, 15(15), 5730. https://doi.org/10.3390/en15155730

Chien, F., Hsu, C. C., Zhang, Y., & Sadiq, M. (2023). Sustainable assessment and analysis of energy consumption impact on carbon emission in G7 economies: mediating role of foreign direct investment. Sustainable Energy Technologies and Assessments, 57, 103111. https://doi.org/10.1016/j.seta.2023.103111

Choi, I.n. (2001). Unit root tests for panel data. Journal of International Money and Finance, 20(2), 249–272. https://doi.org/10.1016/S0261-5606(00)00048-6

Danish, Ulucak R, Khan SU (2020) Determinants of the ecological footprint: role of renewable energy, natural resources, and urbanization. Sustain Cities Soc 101996 https://doi.org/10.1016/j.scs.2019.101996

De Hoyos, R. E., & Sarafidis, V. (2006). Testing for cross-sectional dependence in panel-data models. The stata journal, 6(4), 482-496. https://doi.org/10.1177/1536867X0600600403.

Destek, M. A. (2020). Investigation on the role of economic, social, and political globalization on environment: evidence from CEECs. Environmental Science and Pollution Research, 27(27), 33601-33614. https://doi.org/10.1007/s11356-019-04698-x

Destiartono, M. E., & Hartono, D. (2022). Does Rapid Urbanization Drive Deforestation? Evidence From Southeast Asia. Economics Development Analysis Journal, 11(4), 442-453.

Dhar P (2020) The carbon impact of artificial intelligence. Nat Mach Intell 2(8):423–425. https://doi.org/10.1038/s42256-020-0219-9

Dietz, T., & Rosa, E. A. (1997). Effects of population and affluence on CO2 emissions. Proceedings of the National Academy of Sciences, 94(1), 175-179. https://doi.org/10.1073/pnas.94.1.175

Dogan, E., Majeed, M. T., & Luni, T. (2022). Revisiting the nexus of ecological footprint, unemployment, and renewable and non-renewable energy for South Asian economies: Evidence from novel research methods. Renewable Energy, 194, 1060-1070. https://doi.org/10.1016/j.renene.2022.05.165

Driscoll JC, Kraay AC (1998) Consistent covariance matrix estimation with spatially dependent panel data. Rev Econ Stat 80(4):549–560

Dumitrescu, E. I., & Hurlin, C. (2012). Testing for Granger non-causality in heterogeneous panels. Economic modelling, 29(4), 1450-1460. https://doi.org/10.1016/j.econmod.2012.02.014

Ehrlich, P. R., & Holdren, J. P. (1971). Impact of Population Growth: Complacency concerning this component of man's predicament is unjustified and counterproductive. Science, 171(3977), 1212-1217. https://doi.org/10.1126/science.171.3977.1212

Gasimli O, ul Haq I, Gamage SKN et al (2019) Energy, trade, urbanization and environmental degradation nexus in Sri Lanka: bounds testing approach. Energies 12:1–16. https://doi.org/10.3390/en12091655

Georgescu, I., & Kinnunen, J. (2024). Effects of FDI, GDP and energy use on ecological footprint in Finland: An ARDL approach. World Development Sustainability, 4, 100157. https://doi.org/10.1016/j.wds.2024.100157

GFN (2018) Global Footprint Network. WWW Document https://data.footprintnetwork.org/?_ga=2.134472181.508123949.1609248689-1393775646.1607921298#/

Habiba, U., Xinbang, C. The impact of financial development on CO2 emissions: new evidence from developed and emerging countries. Environ Sci Pollut Res 29, 31453–31466 (2022). https://doi.org/10.1007/s11356-022-18533-3

Hamit-Haggar, M. (2012). Greenhouse gas emissions, energy consumption and economic growth: A panel cointegration analysis from Canadian industrial sector perspective. Energy Economics, 34(1), 358-364. https://doi.org/10.1016/j.eneco.2011.06.005

Hashmi, R., & Alam, K. (2019). Dynamic relationship among environmental regulation, innovation, CO2 emissions, population, and economic growth in OECD countries: A panel investigation. Journal of Cleaner Production, 231, 1100–1109. https://doi.org/10.1016/j.jclepro.2019.05.325

Hashmi, S. H., Fan, H., Habib, Y., & Riaz, A. (2021). Non-linear relationship between urbanization paths and CO2 emissions: A case of South, South-East and East Asian economies. Urban Climate, 37, 100814. https://doi.org/10.1016/j.uclim.2021.100814

Hassan ST, Xia E, Khan NH, Shah SMA (2019) Economic growth, natural resources, and ecological footprints: evidence from Pakistan. Environ Sci Pollut Res 26(3):2929–2938 https://doi.org/10.1007/s11356-018-3803-3

Hazmi, A., Kort, H. M., Khallouli, W., & Raissi, N. (2024). A Dynamic Interrelationships among Clean Energy, Environmental Pollution, and Economic Growth in GCC Economies: A Panel ARDL Approach. International Journal of Energy Research, 2024(1), 5571175. https://doi.org/10.1155/2024/5571175

He L, Shen J, Zhang Y (2018) Ecological vulnerability assessment for ecological conservation and environmental management. J Environ Manag 206:1115–1125. https://doi.org/10.1016/j.jenvman.2017.11.059

Idroes, G.M., Hardi, I., Rahman, M.H. et al. The dynamic impact of non-renewable and renewable energy on carbon dioxide emissions and ecological footprint in Indonesia. Carbon Res. 3, 35 (2024). https://doi.org/10.1007/s44246-024-00117-0

Im, K. S., Pesaran, M. H., & Shin, Y. (2003). Testing for unit roots in heterogeneous panels. Journal of econometrics, 115(1), 53-74. https://doi.org/10.1016/S0304-4076(03)00092-7

Jagers, S. C., & Hammar, H. (2009). Environmental taxation for good and for bad: The efficiency and legitimacy of Sweden's carbon tax. Environmental Politics, 18(2), 218–237. https://doi.org/10.1080/09644010802682601

Janković, R., Mihajlović, I., Štrbac, N. et al. Machine learning models for ecological footprint prediction based on energy parameters. Neural Comput & Applic 33, 7073–7087 (2021). https://doi.org/10.1007/s00521-020-05476-4

Jokinen, J., Nilsson, K., Karlsdóttir, A., Heleniak, T., Kull, M., Stjernberg, M., ... & Gassen, N. S. (2020). State of the Nordic Region 2020. Nordic Council of Ministers.

Kao, C. (1999). Spurious regression and residual-based tests for cointegration in panel data. Journal of econometrics, 90(1), 1-44. https://doi.org/10.1016/S0304-4076(98)00023-2

Kareem, P. H., Ali, M., Tursoy, T., & Khalifa, W. (2023). Testing the effect of oil prices, ecological footprint, banking sector development and economic growth on energy consumptions: Evidence from bootstrap ARDL approach. Energies, 16(8), 3365. https://doi.org/10.3390/en16083365

Kashka, F. M., Sarvestani, Z. T., Pirdashti, H., Motevali, A., & Nadi, M. (2022). Predicting of Agro-environmental Footprint with Artificial Intelligence (Soybean cultivation in various scenarios). https://doi.org/10.21203/rs.3.rs-1098555/v1

Khan, I., Hou, F., & Le, H. P. (2021). The impact of natural resources, energy consumption, and population growth on environmental quality: Fresh evidence from the United States of America. Science of the Total Environment, 754, 142222. https://doi.org/10.1016/j.scitotenv.2020.142222

Khan, M. A., & Rehan, R. (2022). Revealing the impacts of banking sector development on renewable energy consumption, green growth, and environmental quality in China: does financial inclusion matter?. Frontiers in Energy Research, 10, 940209. https://doi.org/10.3389/fenrg.2022.940209

Khan, M.K., Abbas, F., Godil, D.I. et al. Moving towards sustainability: how do natural resources, financial development, and economic growth interact with the ecological footprint in Malaysia? A dynamic ARDL approach. Environ Sci Pollut Res 28, 55579–55591 (2021). https://doi.org/10.1007/s11356-021-14686-9

Khanal, A. (2021). Does energy consumption impact the environment?: Evidence from Australia using the JJ Bayer-Hanck cointegration technique and the autoregressive distributed lag test. International Journal of Energy Economics and Policy, 11(4), 185-194. https://doi.org/10.32479/ijeep.11163.

KPMG, 2022. Survey of Sustainability Reporting 2022. Available at https://kpmg.com/no/nb/home/nyheter-og-innsikt/2022/10/survey-of-sustainability-reporting-2022.html.

Kumari, N., & Pandey, S. (2023). Application of artificial intelligence in environmental sustainability and climate change. In Visualization techniques for climate change with machine learning and artificial intelligence (pp. 293-316). Elsevier. https://doi.org/10.1016/B978-0-323-99714-0.00018-2

Levin, A., Lin, C. F., & Chu, C. S. J. (2002). Unit root tests in panel data: asymptotic and finite-sample properties. Journal of econometrics, 108(1), 1-24. https://doi.org/10.1016/S0304-4076(01)00098-7

Li, R., Wang, X., & Wang, Q. (2022). Does renewable energy reduce ecological footprint at the expense of economic growth? An empirical analysis of 120 countries. Journal of Cleaner Production, 346, 131207. https://doi.org/10.1016/j.jclepro.2022.131207

Liang S, Yang J, Ding T (2022) Performance evaluation of AI driven low carbon manufacturing industry in China: an interactive network DEA approach. Comput Ind Eng 170:108248. https://doi.org/10.1016/j.cie.2022.108248

Liu, K., Mahmoud, H. A., Liu, L., Halteh, K., Arnone, G., Shukurullaevich, N. K., & Alzoubi, H. M. (2024). Exploring the Nexus between Fintech, natural resources, urbanization, and environment sustainability in China: A QARDL study. Resources Policy, 89, 104557. https://doi.org/10.1016/j.resourpol.2023.104557

Liu, L., Rasool, Z., Ali, S., Wang, C., & Nazar, R. (2024). Robots for sustainability: Evaluating ecological footprints in leading AI-driven industrial nations. Technology in Society, 76, 102460. https://doi.org/10.1016/j.techsoc.2024.102460

Loayza, N. V., & Rancière, R. (2006). Financial development, financial fragility, and growth. Journal of Money, Credit, and Banking, 38(4), 1051–1076.

Longsheng, C., Shah, S. A. A., Solangi, Y. A., Ahmad, M., & Ali, S. (2022). An integrated SWOT-multi-criteria analysis of implementing sustainable waste-to-energy in Pakistan. Renewable Energy, 195, 1438-1453. https://doi.org/10.1016/j.renene.2022.06.112

Maczionsek, M. I. J., Dillman, K. J., & Heinonen, J. (2023). Linking perception and reality: Climate-sustainability perception and carbon footprints in the Nordic countries. Journal of Cleaner Production, 430, 139750. https://doi.org/10.1016/j.jclepro.2023.139750

Mhadhbi, M., Gallali, M. I., Goutte, S., & Guesmi, K. (2021). On the asymmetric relationship between stock market development, energy efficiency and environmental quality: A nonlinear analysis. International Review of Financial Analysis, 77, 101840.

Mikayilov JI, Galeotti M, Hasanov FJ (2018) The impact of economic growth on CO2 emissions in Azerbaijan. J Clean Prod 197:1558–1572. https://doi.org/10.1016/j.jclepro.2018.06.269

Nathaniel S, Nwodo O, Sharma G, Shah M (2020b) Renewable energy, urbanization, and ecological footprint linkage in CIVETS. Environ Sci Pollut Res 27(16):19616–19629 https://doi.org/10.1007/s11356-020-08466-0

Nathaniel SP, Barua S, Ahmed Z (2021) What drives ecological footprint in top ten tourist destinations? Evidence from advanced panel techniques. Environ Sci Pollut Res:1–10. https://doi.org/10.1007/s11356-021-13389-5

Nathaniel, S. P. (2021). Natural resources, urbanisation, economic growth and the ecological footprint in South Africa: the moderating role of human capital. Quaestiones Geographicae, 40(2), 63-76. https://doi.org/10.2478/quageo-2021-0012

Nathaniel, S. P., Ahmed, Z., Shamansurova, Z., & Fakher, H. A. (2024). Linking clean energy consumption, globalization, and financial development to the ecological footprint in a developing country: Insights from the novel dynamic ARDL simulation techniques. Heliyon, 10(5). https://doi.org/10.1016/j.heliyon.2024.e27095

Nathaniel, S., Anyanwu, O. & Shah, M. Renewable energy, urbanization, and ecological footprint in the Middle East and North Africa region. Environ Sci Pollut Res 27, 14601–14613 (2020a). https://doi.org/10.1007/s11356-020-08017-7

Nguyen, D. K., Huynh, T. L. D., & Nasir, M. A. (2021). Carbon emissions determinants and forecasting: Evidence from G6 countries. Journal of Environmental Management, 285, 111988. https://doi.org/10.1016/j.jenvman.2021.111988

Nordic Statistic database, (2022). accessible at www.nordicstatistics.org. Accessed on 03 May 2022.

Nuta, F., Shahbaz, M., Khan, I. et al. Dynamic impact of demographic features, FDI, and technological innovations on ecological footprint: evidence from European emerging economies. Environ Sci Pollut Res 31, 18683–18700 (2024). https://doi.org/10.1007/s11356-024-32345-7

Obiora, S. C., Bamisile, O., Opoku-Mensah, E., & Kofi Frimpong, A. N. (2020). Impact of banking and financial systems on environmental sustainability: An overarching study of developing, emerging, and developed economies. Sustainability, 12(19), 8074. https://doi.org/10.3390/su12198074

Owusu, S. M., Chuanbo, F., & Qiao, H. (2024). Examining economic policy uncertainty's impact on environmental sustainability: Insights from nordic nations. Journal of Cleaner Production, 449, 141688. https://doi.org/10.1016/j.jclepro.2024.141688

Ozturk I, Aslan A, Altinoz B (2021) Investigating the nexus between CO2 emissions, economic growth, energy consumption and pilgrimage tourism in Saudi Arabia. Econ Res-Ekonomska Istraživanja 35(1):3083–3098. https://doi.org/10.1080/1331677X.2021.1985577

Ozturk, I., & Acaravci, A. (2013). The long-run and causal analysis of energy, growth, openness and financial development on carbon emissions in Turkey. Energy economics, 36, 262-267. https://doi.org/10.1016/j.eneco.2012.08.025

Paramati, S. R., Mo, D., & Gupta, R. (2017). The effects of stock market growth and renewable energy use on CO2 emissions: evidence from G20 countries. Energy economics, 66, 360-371. https://doi.org/10.1016/j.eneco.2017.06.025

Pata, U. K., Aydin, M., & Haouas, I. (2021). Are natural resources abundance and human development a solution for environmental pressure? Evidence from top ten countries with the largest ecological footprint. Resources policy, 70, 101923. https://doi.org/10.1016/j.resourpol.2020.101923

Pattak, D. C., Tahrim, F., Salehi, M., Voumik, L. C., Akter, S., Ridwan, M., ... & Zimon, G. (2023). The driving factors of Italy's CO2 emissions based on the STIRPAT model: ARDL, FMOLS, DOLS, and CCR approaches. Energies, 16(15), 5845. https://doi.org/10.3390/en16155845

Pesaran, M. H. (2007). A simple panel unit root test in the presence of cross-section dependence. Journal of applied econometrics, 22(2), 265-312. https://doi.org/10.1002/jae.951

Pesaran, M. H., & Shin, Y. (1995). An autoregressive distributed lag modelling approach to cointegration analysis (Vol. 9514, pp. 371-413). Cambridge, UK: Department of Applied Economics, University of Cambridge.

Pesaran, M. H., & Yamagata, T. (2008). Testing slope homogeneity in large panels. Journal of Econometrics, 142(1), 50–93. https://doi.org/10.1016/j.jeconom.2007.05.010

Pesaran, M. H., Shin, Y., & Smith, R. J. (2001). Bounds testing approaches to the analysis of level relationships. Journal of applied econometrics, 16(3), 289-326. https://doi.org/10.1002/jae.616

Phillips, P. C., & Perron, P. (1988). Testing for a unit root in time series regression. biometrika, 75(2), 335-346. https://doi.org/10.1093/biomet/75.2.335

Polcyn, J., Voumik, L. C., Ridwan, M., Ray, S., & Vovk, V. (2023). Evaluating the influences of health expenditure, energy consumption, and environmental pollution on life expectancy in Asia. International Journal of Environmental Research and Public Health, 20(5), 4000. https://doi.org/10.3390/ijerph20054000

Quan Q, Gao S, Shang Y, Wang B (2021) Assessment of the sustainability of Gymnocypris eckloni habitat under river damming in the source region of the Yellow River. Sci Total Environ 778:146312. https://doi.org/10.1016/j.scitotenv.2021.146312

Radulescu, M., Balsalobre-Lorente, D., Joof, F., Samour, A., & Türsoy, T. (2022). Exploring the impacts of banking development, and renewable energy on ecological footprint in OECD: new evidence from method of moments quantile regression. Energies, 15(24), 9290. https://doi.org/10.3390/en15249290

Raihan, A., & Voumik, L. C. (2022). Carbon emission reduction potential of renewable energy, remittance, and technological innovation: empirical evidence from China. Journal of Technology Innovations and Energy, 1(4), 25-36. https://doi.org/10.56556/jtie.v1i4.398

Raihan, A., Atasoy, F. G., Atasoy, M., Ridwan, M., & Paul, A. (2022a). The role of green energy, globalization, urbanization, and economic growth toward environmental sustainability in the United States. Journal of Environmental and Energy Economics, 1(2), 8-17. https://doi.org/10.56946/jeee.v1i2.377

Raihan, A., Bala, S., Akther, A., Ridwan, M., Eleais, M., & Chakma, P. (2024a). Advancing environmental sustainability in the G-7: The impact of the digital economy, technological innovation, and financial accessibility using panel ARDL approach. Journal of Economy and Technology. https://doi.org/10.1016/j.ject.2024.06.001

Raihan, A., Ridwan, M., Tanchangya, T., Rahman, J., & Ahmad, S. (2023a). Environmental Effects of China's Nuclear Energy within the Framework of Environmental Kuznets Curve and Pollution Haven Hypothesis. Journal of Environmental and Energy Economics, 2(1), 1-12.

Raihan, A., Tanchangya, T., Rahman, J., & Ridwan, M. (2024b). The Influence of Agriculture, Renewable Energy, International Trade, and Economic Growth on India's Environmental Sustainability. Journal of Environmental and Energy Economics, 37-53.

Raihan, A., Tanchangya, T., Rahman, J., Ridwan, M., & Ahmad, S. (2022b). The influence of Information and Communication Technologies, Renewable Energies and Urbanization toward Environmental Sustainability in China. Journal of Environmental and Energy Economics, 1(1), 11-23.

Raihan, A., Voumik, L. C., Ridwan, M., Ridzuan, A. R., Jaaffar, A. H., & Yusoff, N. Y. M. (2023b). From growth to green: navigating the complexities of economic development, energy sources, health spending, and carbon emissions in Malaysia. Energy Reports, 10, 4318-4331. https://doi.org/10.1016/j.egyr.2023.10.084

Rana, M. N. U., Al Shiam, S. A., Shochona, S. A., Islam, M. R., Asrafuzzaman, M., Bhowmik, P. K., ... & Asaduzzaman, M. (2024). Revolutionizing Banking Decision-Making: A Deep Learning Approach to Predicting Customer Behavior. Journal of Business and Management Studies, 6(3), 21-27.

Rasheed, M. Q., Yuhuan, Z., Haseeb, A., Ahmed, Z., & Saud, S. (2024). Asymmetric relationship between competitive industrial performance, renewable energy, industrialization, and carbon footprint: Does artificial intelligence matter for environmental sustainability?. Applied Energy, 367, 123346. https://doi.org/10.1016/j.apenergy.2024.123346

Rauf, A., et al. (2018). Testing EKC hypothesis with energy and sustainable development challenges: A fresh evidence from belt and road initiative economies. Environmental Science and Pollution Research, 25, 32066–32080. https://doi.org/10.1007/s11356- 018-3052-5

Ridwan, M. (2023). Unveiling the powerhouse: Exploring the dynamic relationship between globalization, urbanization, and economic growth in Bangladesh through an innovative ARDL approach.

Ridwan, M., Raihan, A., Ahmad, S., Karmakar, S., & Paul, P. (2023). Environmental sustainability in France: The role of alternative and nuclear energy, natural resources, and government spending. Journal of Environmental and Energy Economics, 2(2), 1-16. https://doi.org/10.56946/jeee.v2i2.343

Ridwan, M., Urbee, A. J., Voumik, L. C., Das, M. K., Rashid, M., & Esquivias, M. A. (2024). Investigating the environmental Kuznets curve hypothesis with urbanization, industrialization, and service sector for six South Asian Countries: Fresh evidence from Driscoll Kraay standard error. Research in Globalization, 8, 100223. https://doi.org/10.1016/j.resglo.2024.100223

Ridzuan, A. R., Rahman, N. H. A., Singh, K. S. J., Borhan, H., Ridwan, M., Voumik, L. C., & Ali, M. (2023, May). Assessing the Impact of Technology Advancement and Foreign Direct Investment on Energy Utilization in Malaysia: An Empirical Exploration with Boundary Estimation. In International Conference on Business and Technology (pp. 1-12). Cham: Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-55911-2_1

Roumiani, ., Mofidi, A. Predicting ecological footprint based on global macro indicators in G-20 countries using machine learning approaches. Environ Sci Pollut Res 29, 11736–11755 (2022). https://doi.org/10.1007/s11356-021-16515-5

Roumiani, A., & Mofidi, A. (2021). Ecological Footprint Prediction based on Global Macro Indicators in G-20 Countries using Machine Learning Approaches. https://doi.org/10.21203/rs.3.rs-489246/v1

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. https://doi.org/10.1016/j.enpol.2010.11.034

Sahoo, M., Sethi, N. The intermittent effects of renewable energy on ecological footprint: evidence from developing countries. Environ Sci Pollut Res 28, 56401–56417 (2021). https://doi.org/10.1007/s11356-021-14600-3

Salahuddin M, Ali MI, Vink N, Gow J (2019) The effects of urbanization and globalization on CO 2 emissions: evidence from the Sub-Saharan Africa (SSA) countries. Environ Sci Pollut Res 26(3):2699–2709

Salahuddin, M., Ali, M.I., Vink, N. et al. The effects of urbanization and globalization on CO2 emissions: evidence from the Sub-Saharan Africa (SSA) countries. Environ Sci Pollut Res 26, 2699–2709 (2019). https://doi.org/10.1007/s11356-018-3790-4

Samour, A., Isiksal, A. Z., & Resatoglu, N. G. (2019). TESTING THE IMPACT OF BANKING SECTOR DEVELOPMENT ON TURKEY'S CO 2 EMISSIONS. Applied Ecology & Environmental Research, 17(3). http://dx.doi.org/10.15666/aeer/1703_64976513

Samour, A., Moyo, D., & Tursoy, T. (2022). Renewable energy, banking sector development, and carbon dioxide emissions nexus: A path toward sustainable development in South Africa. Renewable Energy, 193, 1032-1040. https://doi.org/10.1016/j.renene.2022.05.013

Shahbaz, M., Dogan, M., Akkus, H.T. et al. The effect of financial development and economic growth on ecological footprint: evidence from top 10 emitter countries. Environ Sci Pollut Res 30, 73518–73533 (2023). https://doi.org/10.1007/s11356-023-27573-2

Shahbaz, M., Jam, F. A., Bibi, S., & Loganathan, N. (2016). Multivariate Granger causality between CO2 emissions, energy intensity and economic growth in Portugal: evidence from cointegration and causality analysis. Technological and Economic Development of Economy, 22(1), 47-74.

Shahbaz, M., Loganathan, N., Muzaffar, A. T., Ahmed, K., & Jabran, M. A. (2016). How urbanization affects CO2 emissions in Malaysia? The application of STIRPAT model. Renewable and Sustainable Energy Reviews, 57, 83-93. https://doi.org/10.1016/j.rser.2015.12.096

Sharif A, Baris-Tuzemen O, Uzuner G, Ozturk I, Sinha A (2020) Revisiting the role of renewable and non-renewable energy consumption on Turkey’s ecological footprint: evidence from quantile ARDL approach. Sustain Cities Soc 57(February):102138. https://doi.org/10.1016/j.scs.2020.102138

Sharma, G. D., Tiwari, A. K., Erkut, B., & Mundi, H. S. (2021). Exploring the nexus between non-renewable and renewable energy consumptions and economic development: Evidence from panel estimations. Renewable and Sustainable Energy Reviews, 146, 111152. https://doi.org/10.1016/j.rser.2021.111152

Sovacool, B. K. (2013). Energy policymaking in Denmark: Implications for global energy security and sustainability. Energy Policy, 61, 829-839. https://doi.org/10.1016/j.enpol.2013.06.106

Sovacool, B. K. (2017). Contestation, contingency, and justice in the Nordic low-carbon energy transition. Energy Policy, 102, 569-582. https://doi.org/10.1016/j.enpol.2016.12.045

Stock, J. H., & Watson, M. W. (1993). A simple estimator of cointegrating vectors in higher order integrated systems. Econometrica: journal of the Econometric Society, 783-820. https://doi.org/10.2307/2951763

Su, N. (2023). Green energy imports, FDI, Stock market capitalization, globalization and environmental degradation in China: Paving the Path to Sustainability in COP26 Agenda. https://doi.org/10.21203/rs.3.rs-3244670/v1

Taghizadeh-Hesary, F., Zakari, A., Alvarado, R., & Tawiah, V. (2022). The green bond market and its use for energy efficiency finance in Africa. China Finance Review International, 12(2), 241-260. https://doi.org/10.1108/CFRI-12-2021-0225

Topcu, M., Tugcu, C. T., & Ocal, O. (2020). How Does Environmental Degradation React to Stock Market Development in Developing Countries?. Econometrics of Green Energy Handbook: Economic and Technological Development, 291-301.

Tsagkanos, A., Siriopoulos, C., & Vartholomatou, K. (2019). Foreign direct investment and stock market development: Evidence from a "new" emerging market. Journal of Economic Studies, 46(1), 55-70. https://doi.org/10.1108/JES-06-2017-0154

Ulucak, R., & Khan, S. U. D. (2020). Determinants of the ecological footprint: role of renewable energy, natural resources, and urbanization. Sustainable Cities and Society, 54, 101996. https://doi.org/10.1016/j.scs.2019.101996

Urban, F., & Nordensvärd, J. (2018). Low carbon energy transitions in the Nordic countries: Evidence from the environmental Kuznets curve. Energies, 11(9), 2209. https://doi.org/10.3390/en11092209

Voumik, L. C., & Ridwan, M. (2023). Impact of FDI, industrialization, and education on the environment in Argentina: ARDL approach. Heliyon, 9(1). https://doi.org/10.1016/j.heliyon.2023.e12872

Voumik, L. C., Hossain, M. S., Islam, M. A., & Rahaman, A. (2022). The Impact of Electricity Production Sources on CO2 Emission in BRICS Countries: A GMM and Quantile Regression Analysis. Strategic Planning for Energy and the Environment, 41(4), 1-24. https://doi.org/10.13052/spee1048-5236.4143

Voumik, L. C., Islam, M. A., Ray, S., Mohamed Yusop, N. Y., & Ridzuan, A. R. (2023a). CO2 emissions from renewable and non-renewable electricity generation sources in the G7 countries: static and dynamic panel assessment. Energies, 16(3), 1044. https://doi.org/10.3390/en16031044

Voumik, L. C., Ridwan, M., Rahman, M. H., & Raihan, A. (2023b). An investigation into the primary causes of carbon dioxide releases in Kenya: Does renewable energy matter to reduce carbon emission?. Renewable Energy Focus, 47, 100491. https://doi.org/10.1016/j.ref.2023.100491

Wang, Q., Sun, T. & Li, R. Does artificial intelligence (AI) reduce ecological footprint? The role of globalization. Environ Sci Pollut Res 30, 123948–123965 (2023). https://doi.org/10.1007/s11356-023-31076-5

Westerlund, J. (2007). Testing for error correction in panel data. Oxford Bulletin of Economics and Statistics, 69(6), 709–748. https://doi.org/10.1111/j.1468- 0084.2007.00477.x

Westerlund, J., & Edgerton, D. L. (2008). A simple test for cointegration in dependent panels with structural breaks. Oxford Bulletin of Economics and statistics, 70(5), 665-704. https://doi.org/10.1111/j.1468-0084.2008.00513.x

Younis, I., Naz, A., Shah, S.A.A. et al. Impact of stock market, renewable energy consumption and urbanization on environmental degradation: new evidence from BRICS countries. Environ Sci Pollut Res 28, 31549–31565 (2021). https://doi.org/10.1007/s11356-021-12731-1

Zafar, M. W., Zaidi, S. A. H., Sinha, A., Gedikli, A., & Hou, F. (2019). The role of stock market and banking sector development, and renewable energy consumption in carbon emissions: Insights from G-7 and N-11 countries. Resources Policy, 62, 427-436. https://doi.org/10.1016/j.resourpol.2019.05.003

Zafar, M. W., Zaidi, S. A. H., Sinha, A., Gedikli, A., & Hou, F. (2019). The role of stock market and banking sector development, and renewable energy consumption in carbon emissions: Insights from G-7 and N-11 countries. Resources Policy, 62, 427-436. https://doi.org/10.1016/j.resourpol.2019.05.003

Zeqiraj, V., Sohag, K., & Soytas, U. (2020). Stock market development and low-carbon economy: The role of innovation and renewable energy. Energy Economics, 91, 104908. https://doi.org/10.1016/j.eneco.2020.104908

Zhang L, Li Z, Kirikkaleli D, Adebayo TS, Adeshola I, Akinsola GD (2021) Modeling CO2 emissions in Malaysia: an application of Maki cointegration and wavelet coherence tests. Environ Sci Pollut Res 28(20):26030–26044

Zhang, Q., Shah, S. A. R., & Yang, L. (2022). Modeling the effect of disaggregated renewable energies on ecological footprint in E5 economies: Do economic growth and R&D matter?. Applied Energy, 310, 118522. https://doi.org/10.1016/j.apenergy.2022.118522

Zhao, J., Shahbaz, M., Dong, X., & Dong, K. (2021). How does financial risk affect global CO2 emissions? The role of technological innovation. Technological Forecasting and Social Change, 168, 120751. https://doi.org/10.1016/j.techfore.2021.120751

Zhu H, Xia H, Guo Y, Peng C (2018) The heterogeneous effects of urbanization and income inequality on CO 2 emissions in BRICS economies: evidence from panel quantile regression. Environ Sci Pollut Res 25:17176–17193 1-18

RESEARCH ARTICLE

The effects of trade openness on CO_2 emissions in Sub-Saharan Africa: fresh evidence from new measure

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Abstract
This study assesses the effects of trade openness on carbon dioxide (CO_2) emissions in Sub-Saharan Africa (SSA). In contrast to previous studies, and in order to make a significant contribution to the empirical literature on the subject, we capture trade openness through a new and innovative approach that takes into account not only the share of a country's trade in its gross domestic product but also the size of its trade in world trade. In addition, this study also stands out for its consideration of trade openness in different sectors of the economy (primary, secondary and tertiary). For the econometric strategies, the study used data from 38 SSA countries between 2002 and 2022 and estimated the effects by the Generalized Method of Moments (GMM) system and the double ordinary least squares method. The main results show that in SSA: trade openness contributes to rising CO_2 emissions. In addition, trade in the primary (agriculture), secondary (industry) and tertiary (services) sectors contributes to the increase in CO_2 emissions. The models used are controlled by several variables. The results show that the renewable energy consumption is a key driver of environmental quality, which seems to reduce CO_2 emissions. On the other hand, human capital, population growth and the quality of institutions increase CO_2 emissions. Furthermore, the interaction between openness and institutional quality has a negative impact on CO_2 emissions. Therefore, in order to reduce CO_2 emissions, SSA needs to put the environment on the agenda of future trade negotiations; to implement policies and strategies that guarantee growth without abandoning the environment.

Keywords: Trade openness, CO_2 emissions, Sub-Saharan Africa.

Introduction

In the context of trade protectionism impacting economic and environmental sustainability, a more comprehensive understanding of the impact of trade on carbon emissions is critical to economic and environmental sustainability (Wang et *al.* 2024). The global economy is facing environmental problems that, for the most part, are the results of CO_2 air pollution. In addition to the serious environmental challenges posed by global warming and climate change, concerns about emissions are central to policymaking in many countries (Junaid et *al.* 2023). Among the causes of environmental damage, CO_2 emissions are known to represent the main contributor to recent climate change (Mengal et *al.* 2019; Cai et *al.* 2018). The global challenge of climate change has prompted countries worldwide to shift towards renewable energy sources to reduce CO_2 emissions and mitigate the impacts of climate change (Mohsin, 2024; Kwakwa, 2023). Among the greenhouse gases responsible for climate change, carbon emissions have the greatest impact. Indeed, these emissions account for 80% of total emissions, and reducing them has become an effective way of tackling climate change (Huang et *al*. 2022). Global warming and greenhouse gas emissions pose a serious threat to environmental sustainability in every country in the world. A sustainable environment is a prerequisite for long-term socioeconomic growth and human survival (Haseeb et *al*. 2023). Moreover, global CO_2 emissions have risen remarkably over the years, from 3,112,685,279 metric tons per capita in 1960 to 3,874,290,347 metric tons per capita in 1980 and over 13 billion metric tons per capita in 2018, according to World Bank data (WDI, 2023). International entities have highlighted the issue of climate change and global efforts toward becoming carbon neutral by 2050 (Emma, 2024).

Global warming is one of the most severe environmental problems that human beings are currently facing. The rising level of CO_2, the primary contributor to the greenhouse effect, appears to exacerbate the situation (Goswami, 2023).The substantial increase in CO_2 emissions is alarming, as they have had a negative impact on economic wealth, human health, food security and, to a greater extent, the environment (Duodu & Mpuure, 2023). The quest for rapid economic development by modern nations has led to an unprecedented increase in carbon emissions (Chhabra et *al*. 2023). Global warming due to CO_2 emissions is leading to a reduction in food production and biodiversity, as well as rising sea levels and mortality rates (Liu et *al.* 2022a). According to Intergovernmental panel on climate change (IPCC, 2021), the most important GHG is CO_2, accounting for around 72% of emitted gases. CO_2 emissions contribute to 76% of global GHG emissions (Coskuner et *al.* 2020; Zakari & Tawiah, 2019). The increase in world carbon emissions is always in line with national economic growth programs, which create negative environmental externalities (Hariyani et *al.* 2024). Although SSA is not one of the main CO_2 emitters, the area is exposed to the major harmful effects of CO_2 emissions, which hampers its economic growth and development (Duodu and Mpuure, 2023). For example, CO_2 emissions in SSA rose from 784540.02 kilotonnes (kt) in 2016 to 823770.02 kt in 2019, representing a growth rate of 2.75% in 2019 versus 1.57% in 2016 according to World Bank data (WDI, 2023). Furthermore, although SSA accounts for less than 3% of global carbon emissions, these emissions are increasing over these decades, given ongoing economic and institutional reforms aimed at improving economic growth, strengthening industrialization and diversification, improving transport systems and responding to energy crises (Avom et *al.* 2020). With specific regard to Africa, it has been documented that decision-makers in SSA are very concerned because the consequences of global warming are the most damaging in the sub-region (Efobi et *al.* 2019). SSA's economic and social status is still precarious and open to internal and external shocks (Andriamahery et *al.* 2022). The developing economies of Africa, and more specifically the countries of SSA, have deployed various practices to ensure the emancipation of their level of sustainable development. Some of these include the promotion of economic growth, industrialization, real agricultural development, financial development, renewable energy consumption and human capital sustainability (Ganda, 2021). 600,000 people die every year in the African region from causes related to emissions from wood and charcoal combustion (Chirambo, 2018). The situation is more severe for SSA due to poverty, low technological know-how and most importantly, more than half of the population depends on climate-driven enterprises such as small-scale farming, peasant farming, agriculture and hawking (Ngwenya et *al.* 2018). Although SSA is the least integrated and pollutes the environment the least, it is the most vulnerable to future climate change (Acheampong et *al.* 2019). The main contributors are South Africa, Angola and Nigeria, with 853107.128 kt, 34693.487 kt and 120369.275 kt emitted in 2019 respectively. Guinea-Bissau, Comoros and Sao Tome and Principe represent the lowest levels, with 293.36 kt, 201.685 kt and 121.011kt of CO_2 emitted in 2019 (WDI, 2023). Furthermore, economic openness through the trade dimension and inward foreign direct investment (FDI) influences environmental damage (Sun et *al.* 2019). The link between trade openness and CO_2 emissions is a key research focus in times of pressing global sustainability needs and ongoing climate change discussions (Barkat et *al.* 2024). With this in mind, it has been proven that around a quarter of CO_2 emissions are associated with trade flows (Brenton & Chemutai, 2021). Moreover, economic openness has increased in recent decades, and this is revealed by measures of trade and financial openness (Lemaallem & Outtaj, 2023). Expansion in world trade gives rise to more production and therefore more creation of industrial structures and units. This broad expansion of production requires energy, considered to be the potential source of CO_2 emissions. Researchers assert that trade openness in a country means greater use of natural resources, which ultimately has a negative impact on the environment (Zamil et *al.* 2019). Compared to other regions, statistics on SSA show that the region contributed 36.81% of global trade in 2016 and 30.04% of air pollution in 2014 (World Bank, 2020). The share of trade in SSA's gross domestic product (GDP) rose from 45.98% in 2016 to 50.03% in 2020 (World Bank, 2022). SSA countries have been relatively open to foreign trade since the 1980s. On average, they have recorded a relatively higher rate of growth in CO_2 emissions than other regions, and are the least resistant to the adverse effects of global warming. Today, SSA's objective is to eradicate energy poverty and income inequality in order to achieve the Sustainable Development Goals. With this in mind, several studies have therefore focused on the problems of income inequality, energy and poverty (e.g. Santiago et *al.* 2020; Potrafke, 2015). In contrast, the environmental problems associated with rising CO_2 emissions in the region have been relatively ignored. However, there are growing concerns about the consequences of economic openness on non-economic variables. Furthermore, the relationship between trade openness and CO_2 emissions in SSA has not been deeply investigated by previous researchers.

Most studies focus on developed countries because of their level of industrialization. A few studies carried out in SSA focus on countries such as South Africa (Udeagha & Ngepah, 2019; Mapapu & Phiri, 2018), Nigeria (Zakari & Tawiah, 2019) and Ghana (Kwakwa et *al.* 2020; Solarin et *al.* 2017). Since the early 1990s, a large and growing literature has studied the role of trade openness in CO_2 emissions. However, empirical contributions have remained contradictory and inconclusive. It appears from the literature that trade openness is one of the methods or strategies that can be used to achieve economic growth (Gnangnon, 2020). However, the real question is how much it will cost. While SSA needs economic growth, we must not lose sight of the need for long-term growth. Therefore, growth that takes into account the quality of the environment must be a top priority. This highlights the link between trade openness and the environment in SSA (Andriamahery et *al.* 2022). In an era defined by the urgent need for global environmental sustainability and amid ongoing discussions surrounding climate change mitigation, the relationship between trade openness and CO_2 emissions has emerged as a paramount field of investigation (Barkat et *al.* 2024). The consequences of CO_2 emissions in SSA countries cannot be ignore given it adverse effect on human health and global warming (Ewane & Ewane, 2023).

This article is structured around five points: an introduction, which sets the context for the subject and analyzes the stylized facts of CO_2 emissions in SSA; a literature review, which clearly shows the lack of consensus in theoretical and empirical studies and also develops a new indicator of trade openness; a methodology, which presents the model specification, the estimation method and defines the model variables; results and discussions, which clearly present the estimation results and their interpretations; and finally, the conclusion and policy recommendations.

Literature Review

The ever-debated relationship between trade and environment has allured the attention of many scholars over a long period (Chhabra et *al.* 2023). The importance of enhancing environmental quality to promote economic development by improving societal well-being and sustainable development on quality of environment haveattracted significant attention from researchers in recent years (Mekuannet, 2024). Existing theoretical literature has identified three channels in international trade through which CO_2 emissions can be affected by trade openness: the scale effect, the composition effect and the technical effect (Antweiler et *al.* 2001). Grossman & Krueger (1993) consider these mechanisms to be the economic determinants of emissions from productive activity. They are economic growth (scale effect), industrial composition (composition effect) and the severity of environmental regulation (technical effect). While the theoretical literature has documented various channels through which openness to international trade can affect environmental quality, its empirical verification remains an open and controversial question for researchers and policy-makers alike. The impact of trade openness on environment is of increasing concern to environmental practitioners, industrialists, and researchers (Dou et *al.* 2023).

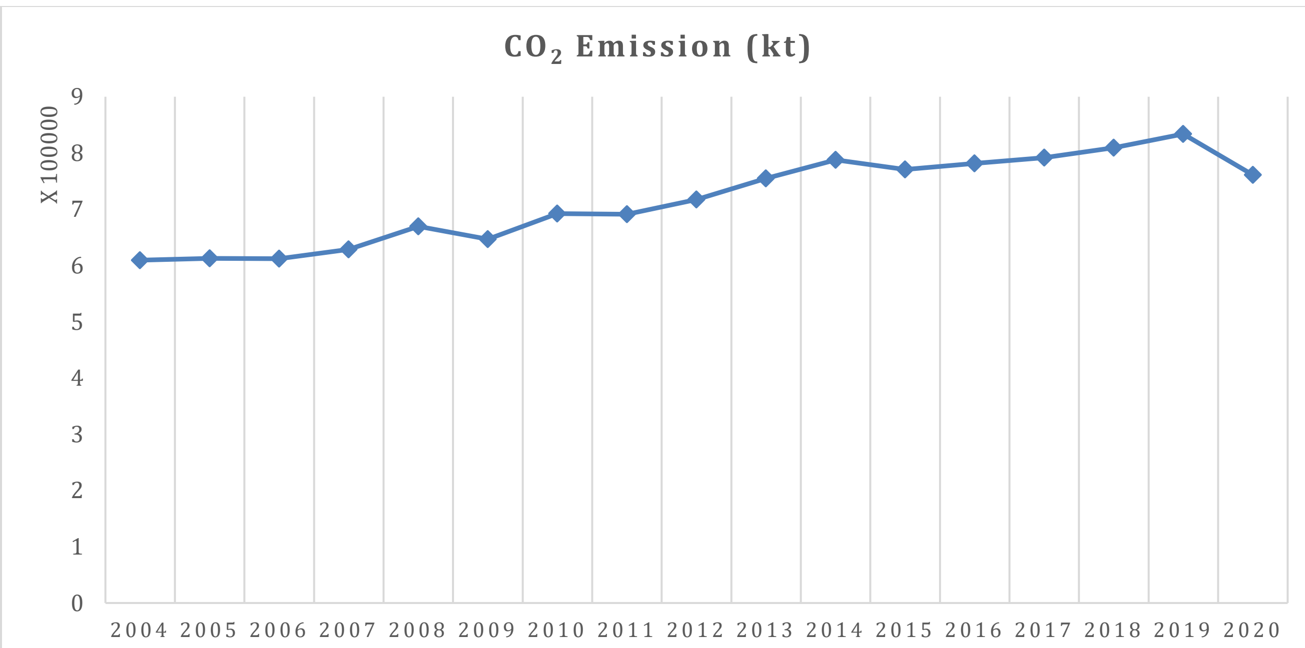

Figure 1. Trends in CO_2 emissions (in kilotonnes) in SSA (2004-2020)

Figure 1 shows the evolution of CO_2 released into the atmosphere by SSA. According to World Bank data (WDI, 2023), CO_2 has followed an upward trend, rising from 497660 kt in 2000 to 695130 kt in 2010, 789380 kt in 2014 and 823770.016 kt in 2019. While some recent studies have shown that trade decreases CO_2 emissions from the development of new energy-saving technologies (e.g. Duodu & Mpuure, 2023; Ibrahim & Ajide, 2022; Okelele et *al.* 2022; Iheonu et *al.* 2021; Muhammad et *al.* 2020; Aydin and Turan, 2020; Kwakwa et *al.* 2020; Awad, 2019; Hu et *al.* 2018; Sinha & Shahbaz, 2018; Acheampong, 2018). Others have found that such activities are harmful to the environment (e.g. Andriamahery et *al.* 2022, Chen et *al.* 2021; Duodu et *al.* 2021; Du et *al.* 2020; Hakimi & Hamdi, 2020; Zamil et *al.* 2019; Acheampong et *al.* 2019; Balsalobre-Lorente et *al.* 2018; Raza & Shah, 2018). In contrast to all these empirical investigations, some studies have provided evidence suggesting that openness has no statistically significant impact on CO_2 emissions (e.g. Salahuddine et *al.* 2019; Inglesi-Lotz & Dogan, 2018; Mapapu & Phiri, 2018; Inglesi-Lotz, 2018). Consequently, regarding the effect of trade openness on CO_2 emissions, the evidence is largely contradictory, and no consensus has been found or reached in the empirical literature. Table 1 below summarizes a number of empirical studies on the effects of trade openness on CO_2 emissions.

Table 1. Summary of empirical studies on the relationship between trade openness and CO_2 emissions

Authors	Periods and Country	Methods used	Results
Bouchoucha (2024)	1990-2019 40 African countries	Simultaneous equations	The results show that trade openness has a positive and significant effect on CO_2 emissions, and therefore CO_2 emissions have a positive association with infant mortality and under-five mortality, while CO_2 emissions have a negative association with life expectancy.
Ghaderi et *al.* (2023)	1995-2018 Middle East and North Africa (MENA)	Granger's test of non-causality, the estimator of the mean group of correlated effects.	Energy consumption and trade openness are the main contributors to CO_2 emissions. The results also showed that although first-generation estimators confirmed the Environmental Kuznets curve (EKC) hypothesis, there is no inverted U-shaped association between economic progress and CO_2 emissions.
Goswami et *al.* (2023)	1981-2021 India	ARDL model and the random forest model	The ARDL model revealed that variables were co-integrated. In the short term, economic growth and trade openness are correlated with CO_2 emissions, while energy consumption and urbanization were positively correlated. In the long term, energy consumption, urbanization and commercial opening are positively correlated with CO_2 emissions, while economic growth and CO_2 emissions are positively correlated.
Pham & Nguyen (2024)	2003-2017 64 developing countries	Bayesian approach to the average	There is no evidence of a statistically significant effect of trade opening on environmental pollution in developing countries. However, the results do not support the pollution paradise hypothesis. In addition to trade openness, the results indicate that financial openness, renewable energy consumption and capital abundance are key drivers of environmental quality, which appear to reduce CO_2 emissions.
Barkat et *al.* (2024)	20 Organisation for Economic Co-operation and Development (OECD) countries over a period of 150 years	Robust cointegration techniques	The direct effect showed a positive correlation between trade opening and CO_2 emissions, while the indirect effect, mediated by income growth, shows a negative influence. These divergent effects support the environmental Kuznets curve hypothesis.
Duodu & Mpuure (2023)	1990-2020 ASS	GMM and the Dumitrescu and Hurlin (D-H) causality test	The overall effect of trade reduces environmental pollution by around 0.10% and 0.79% in both the short and long term, respectively. Again, we observe that exports and imports minimize environmental pollution, we observe that exports and imports minimize environmental pollution by around 0.07% and 0.45% (0.08% and 0.58%) in the short term (long term), respectively. With regard to the D-

			H results, we found a bidirectional causality between total trade and environmental pollution.
Chhabra et *al.* (2023)	1991-2019. BRICS	modern method of dynamic common correlative effects	Confirming the pollution paradise hypothesis, the results reveal that "trade opening" is indeed a cause of environmental damage in BRICS countries.
Omri E. & Saadaoui (2023).	1980-2020 France	NARDL (Non-linear Autoregressive Distributed Lag	Fossil fuels and open trade are increasing emissions. The analysis confirms the presence of an inverted U-curve linking economic growth to carbon emissions.
Ewane & Ewane (2023)	1975-2020 SSA countries	a quadratic modelling approach	It shows evidence that trade openness and foreign direct investment contribute to reducing CO_2 emissions in the short term, but increase in the long term. The study recommends that SSA countries adopt strong environmental policies to achieve sustainable economic growth without harming the environment.
Dou et *al.* (2023)	1990-2021. 76 countries	Non-linear dynamic model	Trade openness has a significant impact on carbon productivity, with a U-shaped relationship between the two variables. In other words, carbon productivity first decreases and then increases from a certain threshold of trade opening. The impact of trade opening on carbon productivity varies from country to country.
Pata et *al.* (2023)	1995-2018 Association of South-East Asian Nations (ASEAN) countries	The ARDL panel estimator and the Dumitrescu-Hurlin panel causality test	Real income and trade openness reduce environmental damage. The EKC hypothesis is valid because the elasticity of income in the long term is lower than in the short term.Renewable energy reduces carbon emissions only in the short term and has no effect on environmental quality in the long term. There is no causal relationship between renewable energy and environmental damage.
Udeagha & Breitenbach (2023)	1960-2020 Southern African Development Community (SADC)	Non-linear, autoregressive distributed delay (NARDL)	The results show mixed evidence of an asymmetric behaviour between trade opening and CO_2 emissions. Long-term asymmetry is found for Botswana, Madagascar, Mozambique and Tanzania, while for the Comoros, Namibia and South Africa there is evidence of both short- and long-term asymmetry. The other cases (Angola, Democratic Republic of the Congo (DRC), Lesotho, Malawi, Mauritius, Seychelles, Zambia and Zimbabwe) show ample evidence of symmetrical behaviour and long-term linear relationships between trade opening and CO_2 emissions.
Junaid et *al.* (2023)	1990-2019 75 BIS countries	Spatial panel data models and methods	First, the estimated results confirm the existence of spatial self-correlations in CO_2 emissions between BIS countries. Second, the trade opening, natural gas consumption and spatial

			effects of these variables positively affect CO_2 emissions.
Awad (2019)	(1990-2017) 46 African countries	DOLS, and a non-parametric technique (FMOLS).	The results suggest that intra-African trade has improved environmental quality on the continent. In addition, the results confirmed the presence of the Kuznets Environmental Curve
Qamruzzaman M. (2021)	(1971-2019) Low-income countries, lower-middle-income countries, upper-middle-income countries and a global sample	Nonlinear ARDL, non-Granger causality test	The results show that positive relationships run from environmental quality, institutional quality and FDI to trade openness, particularly in the long term. Furthermore, asymmetric estimation establishes asymmetry shocks in environmental quality, institutional quality and FDI that are positively related to trade openness, particularly in the long term. Furthermore, the results of the Wald test confirm the presence of asymmetry in both the long and short term..
Andriamahery et *al.* (2022)	(1990-2017) SSA	GMM	The results show that trade significantly increases N_2O, ACH4 and CO_2 emissions for the overall sample of Sub-Saharan Africa and its income groups (upper-middle-income countries, lower-middle-income countries and low-income countries).
Zamil et *al.* (2019)	(1972-2014) Oman	Unit Root Tests, ARDL	GDP, population and trade openness seem to have a positive impact on CO_2 emissions.
Hu et *al*. (2018)	1996-2012 25 developing countries	DOLS, and a non-parametric technique (FMOLS).	trade improves the environment by reducing carbon emissions.
Acheampong (2018)	1990-2014 116 countries of the world	VECM, GMM	open trade improves environmental quality by reducing carbon emissions worldwide,,
Kwakwa et *al*. (2020)	1971-2013 Ghana	theoretical framework composed of the STIRPAT, ARDL model	International trade leads to a reduction in CO_2 emissions in Ghana.
Sinha & Shahbaz (2018)	1971-2015 India	unit root test and (ARDL)	trade openness is negatively correlated with carbon dioxide emissions in India
Hakimi & Hamdi (2019)	2006-2015 143 countries	GMM	Trade is detrimental to the quality of the environment, and the role of institutions is crucial to preserving it.
Acheampong et *al*. (2019)	1980-2015 46 SSA countries	fixed and random effects estimation techniques	Open trade worsens the environment
Raza et Shah (2018)	1972-2014 Pakistan	Ordinary least squares	trade openness deteriorates environmental quality.
Nguyen et *al*. (2020)	1996-2014 33 emerging economies	theoretical framework composed of the STIRPAT, ARDL model	Openness has a positive impact on CO_2 emissions in the short term and a negative impact on CO_2 emissions in the long term.

Udeagha & Ngepah (2019)	1960-2016 South Africa	ARDL	while trade liberalization has a significantly beneficial impact on CO_2 emissions in the short term, it has a detrimental effect in the long term.
Sun et *al*. (2019)	Countries of the South Asian Association for Regional Cooperation (SAARC).	ARDL	Trade, FDI and economic growth have a positive long-term correlation with environmental damage in SAARC countries; whereas FDI and trade flows have a negative relationship with CO_2 emissions in the short term.
Inglesi-Lotz (2018)	1990-2014 BRICS	CO2 Emission Technical breakdown	Commercial openness has no significant impact on environmental conditions.
Mapapu &Phiri (2018)	1970-2014 South Africa	Quantile regression	very low CO_2 emissions are most beneficial for economic growth, and that trade openness has no significant impact on carbon emissions.
Inglesi-Lotz & Dogan (2018)	1980-2011 10 SSA countries	Technical assessment panel robust to cross-sectional dependence	Trade openness has no significant effect on carbon dioxide emissions.
Salahuddin et *al*. (2019)	1984-2016 44 SSA countries	Second-generation panel regression techniques	The effect of globalization (FDI and trade openness) on CO_2 emissions is statistically insignificant.
Kim et *al*. (2019)	Northern countries, southern countries	Instrumental variable panel quantile approach	Northern trade contributes to rising CO_2 emissions, while southern trade reduces CO_2 emissions
Mutascu (2018)	1995-2011 G7 countries	Granger causality	Significant heterogeneity between G7 countries in terms of international trade and environmental issues. Trade openness is a good indicator of CO_2 emissions generated by the production sector.
Sun et *al*. (2019)	1991-2014 49 countries	Current panel cointegration approaches	The study reveals that trade openness has both positive and negative effects on environmental pollution, but the effect varied across these different groups of nations.
Aydin & Turan (2020)	1996-2016 BRICS	Cross-dependency testing, unit root testing, conitegration testing	Open trade reduces pollution in South Africa and India.

Source: Author's compilation.

Note: GMM=Generalized Method of Moments; CO_2=carbon dioxide, SO_2=sulfur dioxide,, SSA=Sub-Saharan Africa; FMOLS= Fully Modified Ordinary Least Square, DOLS= Dynamic Ordinary Least Square, ARDL= autoregressive distributed lag model, VECM= vector error correction model, STIRPAT= Stochastic impacts by regression on population, influx and technology, BRICS= Brazil, Russia, India, China and South Africa, CEE= Central and Eastern European Countries, OECD=Organization for Economic Cooperation and Development.

Table 1 shows that there is a consensus in empirical studies Therefore, it is clear that the theoretical arguments and empirical results of the effect of trade liberalization and FDI on CO_2 emissions are unclear and contradictory (Hakimi & Hamdi, 2016). There is no doubt that the contradictory results of the effects of trade on environmental pollution can, to some extent, be attributed to methodological weaknesses and, it is also possible that the environmental effect of trade depends on the nature of trade (Duodu & Mpuure, 2023). The heterogeneity of data and empirical methods used in these studies can partly explain the diversity of results and contradictory positions in the literature. The diversity may depend on a myriad of factors of different countries selected in the sample, the econometric techniques employed, environmental indicators and a set of control variables used. Other likely reasons for these conflicts include how trade openness is described and measured.

However, despite its popularity, the traditional measure of trade openness and its variants should be used with caution for a number of reasons, most of which are related to GDP normalization (Gräbner et *al.* 2021). Another possible explanation for the contradictions is that the authors evaluate the hypothesis by ignoring the importance of structural effects that stimulate economic growth (Nkengfack et *al.* 2019).

The present study is innovative in that it introduces variables that are recommended by researchers in the current literature on growth and the environment. Indeed, to describe the proxy variable for trade openness, this study uses two indicators: the composite trade intensity of Squalli & Wilson (2011) and the openness rate (a traditional indicator of openness). In order to see which sector contributes the most to CO_2 emissions, this study takes into account the openness in different sectors of the economy (primary, secondary and tertiary).

Development of the new indicator of trade openness

Following the various criticisms addressed to the degree of openness as a measure of the level of trade openness of a country, we develop, in accordance with Squalli & Wilson (2011), a new indicator taking into account both dimensions of openness. However, despite its popularity, Trade/GDP and its variants should be used with caution for a number of reasons, most of which are related to the normalization by GDP. In order to take into account the arbitrage bias that exists in the use of unidimensional measures of openness, we will propose an alternative method of calculating these indicators. This method takes into account both unidimensional measurement criteria (TI and WTS).

$WTS_i = \frac{(X+M)_i}{\sum_{j=1}^{n}(X+M)_j}$, in this formula we can rewrite the volume of world trade as follows:

$$\sum_{j=1}^{n}\left(X+M\right)_j = \left(X+M\right)_i + \sum_{J=1}^{n-1}\left(X+M\right)_J \quad (1)$$

$$= X_i + M_i + \sum_{j=1}^{n-1} X_i + \sum_{j=1}^{n-1} M_i$$

With $\sum_{j=1}^{n-1} X_i$ and $\sum_{j=1}^{n-1} M_i$ respectively the volume of exports and imports from the rest of the world. If the exports of country i (X_i) are almost equal to what the rest of the world exports and what country i imports (M_i) are almost equal to the exports of the rest of the world, in other words if the quantity of products exported by country i to the rest of the world is the same, and that imported by the latter is also equal to the quantity imported by the rest of the world; then we will have:

$$\sum_{j=1}^{n}\left(X+M\right)_j=2\left(X+M\right)_i \Leftrightarrow \frac{\left(X+M\right)_i}{\sum_{j=1}^{n}\left(X+M\right)_j}=\frac{1}{2} \quad (2)$$

WTS cannot therefore exceed 0.5 since no country can export and import more than the rest of the world. Alternatively we will have:

$$\sum_{i=1}^{n}\left[\frac{\left(X+M\right)_i}{\sum_{j=1}^{n}\left(X+M\right)_J}\right]=1 \quad (3)$$

$$\bar{x}=\frac{\sum_{i=1}^{n}\left[\frac{\left(X+M\right)_i}{\sum_{j=1}^{n}\left(X+M\right)_J}\right]}{n}=\frac{1}{n} \quad (4)$$

The new measure of trade openness takes into account the two previous criteria *WTSi* and *TIi*, that is, between the trade intensity of the country in relation to the performance of its local economy on the one hand, and on the other hand, it takes into account the relative trade intensity of the latter in relation to the volume of world trade. And it can be presented as a "composite trade intensity measure" *CTI* in the following form:

$$CTI_i=\left(1+D_y\right)TI_i \quad (5)$$

With D*y* representing the ratio of the measured distance to the deviation of from the mean and is presented by the following form:

$$D_y=\frac{WTS_i}{\bar{X}}-1 \quad (6)$$

$D_y \geq 0$, when $WTS_i \geq 0$ and $D_y \leq 0$ if $WTS_i \leq 0$

According to these last two formulas and replacing equations (1) and (4) by their expressions, we will have: $CTI_i=\frac{1}{\bar{X}}(WTS_i \times TI_i)=\mathrm{n}(WTS_i \times TI_i)$, by replacing *WTS* and *TI* by their expressions, we will finally have the expression of the new indicator of trade openness:

$$CTI_i=\frac{n(X+M)_i^2}{PIB_i\sum_{j=1}^{n}(X+M)_j} \quad (7)$$

Where *CTI* stands for composite trade intensity which is the new indicator for measuring trade openness. When comparing TI-based trade openness measures, a striking anomaly arises. Indeed, as shown in Table 2, according to *TI*, China, Russia, Malaysia, Japan and the United States are among the most closed economies in the world. On the contrary, Equatorial Guinea and Congo belong to the most open countries in the world. Consequently, according to TI, the world's largest trading powers are relatively closed economies, because their share of trade (*WTS*) in overall economic activity is very low by global standards. But is it right to classify countries like the United States, the leading trading power, Japan and Russia as closed economies? The obvious explanation is that TI and related indicators are one-dimensional measures of trade openness and in this way, they penalize large economies by classifying them as closed. Table 2 ranks countries according to squalli & wilson (2011) indicators of trade openness.

Table 2. Ranking of countries according to trade openness indicators

Countries	X+M/GDP	Rank	WTS	Rank	CTS	Rank
Cameroon	57,44	100	0,083	84	645,90	89
Congo	132,5	18	0,043	100	767,59	86
Gabon	71,79	76	0,029	109	282,08	105
Equatorial Quinea	153,05	10	0,03	107	630,81	93
Chad	48,6	112	0,015	117	99,72	122
United States	26,2	133	10,810	1	38517,96	9
Japon	20,1	136	2,781	10	7603,43	35
Russia	70,68	77	8,210	4	41574,34	7
Belgium	169,33	7	1,826	19	42056,33	6
China	48,36	113	9,841	2	64724,01	4
Hong Kong	295,19	2	2,354	14	94491,06	1
Malaysia	230,33	4	2,124	17	66527,34	3

Source : Squalli & Wilson (2011)

Methodology

To examine the effects of trade openness on CO_2 emissions in SSA, various econometric techniques are used for a panel of 38 countries (Angola, Democratic Republic of Congo, Equatorial Quinea, Ivory Coast, Togo, Eswatini, Mozambique, Botswana, Ghana, Namibia, Uganda, Gabon, Rwanda, Burkina Faso, Guinea, Senegal, Burundi, Guinea-Bissau, Seychelles, Cape Verde, Kenya, Sierra Leone, Cameroon, Madagascar, South Africa, Benin, Nigeria, Niger, Zimbabwe, Mauritius, Lesotho, Malawi, Comoros, Mali, Sudan, Republic of Congo, Tanzania, Mauritius) over the period 2005-2022. The choice of the study period is dictated by the constraint of availability of relevant data on CO_2. All data come from the World Development Indicator and World Governance Indicator of the World Bank (WDI and WGI, 2023).

Model Specification

In this study, we draw inspiration from the above econometric models for the specification of our analysis model. Indeed, following Acheampong et *al.* (2019) and Hakimi & Hamdi (2020), we have the following specification:

$$CO2_{i,t} = \alpha_0 + (1+\beta_1)CO2_{i,t-1} + \beta_2 OUV_{i,t} + \beta_3 PIB/h_{i,t} + \beta_4 PIB^2/h_{i,t} + \beta_5 CapPh_{i,t} + \beta_6 Caphu_{i,t}$$
$$+\beta_7 Df_{i,t} + \beta_8 ER_{i,t} + \beta_9 Pop_{i,t} + \beta_{10} Gov_{i,t} + \Sigma_{i,t} \quad (8)$$

Let's ask $\Sigma_{i,t} = \eta_i + \lambda_t + \upsilon_{i,t}$, with unobservable components such as a country specific component (η_i), a specific time component (λ_t) and the residual term ($\upsilon_{i,t}$). *i* and *t* represent countries and periods respectively. In the form of a dynamic panel model, equation (8) is rewritten as follows:

$$CO2_{i,t} - CO2_{i,t-1} = \alpha_0 + \beta_1 CO2_{i,t-1} + \beta_2 OUV_{i,t} + \beta_3 EE_{i,t} + \beta_4 ET_{i,t} + \beta_5 CapPh_{i,t} + \beta_6 Caphu_{i,t}$$
$$+\beta_7 Df_{i,t} + \beta_8 ER_{i,t} + \beta_9 Pop_{i,t} + \beta_{10} Gov_{i,t} + \Sigma_{i,t} \quad (9)$$

In this model, $CO2_{it}$ represents CO_2 emissions; $OUV_{i,t}$ trade openness; $ET_{i,t}$ technical effect; $CapPh_{i,t}$ physical capital investment; $EE_{i,t}$ scale effect; $POP_{i,t}$ population; $Gov_{i,t}$ institutional governance; $ER_{i,t}$ renewable energy and $Dfi_{i,t}$ financial development, and $CapHu_{i,t}$ human capital.
We can simplify (13) as follows:

$$CO2_{i,t} - CO2_{i,t-1} = \beta_1 CO2_{i,t-1} + \beta_2 OUV_{i,t} + \vec{\beta}_3^{'} CV_{i,t} + \eta_i + \lambda_t + \nu_{i,t} \quad (10)$$

Where : $CO_{2i,t}$ and $CO_{2i,t-1}$ represent respectively the logarithm of CO_2 emissions in metric tons per capita and the logarithm of the same variable delayed by one period; CV_{it} is the vector of explanatory variables; OUV_{it} is the variable representing trade openness; η_i and λ_t respectively denote the unobserved individual and temporal specific effects; V_{it} is the error term; i and t represent countries and periods respectively; β_1 and β_2 are parameters to be estimated; $\vec{\beta}_3^{'}$ is the transpose of a parameter vector to be estimated. With i=1,,,N and t=1,,,T. The hypothesis of convergence between the economies studied suggests that the coefficient (β_1) is negative and significant in the model, i.e. $0 \prec 1 + \beta_1 \prec 1$. We can further rewrite model (10) as follows:

$$CO2_{i,t} = \tilde{\beta}_1 CO2_{i,t-1} + \beta_2 OUV_{i,t} + \vec{\beta}_3^{'} CV_{i,t} + \eta_i + \lambda_t + \nu_{i,t} \quad (11)$$

With $\tilde{\beta}_1 = 1 + \beta_1$

Consistent with Huang et *al.* (2022), Zheng et *al.* (2021), Ehigiamusoe et *al*. (2020), in order to examine how the effect of trade openness on the environment varies when it interacts with complementary policies (CPs), equation (11) can be modified as follows:

$$CO2_{i,t} = \tilde{\beta}_1 CO2_{i,t-1} + \overline{\beta}_2 CV_{i,t} + \beta_3 OUV * PC_{i,t} + \eta_i + \lambda_t + \nu_{i,t} \quad (12)$$

In our work, institutional governance is the complementary policy. All data used are in logarithms. Indeed, there are important reasons associated with transforming the data into logarithms. The first is the use of direct elasticities and obtaining more consistent and efficient results. Second, the logarithm specification increases the stationarity of the series. And finally, heteroscedasticity is reduced (Awad, 2019; Zakari & Tawiah, 2019).

Estimation method

This study does not use the Ordinary Least Square (OLS) model, the fixed effect model and the random effect model due to the problem of autocorrelation between the lags of the dependent variables and the error terms as well as the possible problem of endogeneity of the dependent variables. However, following the recent literature on the subject (Yameogo et *al*. 2021; Hakimi & Hamdi, 2020), the Arellano & Bover (1995) system GMM is used to solve these problems. This method eliminates the problem of weak instruments in the analysis, thus making the results of the two-stage process more robust and efficient. We will use this method for the estimation of the model (9). The two-step GMM approach is asymptotically efficient and robust to heteroscedasticity. In order to have efficient estimators, the ratio of the number of individuals (N) to the number of instruments (i) (r=N/i) must be greater than 1 and to solve the problem of the nature of the instruments, it is judicious to introduce variables that have nothing in common such as institutional variables or to delay some or all of the explanatory variables and test their validity by a Sargan and Hansen test (Roodman, 2009).

Definition of variables

Here we define the dependent variable of the study and the explanatory variables. Table 3 describes the variables used in this study.

Table 3. Description of variables.

Variables	Expected sign	Description	Authors	Sources
CO_2 **(**Carbon dioxide emissions)		We use CO_2 emissions in metric tons per capita which in most studies describe environmental quality.	Asif (2024); Adebanjo & Akintunde (2024), Andriamahery et *al.* (2022); Kalayci & Hayaloglu (2019),	(WDI, 2023)
OUV (trade openness)	+	The composite trade intensity of Squalli & Wilson (2011), is used to describe the degree of openness of SSA countries.	Udeagha & Ngepah (2019) ; Udeagha & Breitenbach (2023).	(WDI, 2023)
EE (Scale Effect)	+	Captured as in most studies by GDP/capita.	Shahbaz & Sinha (2019); Sabir et *al.* (2020), To et *al.* (2019), Dauda et *al.* (2019)	(WDI, 2023)
ET (Technical effect)	-	Captured as in most studies by the square of GDP/capita	Awad (2019); Acheampong et *al.* (2019) ; Antweiler et *al.* (2001)	(WDI, 2023)
CaPh (Physical Capital)	+ou-	Captured by gross fixed capital formation (%GDP)	Duodu & Mpuure, (2023); Hakimi & Hamdi (2020); Sun et *al.* (2019); Fauzel (2017)	(WDI, 2023)
CapH (Human Capital)	+ ou -	It is approximated by the secondary school enrollment rate	Andriamahery et *al.* (2022); Dauda et *al.* (2020), Ahmed & Wang (2019); Ponce et *al.* (2019).	(WDI, 2023)
Df (Financial development)	+ ou -	The ratio of domestic credit to the private sector (%GDP) is used	Zakari & Tawiah (2019), Haseeb et *al.* (2018), Ali et *al.* (2019)	(WDI, 2023)
ER (Renewable Energy)	-	Renewable energy consumption (as % of total energy consumption) is used to capture renewable energy	Toumi & Toumi, (2019); Nathaniel & Iheonu (2019); Baloch et *al.* (2019); Waheed et *al.* (2018); Dong et *al.* (2018).	(WDI,2023)
Pop (Population)	+ ou -	Population growth (annual %)	Acheampong et *al.* (2019) ; Huang et *al.* (2022)	(WDI,2023)
GOV (Quality of institutions)	-	The synthetic indicator of six (6) dimensions of governance is used	Habib et *al.* (2020); Usman et *al.* (2019);	(WGI,2023)

Source: author

Results and discussions

Before doing so, however, it is necessary to carry out a descriptive analysis of the study variables and of the correlation matrix between the dependent variable and the different explanatory variables of the model.

Descriptive analysis of variables

The descriptive statistics (Table 4) of the main analysis variables are contained in the table below and show the same number of observations (684) for all variables (38*18=684). The average CO_2 emissions of SSA countries is of the order of (2.9143). The trade openness captured by the Squalli and Wilson indicator (2011) has an average of 1.276.

Table 4: Descriptive statistics of the variables

Variable	Obs	Average	Standard deviation	Min	Max	Sdt.dev	Skewness	Kurtosis	J-B
EmissCO$_{2}$~I	684	2.91433	0.25122	19.6215	85.8251	0.6215	0.2584	5.2514	51.21*
Ouv~l	684	1.276606	4.215802	-12.55692	14.21594	0.6252	-1.5215	1.2482	23.14*
EE	684	7.8493	0.321581	-2.65693	2.22592	1.2513	2.0516	8.2154	11.11*
ET~t	684	40.74841	0.592519	-1.987359	1.12548	14.0125	2.1470	7.2154	9.215*
CapPh~é	684	52.19036	0.72318	-1.01227	0.21584	0.2147	2.1111	4.9651	8.858*
Ouv(X+M/PIB)	684	1.57136	0.32582	-1.99927	0.32547	0.4474	1.9686	9.2154	13.36*
OuvPrimary~e	684	2.56074	0.33258	-9.63093	2.01251	0.33332	3.3335	10.1014	12.28*
OuvSecon~n	684	2.62589	0.35489	-1.81262	0.32189	1.4857	3.1117	9.2154	12.11*
OuvTertia	684	2.61299	0.11245	-1.2582	1.25148	4.3251	2.9975	7.8541	8.977*
Caph~l	684	41.10621	4.21548	21.21521	41.41441	2.3152	5.2874	8.3699	23.28*
Df~a	684	5.15507	7.25184	15.21589	99.8921	0.2154	7.6254	8.2157	22.87*
ER~e	684	6.67003	0.34852	-1.01258	1.144352	0.87956	1.2221	5.4849	14.88*
Pop~t	684	15.1267	7.215489	2.01586	89.32145	0.2187	2.3731	6.6696	11.21*
GovInst~l	684	1.9205	25.51482	-15.0215	14.21586	0.77812	-0.2014	0.6598	5.897*

Source: author from world bank data. **Note:** *, ** and *** significance at the respective thresholds of 1%, 5% and 10%.

Furthermore, the traditional indicator of trade openness gives an average of 1.571 while it is of the order of 2.56; 2.62; and 2.61 in the tertiary, secondary and primary sectors respectively. The composition effect captured by the ratio between capital and labor is characterized by the smallest average value (-0.1903) and also the smallest maximum value (0.215). The scale effect captured by GDP per capita has an average of 7.849 while the technical effect has an average of around 40.74. Physical capital is characterized by the largest average value (52.19) followed by human capital (41.106), while financial development has on average the largest maximum value (99.892). Population growth has a mean value of 15.126 while it is of the order of 1.92 for institutional governance. It is also observed that renewable energy consumption has a mean of 6.67. The difference between the minimum and maximum values of all the variables is between 0.2147 and 14.012.

Overall, the descriptive statistics show low variations. The results further show that only institutional governance and trade openness are negatively skewed while the others are positively skewed. The Kurtosis values reveal that governance and trade openness are platykurtic while the other variables have a leptokurtic distribution. The Jarque-

Table 5. Correlation matrix between variables

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
$EmissCO_2$~I	1.0000													
Ouv~l	0.0147	1.0000												
EE	0.3744	0.1002	1.0000											
ET~t	-0.5897	-0.0586	0.7265	1.0000										
CapPh~é	0.2147	0.1104	0.8420	0.7220	1.0000									
Ouv(X+M/GDP)	-0.3360	0.0519	-0.6746	0.6275	0.6519	1.0000								
OuvPrimary~e	0.2871	0.0538	0.8141	0.7534	0.9110	0.6311	1.0000							
OuvSecon~n	0.2544	0.0765	0.8858	0.7944	0.9090	0.7472	0.8785	1.0000						
OuvTertia	-0.2581	0.0806	0.8701	0.7857	0.9271	0.8635	0.9097	0.9956	1.0000					
Caph~l	-0.0651	-0.0200	-0.1121	0.0079	0.1149	-0.1336	0.0103	0.1419	-0.1169	1.0000				
Df~a	-0.0122	-0.0828	-0.0767	-0.0887	-0.0747	-0.1087	-0.0924	-0.0924	-0.1112	0.0009	1.0000			
ER~e	-0.3281	0.0129	0.1630	0.2536	0.3027	0.3271	0.2298	0.2450	0.3098	0.0976	-0.0199	1.0000		
Pop~t	0.3697	0.0628	0.1008	0.1932	0.2320	0.0960	-0.2251	0.1495	0.1836	-0.1130	-0.0178	0.2503	1.0000	
GovInst~l	-0.0213	0.9998	0.0147	0.4472	0.2140	0.0147	0.3251	0.9980	0.1987	-0.0580	-0.0258	0.9871	1.0000	1.0000

Source: Author from world bank data

Bera statistic affirms the normality of our data series, which indicates the adequacy of the data for any empirical analysis.

Correlation matrix analysis

Table 5 provides a description of the correlations between the different analysis variables. The correlation matrix shows the existence of correlations between the different variables used. The correlations between CO_2 emissions and GDP per capita on the one hand, CO_2 emissions and the square of GDP on the other hand, are 0.3744 and -0.5897 respectively. The correlations between CO_2 emissions and physical capital; CO_2 and trade openness (Squalli & Wilson, 2011) are 0.2147 and 0.0147 respectively. Furthermore, the highest correlations appear between trade openness and institutional governance (0.9998); between openness in the secondary sector and governance (0.998); between openness in the secondary sector and openness in the tertiary sector (0.9956).
Indeed, having an observation of more than 200 can result in a correlation coefficient between 0.7 and 0.8 without causing a problem in the estimations. This proves that there is no multi-collinearity between the independent variables. However, the weakest correlations appear between CO_2 emissions and the scale effect (-0.5897), between CO_2 emissions and trade openness captured by the traditional indicator (human capital and the composition effect (-0.9816); -0.3281 between institutional governance and trade openness captured by the traditional indicator (-0.1204); governance and CO_2 emissions (-0.1750); between CO_2 emissions and renewable energy consumption (-0.3281) and finally population growth and openness in the primary sector (-0.2251). However, the correlations between the different variables analyzed are not

Presentation and interpretation of the results

Here, we present and interpret the results obtained by the generalized moments method as well as the interpretations. This part therefore begins with the presentation of the results obtained using the generalized moments method in system. For the sensitivity of the results, we re-estimate the model using the Ordinary Double Least Squares method. In all estimations, the reported coefficients are in logarithms, hence can be interpreted as long-run elasticities.

Interpretation of results (GMM in system)

In the five models (1, 2, 3, 4 and 5) of Table 6, the probabilities associated with the Hansen tests are greater than 5%, which means that the instruments are overall exogenous, in other words the instruments used in the regressions are valid. Furthermore, the probability associated with the second-order autocorrelation test is also greater than 5%, therefore the hypothesis of second-order autocorrelation, AR (2), can also be rejected. The observation of the statistics therefore shows that the condition of non-correlation is satisfied and the dynamic model in panel data used is good. The ratio between the number of individuals (group or country) and the number of instruments is greater than 1 in the different models.
Regarding the estimation results, model (1) represents the results obtained using the Squalli & Wilson (2011) indicator as a proxy for overall real openness. On the other hand, model (2) represents the results obtained when trade openness is captured by the traditional indicator (the sum of exports and imports reported to GDP).

Table 6. Summary of results: first GMM-Sys estimation

CO2 emission	Model 1	Model 2	Model 3	Model 4	Model 5
CO_{2t-1}	0.857**	0.987**	0.327***	0.964**	0.743**
	(1.36)	(1.44)	(1.97)	(1.02)	(1.07)
Global real opening	0.161**	0.194	0.051***	0.102**	0.117***
	(0.54)	(0.55)	(0.71)	(0.98)	(0.32)
GDP/h (Scale effect)	0.010***	0.011**	0.021**	0.087**	0.093***
	(0.89)	(0.93)	(0.44)	(0.24)	(0.53)
GDP^2/h (Technical effect)	-0.014***	-0.027**	-0.113**	-0.009**	-0.021
	(0.11)	(0.37)	(0.09)	(0.31)	(0.81)
Physical Capital	0.038***	0.078**	0.337**	0.781**	0.018
	(0.66)	(0.91)	(1.25)	(0.57)	(0.29)
Human Capital	0.071**	0.210	0.023	0.831**	0.711
	(0.47)	(0.11)	(0.80)	(0.87)	(0.24)
Financial Dev.	-0.007	-0.008	0.222**	-0.001	0.003
	(0.77)	(0.20)	(0.90)	(0.73)	(0.74)
Energy Re	-0.782**	-0.982***	-0.966***	-0.666**	-0.358***
	(1.72)	(1.82)	(1.73)	(1.28)	(1.91)
Population	0.004**	0.0001	0.444***	0.003	0.009
	(0.88)	(1.66)	(1.02)	(1.07)	(1.01)
Governance	0.875**	0.002**	0.336***	0.563**	0.552
	(0.86)	(0.84)	(1.52)	(1.69)	(1.55)
Constant	9.002**	4.421**	1.853**	3.002**	6.331**
	(1.22)	(1.72)	(1.43)	(1.03)	(0.78)
Observations	684	586	683	683	684
Groups	38	38	38	38	38
Instruments	31	26	24	28	30
AR (1) p-value	0.000	0.000	0.000	0.000	0.000
AR(2) p-value	0.321	0.225	0.351	0.241	0.254
Hansen p-value	0.212	0.256	0.219	0.252	0.244

Source: Author from world bank data.

Note: Numbers in parentheses denote Student's t-scores in absolute values; *, ** and *** the significance at the 1%, 5% and 10% thresholds, respectively. Notations: models: 1. trade openness is captured by the Squalli & Wilson (2011) indicator; 2. trade openness is captured by the traditional indicator; 3. trade openness in the primary sector (agriculture); 4. trade openness in the secondary sector (sum of exports of manufactured goods and imports as a percentage of exports and imports of goods); 5. trade openness in the tertiary sector (trade in services as a percentage of gross domestic product).

And finally, models 3, 4 and 5 represent the results obtained when the overall real openness is observed respectively in the primary sector (agriculture), the secondary sector (industry) and the tertiary sector (service). In the case of model (1), the hypothesis of the Kuznets environmental curve is verified (because GDP/h has a positive coefficient of 0.01, and its square has a negative coefficient of -0.014 and both are significant at 10%). This result corroborates those found by Hakimi & Hamdi (2019); Shahbaz & Sinha (2019); Sabir et *al*. (2020), To et *al*. (2019), Dauda et *al*. (2019), Emrah & Aykut (2018). This result is quite revealing, since unlike advanced countries, SSA countries are at their early stage of development, and use less sophisticated techniques to reduce carbon emissions. This model shows that trade openness has a positive and significant effect at 5% on CO_2 emissions in SSA.

Indeed, a 1% increase in trade openness leads to a 0.16% increase in CO_2 emissions in SSA in the long term. Physical capital has a positive and significant coefficient at 10%. A 1% increase in gross fixed capital formation leads to a 0.038% increase in CO_2 emissions in SSA. This impact is significant in most models. And this result is contradictory to that found by Fauzel (2017) in Mauritius. This result shows that domestic investments in SSA do not take environmental issues into account. When the overall real openness is captured by the traditional indicator (model 2), the coefficient associated with openness remains positive (0.194) but not significant. This can be explained by the fact that this indicator does not truly capture the level of commercial openness of a country. Furthermore, this model shows that the scale effect has a positive and significant coefficient of the order of 0.01. Furthermore, the technical effect contributes as in model 1 to reducing CO_2 emissions in SSA.

When we look at the different sectors of the economy, trade openness in the primary sector (trade in agricultural goods as a percentage of goods) has a positive and significant effect at 10% on CO_2 emissions in SSA. Indeed, the results of model (3) show that a 1% increase in trade in agricultural products leads to a 0.051% increase in atmospheric pollution by CO_2 in SSA. These results can be explained by the different archaic techniques used in agriculture in most SSA countries. The coefficients associated with the scale and technical effects are of the order of 0.021 and -0.113 respectively. In the secondary sector (model 4), the overall real openness is captured by trade in manufactured goods, i.e. goods resulting from human activity based on raw materials. In this model, trade openness has a positive and significant impact at 5% on atmospheric pollution by CO_2 in SSA. Indeed, if the opening of trade in manufactured goods increases by 1%, CO_2 emissions increase by 0.102%.

In this sector, the scale effect has a positive coefficient (0.087) while the technical effect negatively affects (-0.009) CO_2 emissions in SSA. This can show that the positive effect of global openness on CO_2 emissions in SSA is due to activities in the industrial sector such as extractive industries, which have too lax environmental regulations. In model (5), trade openness is captured by trade in services. The associated coefficient is positive (0.117) and significant. This shows that this sector also influences CO_2 emissions in SSA. The signs of the theoretical channels of international trade (scale and technical effects) through which openness affects emissions respect the theoretical prediction. Furthermore, in all the results, the coefficient of renewable energy consumption remains negative and significant at 5%, 10%, 10%, 5% and 10% respectively for models 1, 2, 3, 4 and 5.

This shows overall that renewable energy consumption contributes significantly to reducing CO_2 emissions in SSA. Furthermore, there is mainly strong evidence that carbon emissions decrease with increasing use of renewable energy, as shown by Acheampong et *al.* (2019). These results strongly corroborate the empirical results of Dong et *al.* (2018) who found that renewable energy consumption plays an important role in mitigating carbon emissions. This suggests that the continued use of fossil energy (oil, gas and coal) for commercial purposes contributes to carbon emissions. In addition, and to some extent, the increasing use of non-renewable energy and the lack of substitutable energy in SSA seems to be the most important challenge to reduce global warming, a situation that calls for much attention. Therefore, our results show that greater consumption of renewable energy reduces CO_2 emissions in SSA.

Many of the empirical studies have explored the causal relationship between the use of renewable energy and CO_2 emissions (Toumi & Toumi, 2019; Nathaniel & Iheonu, 2019; Baloch et *al.* 2019; Waheed et *al.* 2018; Dong et *al.* 2018; Charfeddine et *al.* 2018). In all the results, it is also found that the increase in population growth leads to an increase in CO_2 emissions in SSA. Indeed, in the first model, the coefficient associated with population growth is positive and significant at 5% (0.004). This coefficient is also positive and significant at 10% (0.444) in Model 3. In the other models, the effect is positive and insignificant. Therefore, the increase in population in SSA contributes to air pollution. Acheampong et al. (2019) also found that population growth contributes to the increase in CO_2

emissions in SSA. Regarding financial development, its effect on carbon emissions in SSA is not pronounced in this study. Indeed, it has a positive coefficient in some models and negative in others, and none of the results are significant. This is necessarily due to the weakness of the financial sector in SSA.

In all models, our results revealed that institutional quality measured using the composite index (which includes six governance indicators: freedom of speech and accountability, political stability, state effectiveness, regulatory quality, rule of law and control of corruption) positively impacts CO_2 emissions in SSA. Indeed, governance has a positive and significant coefficient on CO_2 emissions in all models except model 5. This result can be explained by the poor application of governance dimensions in CO_2 mitigation in SSA. For example, corruption can influence subsidies received by companies or the level of trade protection. Corruption also indirectly affects emissions through its effect on income level (Cole, 2007). In model 1 and model 4, human capital positively and significantly impacts CO_2 emissions in SSA at 5%. The implication of this result is that the level of education is low in SSA, and the population is still unaware of environmental issues.

This result corroborates those of Dauda et a*l*. (2020) in African countries. Human capital has become an important element of CO_2 mitigation strategies over the years, as a certain level of education allows people to understand the importance of complying with environmental rules and the need to reduce CO_2 emissions. When certain actions such as vocational training, learning by doing, research and development are not taken into account, human capital activities can affect environmental CO_2 pollution. Furthermore, environmental policies are likely to be achieved in places where the level of education of citizens is moderately high because there is a tendency to obey environmental rules (Desha et *al*. 2015).

Robustness analysis 1: Reestimation by the system GMM

In this section, we will repeat the estimation of our study model using the GMM method, taking into account the institutional variable each time. The results are reported in Table 7 below. In the seven models (1, 2, 3, 4, 5, 6 and 7) in Table 7, the probabilities associated with the Hansen tests are greater than 5%, which means that the instruments are generally exogenous, in other words the instruments used in the regressions are valid. Furthermore, the probability associated with the second-order autocorrelation test is also greater than 5%, therefore the hypothesis of second-order autocorrelation, AR(2), can also be rejected. The observation of the statistics therefore shows that the condition of non-correlation is satisfied and the dynamic model in panel data used is good. Model 1 presents the results of the estimation when corruption and its interaction with openness are taken into account. In the same logic, political stability is taken into account in model 2; voice and accountability in model 3; government effectiveness in model 4; regulatory quality in model 5; rule of law in model 6 and the composite index in model 7.

In the seven models, trade openness positively impacts CO_2 emissions in SSA. This confirms the results obtained previously. The CEK hypothesis is also confirmed in all models in accordance with the previous results and the theoretical prediction. Furthermore, these results show that the weakness of institutions in SSA is a handicap for improving its environment. Indeed, the six indicators of institutional quality have a positive and significant effect on CO_2 emissions in SSA. For example, when corruption, voice and accountability, regulatory quality each increase by 1%, CO_2 emissions increase by 0.32%; 0.05%; 0.9% respectively in SSA. On the other hand, when trade openness interacts with a complementary policy, in this case the indicators of the quality of governance in the context of this work, the coefficient of the interaction remains negative. Indeed, the interaction gives negative coefficients (-0.002) for model 1; -0.002 for model 2; -0.0001 for model 3; -0.02 for model 4 and -0.75 for model 5, -0.54 for model 6, -0.01 for model 7. Consequently, for trade openness to improve the quality of the environment by reducing CO_2 emissions in SSA, it must be accompanied by effective institutions.

Table 7. Summary of results: second GMM-Sys estimation

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
				SYS-GMM			
VARIABLES				CO_2 emissions			
CO_{2t-1}	0.012**	0.452**	0.513**	0.836**	0.791**	0.215**	0.325**
	(0.0472)	(0.0321)	(0.0445)	(0.0258)	(0.0398)	(0.0142)	(0.0784)
Trade openness	0.193**	0.0369***	0.0114**	0.0235***	0.0714**	0.0321**	0.387**
	(0.447)	(0.00112)	(0.0714)	(0.2541)	(0.0147)	(0.0883)	(0.0892)
GDP/h (Scale effect)	0.111***	0.0216***	0.0601***	0.00944	0.0169***	0.0422***	-0.0155***
	(0.0854)	(0.2514)	(0.0105)	(0.0258)	(0.2780)	(0.00428)	(0.00630)
GDP^2/h (Technical effect)	-0.0177**	-0.0315***	-0.0875***	-0.0782**	-0.0981***	-0.0410*	-0.0108***
	(0.0143)	(0.000801)	(0.00808)	(0.00821)	(0.00841)	(0.00983)	(0.00347)
Physical Capital	0.0247	0.7412***	1.0008***	0.7360***	0.888***	1.0014***	1.0082***
	(0.677)	(0.641)	(0.819)	(0.398)	(0.401)	(0.442)	(0.871)
Human Capital	0.2221**	0.1009***	0.00007***	0.0014*	0.215***	0.8214***	0.3671*
	(0.012)	(0.7210)	(0.0418)	(0.0214)	(0.0014)	(0.2170)	(0.07618)
Financial Development	-0.3325	0.214	0.6020	0.01408	-0.0218	-0.4436	-0.8754
	(0.362)	(0.0325)	(0.0711)	(0.0896)	(0.0451)	(0.0963)	(0.0321)
Renewable Energy	-0.2314**	-0.2143***	-0.0047*	-0.0001*	-0.00008**	-0.0214**	0.302***
	(0.134)	(0.00459)	(0.0237)	(0.0420)	(0.0304)	(0.0240)	(0.0539)
Population	0.0021***	0.0361	0.0702	0.0014**	0.0961***	0.5551	0.0122***
	(0.135)	(0.0752)	(0.00441)	(0.00652)	(0.00375)	(0.00273)	(0.00523)
Corruption	0.328***	0.00142***	0.0114***	0.0043**	0.00258***	0.00871*	0.0102***
	(1.113)	(0.025)	(0.023)	(0.054)	(0.0021)	(0.0045)	(0.0521)
Trade openness # C. Corruption	-0.0025**						
	(0.145)						
Political Stability		0.211***					
		(0.821)					
Trade openness*Political Stability		-0.0021***					
		(0.0011)					
Voices and responsability			0.0541				
			(0.233)				
Trade openness*Voices and responsability			-0.0001***				
			(0.2141)				
government effectiveness				0.823			
				(0.058)			
Trade openness* government effectiveness				-0.0214***			
				(0.002)			
Regulatory Quality					0.981***		
					(0.251)		
Trade openness *Regulatory Quality					-0.7512		
					(0.0452)		
Rules of law						1.0008***	
						(0.814)	

Trade openness *Rules of law						-0.541 (0.144)	
Composite Governance Index							0.410*** (0.0766)
Trade openness* Composite Governance Index							-0.0140*** (0.0724)
Constant	1.52*** (2.104)	3.752*** (1.741)	5.413*** (1.485)	7.012*** (2.441)	3.113*** (2.783)	10.220*** (2.879)	7.069*** (2.331)
Observations	683	681	675	679	684	683	684
Number of groups	38	38	38	38	38	38	38
Instruments	22	31	27	27	29	30	29
AR (1) p-value	0.000	0.000	0.000	0.000	0.000	0.000	0.000
AR (2) p-value	0.221	0.125	0.329	0.238	0.219	0.105	0.821
Hansen p-value	0.466	0.328	0.420	0.143	0.325	0.413	0.269
Notations **:** Numbers in parentheses denote Student's t-scores in absolute values; *, ** and *** the significance at the 1%, 5% and 10% thresholds, respectively.							

Source: author from world bank data

Robustness Analysis 2: Estimation by the Ordinary Double Least Squares Method

In this section, we re-estimate the effects of trade openness on CO_2 emissions using the instrumental variables approach with the ordinary double least squares method. The results of the estimations without and with control variables are reported in Table 8. The tests confirm the validity of the instruments. Indeed, in the seven models (1, 2, 3, and 4) in Table 8, the probabilities associated with the Hansen tests are greater than 5%, which means that the instruments are overall exogenous, in other words the instruments used in the regressions are valid. Therefore, the absence of rejection of the null hypothesis in the Hansen test confirms the validity of the instruments. In addition, the Fisher statistic for each specification is greater than 10.
The under-identification test (KP-LM) is statistically good since it is of the order of 0.000 for all specifications. The Hansen statistic corroborates the results given by the coefficients of determination and the KP-LM probability. Finally, the F-stats give values greater than 10 for the different specifications signifying the good quality of the result. We conclude that the model is statistically validated.

Table 8. The effects of trade openness on CO_2 emissions: Ordinary Double Least Squares Method

	DEPENDENT VARIABLE : CO_2 EMISSION			
VARIABLES	(1)	(2)	(3)	(4)
TRADE OPENNESS	1,87***	0,31***	0,092**	0,011**
	(0,027)	(0,029)	(0,292)	(0,023)
GDP/H		0,210*	0,211***	0,206***
		(0,011)	(0,022)	(0,031)
GDP^2/H		-0,021***	-0,038	-0,035***
		(0,021)	(0,015)	(0,028)
PHYSICAL CAPITAL		0,025***	0,021**	0,001*
		(0,041)	(0,020)	(0,009)
HUMAN CAPITAL		0,001	0,005	-0,035**
		(0,054)	(0,019)	(0,033)
FINANCIAL.DEV		0,004***	-0,007	0,009**
		(0,017)	(0,016)	(0,041)
RENEWEBLE. ENER			-0,359***	-0,097***
			(0,057)	(0,037)
POPULATION			0,007***	0,041***
			(0,081)	(0,091)
GOVERNANCE				-0,127**
				(0,043)
CONSTANT	4,021*	4,254*	4,012*	3,968***
	(0,144)	(0,321)	(0,211)	(0,201)
OBSERVATIONS	684	684	684	684
R^2	0,119	0,171	0,133	0,152
KP-LM (P-VALUE)	0,000	0,000	0,000	0,000
HANSEN (P-VALUE)	0,325	0,582	0,655	0,758
F-STAT	451,7	605,4	359,8	584,6

Source: author from world bank data. **Note:** Robust standard deviations are reported in parentheses. * p<0,01, ** p<0,05, *** p<0,1

The results of model 1 (first column) of our estimation only retain trade openness as the explanatory variable, which can lead to a question of omission of explanatory variables arbitrarily inflating the expression of the coefficient of this variable. We will objectively interpret the coefficients of the last two columns which contain the maximum of explanatory variables. We will first proceed to the interpretation of the variable of interest and will follow that of the control variables. The variable of interest here is trade openness. This variable has the economically expected sign. Indeed, a one-point increase in trade openness leads, all other things being equal, to an increase of 0.092 points (column 3) or an increase of 0.011 (column 4) in the CO2 emissions rate. This result confirms the results previously obtained via the GMM method in system. Similarly to Sabir et *al.* (2020), the EKC hypothesis is verified for models 3 and 4. Indeed, GDP per capita has a positive and significant impact on CO_2 emissions while its square negatively affects CO_2 emissions.

Also focusing on the other control variables, we observe that they have overall the signs obtained in the GMM estimations. For example, the positive sign of human capital in model 3, the positive sign of population in models 3 and 4, the negative sign of renewable energy consumption, the negative sign of institutional quality and the positive sign of physical capital.

Conclusions and Policy implications

Through an original and innovative measure this study has to evaluate the effects of trade openness on CO_2 emissions in SSA. Through stylized facts, this study analyzed the trade performance, CO_2 emissions and export breakdown of SSA countries. The analysis of CO_2 emissions shows that in SSA, the emission rate is increasing over the period 2005-2022 despite its low contribution to global emissions. In addition, the breakdown of exports shows that this region is increasingly integrated into international trade. This study presented the methodology, results and interpretations. The indicator of Squalli & Wilson (2011) is used to capture the degree of openness of SSA countries. Through the GMM method and the robustness by the Ordinary Double Least Squares Method, the results showed that the estimation methods are unanimous on the positive effect of trade opening on CO_2 emissions. In terms of elasticity, the 1% increase in trade openness results in a 0.16% increase in CO_2 emissions in ASS. The arguments put forward include that trade increases the intensity of fossil energy consumption through the export of goods and services, which makes the industrial sector heavily dependent on fossil energy. The effect is that CO_2 emissions increase as economies tend to accumulate trade surpluses through exports. This study validated the existence of the hypothesis of the environmental curve of Kuznets (because GDP/capita has a positive coefficient of 0.010, and its square has a negative coefficient of -0.0141 and both are significant). In addition, trade opening in different sectors of the economy has shown that the primary (agriculture) and secondary (industry) sectors and the tertiary (services) sector contribute to the increase in CO_2 emissions in SSA. The dynamic model is controlled by several variables. In all the results, it was found that renewable energy consumption contributes significantly to reducing CO_2 emissions in SSA. In addition, the effect of financial development on SSA carbon emissions is not pronounced in this study because no results are significant. This is necessarily due to the weakness of the financial sector in SSA. Institutional quality measured by the composite index (which includes six governance indicators such as freedom of speech and accountability, political stability, state effectiveness, quality of regulation, rule of law and control of corruption) positively impacts CO_2 emissions in SSA. Human capital has a positive and significant impact on CO_2 emissions in SSA. The implication of this finding is that education levels are low in SSA, and people are still unaware of environmental problems.

With the world's rapid climate change, policy makers in SSA are encouraged to develop strategies that improve environmental quality (by reducing CO_2 emissions). To do so, they must: Include the environment component in their agenda for future trade negotiations. Choosing business partners with an eye to their environmental commitment. They must implement policies and strategies that ensure growth without abandoning the environment. Implement strategies to exploit and develop its energy potential and, by extension, reduce CO_2 emissions. The SSA has many natural resources, such as the rainforest which is one of the main carbon sinks on the planet and a potential source of renewable energy. Act on human capital, because a certain level of education allows the population to understand the importance of respecting environmental rules and the need to reduce CO_2 emissions. To achieve this, certain actions such as vocational training, learning by doing and research and development must be taken into account; improving the quality of their institutions by implementing appropriate policies and strategies.

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References

Acheampong A.O., Samuel A. & Elliot B. (2019). Do globalization and renewable energy contribute to carbon emissions mitigation in Sub-Saharan Africa?. *Science of the Total Environment*, 677, 436-446.

Acheampong A.O. (2018). Economic growth, CO2 emissions and energy consumption: What causes what and where?. *Energy Economics*, 74, 677-692.

Adebanjo S. & Akintunde W.B. (2024). Exploring the link between technological innovation, economic development, and CO2 emissions in the US. Application of the ANN and EKC techniques. *Journal of Environmental Science and Economics*, ISSN: 2832-6032, https://doi.org/10.56556/jescae.v3i1.809.

Ahmed Z. & Wang Z. (2019). Investigating the impact of human capital on the ecological footprint in India: An empirical analysis. *Environmental Science and Pollution Research*, 26, 26782-26796.

Ali H.S., Law S.H., Lin W.L., Yusop Z., Chin L. & Bare U.A.A. (2019). Financial development and carbon dioxide emissions in Nigeria: evidence from the ARDL bound approach. *GeoJournal*, 83, 641-655.

Andriamahery A., Danarson J. & Qamruzzaman Md. (2022). Nexus between trade and environmental quality in sub-saharan Africa: Evidence from panel GMM. *Frontiers in Environmental Science*, 10. 10.3389/fenvs.2022.986429.

Antweiler W., Copeland B.R. & Taylor M.S. (2001). Is free trade good for the environment?. *American Economic Review,* 914, 877-908.

Arellano M. & Bover O. (1995). Another look at the instrumental variable estimation of error-components models. *Journal of Econometrics,* 68, 29-51.

Arminen H. & Menegaki A.N. (2019). Corruption, climate and the energy-environment-growth nexus. *Energy Economics*, 80, 621-634.

Asif R. (2024). Influences of foreign direct investment and carbon emission on economic growth in Vietnam, *Journal of Environmental Science and Economics.* https://doi.org/10.56556/jescae.v3i1.670.

Avom D., Nkengfack H., Fotio H.F. & Totouom A. (2020). ICT and environmental quality in Sub-Saharan Africa: Effects and transmission channels. *Technological Forecasting and Social Change,* 155,120028.

Awad A. (2019). Does economic integration damage or benefit the environment? Africa's experience. *Energy Policy,* 132, 991-999.

Aydin M. & Turan Y.E. (2020). The influence of financial openness, trade openness, and energy intensity on ecological footprint: revisiting the environmental Kuznets curve hypothesis for BRICS countries. *Environmental science and pollution Research,* 27, 43233-43245.

Baloch M.A., Mahmood N. & Zhang J.W. (2019). Effect on natural resources, renewable energy and economic development on CO2 emissions in BRICS countries. *Science of the Total Environment,* 678-632-638.

Balsalobre-Lorente D., Shahbaz M., Roubaud D. & Farhani S. (2018). How economic growth, renewable electricity and natural resources contribute to CO2 emissions?. *Energy Policy*, 113, 356-367.

Barkat K., Mouyad A., Al Kwifi O.S. & Shaif J. (2024). Does trade openness mitigate environmental damage in Organisation for Economic Co-operation and Development (OECD) countries? Implications for achieving sustainable development, *Natural Resources Forum*, https://doi.org/10.1111/1477-8947.12412.

Bouchoucha N. (2024). Does Trade Openness and Environmental Quality Matter for Health Status? Evidence from African Countries. *J Knowl Econ,* 15, 5729-5745. https://doi.org/10.1007/s13132-023-01197-w.

Brenton P. & Chemutai V. (2021). The trade and climate change nexus: the urgency and opportunities for developing countries, World Bank, Washington DC.

Cai Y., Chang T. & Inglesi-Lotz R. (2018). Asymmetric persistence in convergence for carbon dioxide emissions based on quintile unit root test with Fourier function. *Energy*, 161,470-481.

Charfeddine L., Al-Malk A. & Korbi K. (2018). Is it possible to improve environmental quality without reducing economic growth: Evidence from the Qatar economy. *Renewable and Sustainable Energy Reviews,* 82, 25-39.

Chatri A., Zouiri H., Zenati A. & Chouati M. (2019). *Trade openness, human capital accumulation and growth: panel data analysis on developing countries. In A. Chatri (ed). Openness, productivity and economic growth in Morocco, Laboratory of Applied Economics & Policy Center for the New South. Rabat.*

Chen F., Jiang G. & Kitila M.G. (2021). Trade Openness and CO2 Emissions: The Heterogeneous and Mediating Effects for the Belt and Road Countries. *Sustainability*, *13*, 1958.

Chhabra M., Giri A.K. & Kumar A. (2023). Do trade openness and institutional quality contribute to carbon emission reduction? Evidence from BRICS countries. *Environmental Scieence and Pollution Research*, 50986-51002. https://doi.org/10.1007/s11356-023-25789-w.

Chirambo D. (2018). Towards the achievement of SDG 7 in sub-Saharan Africa: Creating synergies between Power Africa, Sustainable Energy for All and climate finance in-order to achieve universal energy access before 2030. *Renewable and Sustainable Energy Reviews,* 94, 600-608.

Cole M.A. (2007). Corruption, income and the environment: an empirical analysis. *Ecological Economics*, 62, 637-647.

Coskuner C., Paskeh M.K., Olasehinde-Williams G. & Akadiri S.S. (2020). Economic and social determinants of carbon emissions: Evidence from organization of petroleum exporting countries. *Journal of Public Affairs*, 20, e2092.

Dauda L., Xingle L., Mensah C.N. & Salman M. (2019). The effects of economic growth and innovation on CO2 emissions in different regions. *Environmental Science and Pollution Research*, 26, 15028-15038.

Dauda L, Xingle L., Mensah C.N., Salman M., Boamah K.B., Ampon-Wireko S. & Dogbe K.C.S, (2020). Innovation, trade openness and CO2 emissions in selected countries in Africa. *Journal of Cleaner Production,* 281, 125143.

Desha C., Robinson D. & Sproul A. (2015). Working in partnership to develop engineering capability in energy efficiency. *Journal of Cleaner Production,* 106, 283-291.

Dong K., Hochman G., Zhang Y., Sun R., Li H. & Liao H. (2018). CO2emissions, economic and population growth, and renewable energy: Empirical evidence across regions. *Energy Economics*, 75, 180-192.

Dou Y., Chen F., Kong Z. & Dong K. (2023). Re-estimating the trade openness-carbon emissions nexus: a global analysis considering nonlinear, mediation, and heterogeneous effects. *Applied Economics*, *55*(57), 6793-6808.

Du K., Yu Y. & Li J. (2020). Does international trade promote CO2 emission performance? An empirical analysis based on a partially linear functional-coefficient panel data model. *Energy Econ*, 92:104983.

Duodu E. & Mpuure D.M-N , (2023). International trade and environmental pollution in sub-Saharan Africa: do exports and imports matter ?. *Environmental Science and Pollution Research* ,30,53204-53220.

Duodu E., Kwarteng E., Oteng-Abayie EF. & rimpong PB. (2021). Foreign direct investments and environmental quality in sub-Saharan Africa: the merits of policy and institutions for environmental sustainability. *Environmental Science and Pollution Research*, 28, 66101.66120.

Efobi U., Tanankem B., Orkoh E., Atata S. N., Akinyemi O. & Beecroft I. (2019). Environmental Pollution Policy of Small Businesses in Nigeria and Ghana: Extent and Impact. *Environmental Science and Pollution Research,* 26, 2882-2897.

Ehigiamusoe K.U., Lean H.H. & Smyth R. (2020). The Moderating Role of Energy Consumption in the Carbon Emissions-Income Nexus in Middle-Income Countries. *Applied Energy. 261, 114215. doi:10.1016/j.apenergy.2019.114215*

Emma S.O. (2024). An econometric study of eco-innovation, clean energy, and trade openness toward carbon neutrality and sustainable development in OECD countries. *Sustainable Development,* 32,4, August, Pages 3075-3099.

Emrah K. & Aykut Ş. (2018). The impact of foreign direct investment on CO2 emissions in Turkey: new evidence from cointegration and bootstrap causality analysis. *Environmental Science and Pollution Research International,* 25,790-804.

Essandoh O.K., Islam M. & Kakinaka M. (2020). Linking international trade and foreign direct investment to CO2 emissions: Any differences between developed and developing countries?. *Science of The Total Environment,* 712, 136437.

Ewane E. B. & Ewane E.I. (2023). Foreign Direct Investment, Trade Openness and Environmental Damage in SSA Countries. A Quadratic Modeling and Turning Point Approach. *American Journal of Environmental Economics,* https://doi.org/10.54536/ajee.v2i1.1414.

Fauzel S. (2017). The impact of FDI on CO2 emission in a small island developing state: A cointergration approach. *Economics and Business Letters,* 61, 6-13.

Ganda F. (2021). The influence of growth determinants on environmental quality in Sub-Saharan Africa states. *Environment, Development and Sustainability.* 23,7117-7139.

Ghaderi Z., Saboori B. & Khoshkam M. (2023). Revisiting the Environmental Kuznets Curve Hypothesis in the MENA Region: The Roles of International Tourist Arrivals, Energy Consumption and Trade Openness. *Sustainability*, 15, 2553. https://doi.org/10.3390/ su15032553.

Gnangnon S. K. (2020). Trade openness and diversification of external financial flows for development: An empirical analysis. *South Asian J. Macroecon. Public Finance,* 9, 22-57.

Goswami A., Kapoor H.S., Jangir R.K., Ngigi C.N., Nowrouzi-Kia B. & Chattu V.K. (2023). Impact of Economic Growth, Trade Openness, Urbanization and Energy Consumption on Carbon Emissions: A Study of India. *Sustainability*, 15, 9025. https://doi.org/10.3390/ su15119025.

Gräbner C., Heimberger P., Kapeller J. & Springholz F. (2021). Understanding economic openness: a review of existing measures. *Review of World Economics*, 157, 87-120.

Grossman G.M. & Krueger A.B. (1993). Economic Growth and the Environment. *Quarterly Journal of Economics,* 110, 353-377.

Habib S., Abdelmonen S. & Khaled M. (2020). The effect of corruption on the environmental quality in African countries: A panel quintile regression analysis. *Journal of the Knowledge Economy*, 11, 788-804.

Hakimi A. & Hamdi H. (2016). Trade Liberalization, FDI Inflows, Environmental Quality and Economic Growth: a Comparative Analysis Between Tunisia and Morocco. *Renewable and Sustainable Energy Reviews,* 58, 1445-1456.

Hakimi A. & Hamdi H. (2020). Environmental effects of trade openness: what role do institutions have?. *Journal of Environmental Economics and Policy,* 9,36-56.

Hariyani H.F., Prasetyo D.G., Ha T.T.V. et *al.* (2024). Unlocking CO2 emissions in East Asia Pacific-5 countries: Exploring the dynamics relationships among economic growth, foreign direct investment, trade openness, financial development and energy consumption. *Journal of Infrastructure, Policy and Development*. 8(8): 5639. https://doi.org/10.24294/jipd.v8i8.5639.

Haseeb A., Xia E., Baloch A.M. & Abbas K. (2018). Financial development, globalization, and CO2 emission

Haseeb A., Xia E., Saud S., Usman M. & Quddoos M.U. (2023). Unveiling the liaison between human capital, trade openness, and environmental sustainability for BRICS economies: Robust panel-data estimation, *Natural Resources Forum*, https://doi.org/10.1111/1477-8947.12277.

in the presence of EKC: evidence from BRICS countries. *Environmental Science and Pollution Research,* 25, 31283-31296.

Hu H., Nan X., Debin F. & Xiaoling Z. (2018). The role of Renewable Energy Consumption and commercial services trade in carbon dioxide reduction: Evidence from 25 developing countries. *Applied energy,* 211, 1229-1244.

Huang Y., Chen F., Wei H., Xiang J., Xu Z. & Akram R. (2022). The Impacts of FDI Inflows on Carbon Emissions: Economic Development and Regulatory Quality as Moderators. *Front Energy Research.* 9:820596. doi: 10.3389/fenrg.2021.820596

Ibrahim RL. & Ajide KB. (2022). Trade facilitation and environmental quality: empirical evidence from some selected African countries. *Environment Development and Sustainability,* 24, 1282-1312.

Iheonu C.O., Anyanwu O.C., Odo O.K. & Nathaniel S.P. (2021). Does economic growth, international trade, and urbanization uphold environmental sustainability in sub-Saharan Africa? Insights from quantile and causality procedures. *Environment Science Pollution Research*, 28, 28222-28233.

Inglesi-Lotz R. (2018). Decomposing the South African CO2 emissions within a BRICS countries context: signaling potential energy rebound effects. *Energy*, 147, 648-654.

Inglesi-Lotz R. & Dogan E. (2018). The role of renewable versus non-renewable energy to the level of CO2 emissions a panel analysis of sub-Saharan Africa's Big 10 electricity generators. *Renewable Energy,* 123, 36-43.

IPCC (2021). Climate Change 2022: Mitigation of Climate Change. Genève, Suisse, 175 pages.

Junaid A., Zeeshan A. & Aiman J. (2023). The spatial spillover effects of energy transition and trade openness on CO2 emissions, *Energy and Buildings*, https://doi.org/10.1016/j.enbuild.2023.113167.

Kalayci C. & Hayaloglu P. (2019). The Impact of Economic Globalization on CO2 Emissions: The Case of NAFTA Countries. *International Journal of Energy Economics and Policy,* 9, 356-360.

Kim D.H., Suen Y.B. & Lin S.C. (2019). Carbon dioxide emissions and trade: evidence from disaggregate trade data. *Energy Economics*, 78, 13-28.

Kwakwa P. A. (2023). Climate change mitigation role of renewable energy consumption: Does institutional quality matter in the case of reducing Africa's carbon dioxide emissions? *Journal of Environmental Management*, 342, 118234.

Kwakwa P.A., Alhassan H. & Adu G. (2020). Effect of natural resources extraction on energy consumption and carbon dioxide emission in Ghana. *International Journal of Energy Sector Management,* 10, 20-39.

Lemaallem H., & Outtaj B. (2023). Impact of commercial and financial openness on economic growth: What short- and long-term dynamics? *Alternatives Managériales Economiques,* 5, 375-396.

Liu L., Anwar A., Irmak E. & Pelit I. (2022a). Asymmetric linkages between public-private partnership, environmental innovation, and transport emissions. *Econ Res,* 35,6519-6540

Maku O.A. & Ikpuri O.P. (2020). A Multivariate Analysis between Renewable Energy, Carbon Emission and Economic Growth: New Evidences from Selected Middle East and North Africa Countries. *International Journal of Energy Economics and Policy,* 10, 440-450.

Mapapu B. & Phiri A. (2018). Carbon emissions and economic growth in South Africa: a quantile regression analysis. *International Journal of Energy Economics and Policy,* 8, 195-202.

Mekuannet W.T. (2024). Review on Valuation of Environmental Amenity and Pollution. *Journal of Environmental Science and Economics*, ISSN: 2832-6032https://doi.org/10.56556/jescae.v3i2.837.

Mengal A., Mirjat N.H., DasWalasai G., Khatri S.A., Harijan K. & Uqaili M.A. (2019). Modeling of Future Electricity Generation and Emissions Assessment for Pakistan. *Processes*, 7, 212.

Mohsin R. (2024). Renewable energy adoption and CO2 emissions in G7 economies: In-depth analysis of economic prosperity and trade relations. *Journal of Environmental Science and Economics,* ISSN: 2832-6032, https://doi.org/10.56556/jescae.v3i2.839.

Muhammad S., Long X., Salman M. & Dauda L. (2020). Effect of urbanization and international trade on CO2 emissions across 65 belt and road initiative countries. *Energy* 196:117102.

Mutascu M. (2018). G7 countries: between trade openness and CO2 emissions. *Economics Bulletin*, 38, 1446-1456.

Nathaniel S.P. & Iheonu C.O. (2019). Carbon dioxide abatement in Africa: the role of renewable and non-renewable energy consumption. *Science of the Total Environment,* 679, 337-345.

Nguyen C.P., Schinckus C. & Dinh Su T. (2020). Economic integration and CO2 emissions: evidence from emerging economies. *Climate and Development,* 12, 369-384.

Ngwenya B., Oosthuizen J., Cross M., Frimpong K. & Chaibva C.N. (2018). A review of heat stress policies in the context of climate change and its impacts on outdoor workers: evidence from Zimbabwe. *International Journal of social Ecology and Sustainable Development,* 9, 1-11.

Nkengfack H., Fotio H.K. & Temkeng D.S. (2019). The Effect of Economic Growth on Carbon Dioxide Emissions in Sub-Saharan Africa: Decomposition into Scale, Composition and Technique Effects. *Modern Economy*, 10, 1398-1418.

Okelele DO., Lokina R. & Ruhinduka RD. (2022). Effect of trade openness on ecological footprint in sub-Saharan Africa. *African Journal of Economic Reviews, 10*, 209-233.

Omri E. & Saadaoui H. (2023). An empirical investigation of the relationships between nuclear energy, economic growth, trade openness, fossil fuels, and carbon emissions in France: fresh evidence using asymmetric cointegration. *Environ Sci Pollut Res*, 13224-13245. https://doi.org/10.1007/s11356-022-22958-1.

Pata U.K., Dam M.M. & Kaya F. (2023). How effective are renewable energy, tourism, trade openness, and foreign direct investment on CO_2 emissions? An EKC analysis for ASEAN countries. *Environmental Science and Pollution Research*, 14821-14837. https://doi.org/10.1007/s11356-022-23160-z.

Pham D. T. T. & Nguyen H. T. (2024). Effects of trade openness on environmental quality: evidence from developing countries. *Journal of Applied Economics*, 27(1). doi:10.1080/15140326.2024.2339610.

Ponce P., Alvarado R., Ponce K., Alvarado R., Granda D. & Yaguana K. (2019). Green returns of labor income and human capital: Empirical evidence of the environmental behavior of households in developing countries. *Ecological economics*, 160,105-113.

Potrafke N. (2015). The evidence on globalization. *World Economic*, 38, 509-552.

Qamruzzaman M. (2021). Nexus between environmental quality, institutional quality and trade openness through the channel of FDI: an application of common correlated effects estimation (CCEE), NARDL, and asymmetry causality. *Environ Sci Pollut Res Int*, 37,52475-52498.

Raza S. A. & Shah N. (2018). Impact of financial development, economic growth and energy consumption on environmental damage: evidence from Pakistan. MPRA Paper No. 87095, University Library of Munich, Germany.

Roodman D. (2009). How to do xtabond2: An introduction to difference and system GMM in Stata. *The Stata Journal*, 9, 86-136.

Sabir S., Qayyum U. & Majeed T. (2020). FDI and environmental damage: the role of political institutions in South Asian countries. *Environmental Science and Pollution Reserach,* 27, 32544-32553.

Salahuddin Md., Idris A.M., Nick V. & Jeff G. (2019). The effects of urbanization and globalization on CO2 emissions: evidence from the Sub-Saharan Africa (SSA) countries. *Environmental Science and Pollution Research*, 26, 2699-2709.

Santiago R., Alberto J. & Marques A.C. (2020). The impact of globalization and economic freedom on economic growth: the case of the Latin America and Caribbean countries. *Economic Change and Restructuring,* 53, 61-85.

Shahbaz M. & Sinha A. (2019). Environmental Kuznets curve for CO2 emissions: a literature survey. *Journal of Economics Studies,* 46, 106-168.

Sinha A. & Shahbaz M. (2018). Estimation of Environmental Kuznets Curve for CO2 emission: Role of renewable energy generation in India. *Renewable Energy*, 119, 703-711.

Solarin S.A., Al-Mulali U., Musah I. & Ozturk I. (2017). Investigating the pollution haven hypothesis in Ghana: An empirical investigation. *Energy,* 124, 706-719.

Sun H-P., Tariq G., Haris M. & Mohsin M. (2019). Evaluating the environmental effects of economic openness: evidence from SAARC countries. *Environmental Science and Pollution Research,* 26, 24542-24551.

Sun H., Samuel A.C., Yong G., Kai F. & Joshua C.K.A. (2019). Trade Openness and Carbon Emissions: Evidence from Belt and Road Countries. *Sustainability,* 11, 2682.

To H.A., Dao Ha T-T., Nguyen H.M. & Vo Hong D. (2019). The Impact of Foreign Direct Investment on Environment Damage: Evidence from Emerging Markets in Asia. *International Journal of Environmental Research and Public Health,* 16, 1636.

Toumi S. & Toumi H. (2019). Asymmetric causality among renewable energy consumption, CO2 emissions, and economic growth in KSA: evidence from a non-linear ARDL model. *Environmental Science and Pollution Research,* 26, 16145-16156.

Udeagha M.C. & Breitenbach M.C. (2023). On the asymmetric effects of trade openness on CO_2 emissions in SADC with a nonlinear ARDL approach. *Discov Sustain*, https://doi.org/10.1007/s43621-022-00117-3.

Udeagha M.C. & Ngepah N. (2019). Revisiting trade and environment nexus in South Africa: fresh evidence from new measure. *Environmental Science and Pollution Research,* 26, 29283-29306.

Usman O., Lorember P.T. & Olanipekun I.O. (2019). Revisiting the environmental Kuznets curve (EKC) hypothesis in India: the effects of energy consumption and democracy. *Environmental Science and Pollution Research,* 26, 13390-13400.

Waheed R., Chang D., Sarwar S. & Chen W. (2018). Forest, agriculture, renewable energy, and CO2 emission. *Journal of Cleaner Production,* 172, 4231-4238.

Wang Q., Zhang F. and Li R. (2024). Free trade and carbon emissions revisited: The asymmetric impacts of trade diversification and trade openness, *Sustainable Development,* 32, 1, February, Pages 876-901, https://doi.org/10.1002/sd.2703.

World Bank (2023). World Government Indicator. http://data.worldbank.org/data-catalog.

Word Bank (2023). World development indicators. World Bank, Washington DC.

Yameogo C.E.W., Omojolaibi J.A. & Dauda R.O.S. (2021). Economic globalisation, institutions and environmental quality in Sub-Saharan Africa. *Research in Globalization*, 3,100035.

Zakari A. & Tawiah V. (2019). Impact of Electricity Consumption, Financial Development, Trade Openness on CO2 Emissions: Evidence from Nigeria. *Economic Studies journal,* 4, 143-157.

Zamil A.M.A., Furqan M. & Mahmood H. (2019). Trade openness and CO2 emissions nexus in Oman. *Enterpreunership and Sustainability,* 7, 1319-1329.

Zheng S., Wang R., Mak T. M. W., Hsu S.-C. & Tsang D. C. W. (2021). How Energy Service Companies Moderate the Impact of Industrialization and Urbanization on Carbon Emissions in China?. *Science of the Total Environment,* 751, 141610. doi:10.1016/j.scitotenv.2020.141610

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RESEARCH ARTICLE

Assessing the Impact of Private Investment in AI and Financial Globalization on Load Capacity Factor: Evidence from United States

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Abstract

The need for sustainable solutions has increased globally as a result of the growing environmental problems brought about by urbanization and industrialization. Given this, private investment in artificial intelligence (AI) has become a viable means of promoting environmental sustainability, mainly because of AI's capacity to minimize ecological footprints and maximize resource utilization. This research investigates the role of private investment in AI in promoting environmental sustainability in the United States from 1990 to 2019. It also analyzes the impact of financial globalization, technological innovation, and urbanization by testing the Load Capacity Curve (LCC) hypothesis. The research utilizes stationarity tests, which indicate that the variables are free from unit root problems and exhibit mixed orders of integration. Using the Autoregressive Distributive Lag (ARDL) Model bound test, the analysis finds that the variables are cointegrated in the long run. The short-run and long-run estimations of the ARDL model confirm the existence of the LCC hypothesis in the United States, revealing a U-shaped association between income and load capacity factor. The findings show that private investment in AI has a significant positive correlation with the load capacity factor, thus promoting environmental sustainability. Conversely, technological innovation and financial globalization exhibit a negative correlation with the load capacity factor in both the short and long run. To validate the ARDL estimation approach, the study employs Fully Modified OLS, Dynamic OLS, and Canonical Correlation Regression estimation methods, all of which support the ARDL outcomes. Additionally, the Granger Causality test reveals a unidirectional causal connection from private investment in AI, financial globalization, economic growth, technological innovation, and urbanization to the load capacity factor.

Keywords: Financial Globalization; LCC Hypothesis; Private Investment in AI; Technological Innovation; United States

Introduction

The devastation of the surroundings counts for the greatest pressing issues happening in the modern world today (Raihan et al.,2024; Li et al.,2021; Liu et al., 2021). This is due to its adverse effects on the overall economy, biodiversity, the atmosphere, human health, the quality of the air, and assets, including groundwater, soil, and forests (Rehman et al., 2021). Globally, maintaining economic growth and reducing climate change now depend on reducing CO_2 emission levels and maintaining ecological integrity (Raihan et al., 2022; Abir, 2024). Moreover, a great deal of this emission originates from a few nations (Magazzino et al., 2020). Even though the US economy has been expanding for over three decades, the nation is dealing with major environmental problems (Koondhar et al., 2018). As of right now, China is the nation with the fastest pace of economic growth, with the United States standing in second (He and Richard 2010). Even though China accounts for 28% of global CO_2 emissions, the USA is responsible for 16%, the EU for 11%, India for 6%, and other countries for 39%. However, as China has a population four times that of the USA, the USA has higher CO_2 emissions per capita than China (Koondhar et al., 2018). Moreover, according to 2020 year-end data (WorldBank, 2021), the USA produces almost 14%. These alarming figures underscore the relevance of the present research from a US perspective. Significant outcomes can be obtained by utilizing relevant factors, including financial globalization, technical innovation, and private investment in AI. The research findings can be implemented by policymakers to ensure a green environment in the USA. The effect of multiple socio-economic and technical variables on carbon emissions has been a focus of numerous research (Orhan et al., 2021; Su et al., 2021; Zhang et al., 2021; Guloglu et al.,2023 and Raihan et al.,2023). Even if CO_2 pollutions make up a sizable amount of greenhouse gases, Akinsola et al. (2021) claimed that carbon emissions are insufficient to accurately depict and assess total environmental damage. Conversely, the ecological footprint (EFP) was primarily initiated by Rees (1992), and it was subsequently emphasized by Galli et al. (2012) as the foremost for both financial and environmental indicators for evaluating ecological damage. In spite of this, not much research has been done on the Load Capacity Curve (LCC) concept. Therefore, the available literature fails to have information regarding the LCC hypothesis's validity in emerging economies like the USA. To close this gap, this research assesses the LCC hypothesis's relevancy to the USA. According to Siche et al. (2010), the load capacity factor (LCF) offers a more precise sustainability measurement. The LCF illustrates how strong or able a country is to support its citizens according to their modern lifestyles (Xu et al., 2022,). Therefore, an ecosystem is considered to be hampered when the LCF is less than 1 and sustainable when the LCF is greater than 1 (Pata et al., 2021; Sohail et al.2018a).

We have recently witnessed revolutionary developments in several industries as Artificial Intelligence (AI) has become increasingly integrated, and the environment field is no exception. Worldwide green growth issues can be resolved somewhat by the progress of AI technologies. Moreover, the implementation of AI can lower emissions to the environment (Shang et al.,2024). AI boosts Chinese industries' environmental sustainability and dramatically lowers the intensity of pollutant emissions (Cheng et al., 2024). Artificial intelligence-driven commercialization might reach to $3.9 trillion in 2022, up from $1.2 trillion in 2018, which marked a 70% growth from 2017 (Brown, 2013; Fatorachian and Kazemi, 2018; Richards et al., 2019). The public sector's contribution to AI has been expanding over the past few decades, as seen by the $3.2 billion in investments made by the U.S. government in 2022 (JEC,2023). Additionally, in almost 65% of AI-enabled environmental initiatives, mathematical models are used. All environmental professionals are likely to gain numerous advantages from AI tools (Konya and Nematzadeh, 2024). It can assist policymakers in formulating scientifically grounded strategies and plans for green ecosystems (Asadnia et al.,2014; Asadnia et al.,2017; Farahnakian et al., 2011). AI-driven technologies are crucial for ecological resource conservation as they facilitate the monitoring and preservation of natural habitats, animal populations, and ecosystems (Krishnamoorthy and Sistla, 2023; Sohail et al.2018b). To discover biodiversity hotspots, monitor endangered species, and identify threats to the environment like deforestation, poaching, and pollution, machine learning algorithms can examine satellite images, sensor data, and ecological parameters (Krishnamoorthy and Sistla, 2023). Stakeholders can safeguard biodiversity and ecosystem services by implementing focused interventions and making educated decisions by utilizing AI for environmental monitoring and conservation (Sistla and Konidena, 2023).

There are several ways in which the process of economic growth might result in environmental damage (Kartal et al., 2022). Growth in the economy comes with a substantial consumption of energy, natural assets, and production inputs, which initially pollutes the environment and puts more strain on it (Nurgazina et al., 2022). With time, the pressure on the ecosystem declines, and as environmental knowledge and demand grow, higher income levels help to improve natural health (Pata et al.,2023). On the other hand, in Bangladesh and Indonesia, Bakirtas et al. (2023) observed a reverse U-shaped link between GDP and LCF. In 2024, the US accounted for 13.3% of worldwide GDP and for around 4.21% of the global populace (World Bank, 2024). Meanwhile, almost 16% of global CO_2 emissions came from 5,416 MT of emissions in the United States (BP, 2020). Since the USA is one of the major polluters of greenhouse gases into the atmosphere, it bears some of the blame for the climate crisis and global warming. The catastrophic consequences of the United States' roughly 1.0 degree Celsius climate change are already worrisome, affecting the most vulnerable members of the population with a climate-fueled disaster that caused fatalities, deteriorating health, and the degradation of the natural world (Zhang et al.,2023, Sohail et al.2019). The majority of research has shown that the growing population causes more environmental damage (Voumik and Ridwan, 2023; Khan et al., 2021; Pham et al., 2020; Menz and Welsch, 2012). Financial globalization (FGOB) considers characteristics such as international assets and liabilities, FDI, investment portfolios, and related laws to assess how far a nation has incorporated into the global financial system. As a result, FGOB is a noteworthy measure of financial progress (Dhingra, 2023; Wang et al., 2023). With the progress of financial globalization, foreign direct investment is increasing globally. The most current UNCTAD (2020) showed that from $1.3 trillion in 2018 to $1.5 trillion in 2019, there was a 3.0% rise in worldwide FDI inflows. Scholars like Furceri et al. (2019), Usman et al. (2019), Obstfeld (2021), Gungor et al. (2021), and Awosusi et al. (2022) characterize FGOB as the convergence of global monetary systems into a single sector. Through the optimization of resources, clean energy, garbage disposal, prevention of pollution, and monitoring of the atmosphere, technological innovation can slow down the decline of the environment (Ha 2022; Vyas et al. 2022; Ramzan et al. 2023).

Consequently, our investigation makes multiple significant enhancements to the collection of contemporary literature. First of all, from a U.S. viewpoint, it addresses the largely unexplored field of private investment in AI, which makes it distinctive. The experimental research has presented consistent results concerning the correlation between LCF and private AI investment (PAI). Our study aims to clarify the linkages between LCF and PAI in light of the situation described above, offering additional relevant data for designing green policies. Second, the study makes use of unique PAI data that is categorized as Estimated Investment in AI (US$) and is adapted from Our World in Data. Within the framework of the USA's LCF, this analysis focuses on the trends and key research areas of private investment in artificial intelligence (AI), financial globalization, technical innovation, economic development, and urbanization. Analyzing the LCF within the context of the USA will offer fresh perspectives to scholars exploring the issue and establish a noteworthy contribution to the body of understanding. As far as we are aware, our work is the first to conduct a detailed representation of the literature on the LCF, enabling us to embark on the following research goals: What effect do PAI and FGOB have on the USA's LCF? In what ways can independent and dependent variables interact spontaneously? Furthermore, how do TI, GDP, and URBA affect the LCF? The significance of this research lies in the fact that private investment in artificial intelligence and financial globalization has not been extensively studied in other studies. By recognizing these elements, policymakers and strategy developers might be able to more effectively promote environmentally responsible behavior. More research in this area is essential to building a pleasant and sustainable environment, particularly in light of increasing interest in green cities and public awareness of ecological issues. The implications of GDP, PAI, FGOB, TI, and URBA on the LCF are examined in inquiry using ARDL methodologies from 1990 to 2018. Additionally, the robustness of the findings was analyzed as well using the FMOLS, DOLS, and CCR examinations. This study delivers valuable insights for legislators in the USA and other nations to achieve the SDGs while simultaneously promoting sustainable economic growth and increasing the ecosystem condition (as evaluated by the LCF) by adopting an integrative approach to the issue.

The paper checks the body of investigation on the chosen determinants in the second part. The information, theoretical framework, empirical model development, and estimating methods used to conduct the study are all covered in detail in the "Methodology" section. "Results and Discussion," the fourth part, offers an extensive discussion of the model's findings. The fifth and last part summarizes the analysis and suggested strategies of action.

Literature Review

The consequences of financial globalization, advancements in technology, and GDP development on the LCF have been the subject of several empirical investigations. While numerous analyses examined the ARDL model, the majority of papers focused on how trade openness, urbanization, and green energy usage affect environmental quality. Others have focused on analyzing the connection between trade openness, globalization, economic expansion, and LCF. Previous studies on the concept of ecological degradation in the context of the USA have not yet been extensively conducted as this is a relatively new field. However, the investigation used some prior studies that assisted with the selection of variables and methods. This section will cover a few of these inquiries.

GDP and Load Capacity Factor Nexus

The relationship between GDP development and ecosystem sustainability has been the subject of several studies. Many believe that as the economy grows, there will be an increase in CO_2 emissions. However, things become more complicated when we include load capacity in addition to CO_2 emissions as environmental quality criteria. People's goals for monetary progress encourage them to use all available energy resources, which has an economic effect of producing emissions (Panel et al., 2011). In addition, when business activity expands to achieve incredible growth, natural resource depletion takes place (Teng et al.,2024). Thus, the deterioration of biocapacity, biodiversity, and the LCF in different areas can be linked to carbon emissions and resource depletion for income development (Zhang et al., 2022). In Pakistan, Ali et al. (2023) performed an experiment using a "dynamic autoregressive distributed lags model" and a unique approach called "Kernel-based regularized least squares (KRLS)." They discovered an unexpected negative correlation (-0.270) between the load capacity factor and GDP development over a longer period. According to Pata (2021), growth in GDP significantly degrades the environment in a manner that cannot be balanced by clean power sources or increased medical expenses in the United States. Similar research (Fareed et al., 2021; Huilan et al.,2022; Shang et al., 2022; Abdulmagid Basheer Agila et al., 2022; Jin and Huang.,2023; ÇAMKAYA and KARAASLAN.,2024) that used the LCF and discovered that upsurges in GDP growth exhibited negative consequences on the LCF indicating the destruction of the ecosystem. By examining the consequences of GDP, Li et al. (2023) seek to understand how the next eleven countries improved their LCF between 1990 and 2018. The long-term outcomes illustrate that reliance on economic growth reduced LCF. However, Ullah et al. (2023) insist that while there is no short-term effect, growth in monetary complexity has a positive long-term consequence on LCF. On the other hand, a U-shaped connection between income and the state of the environment was observed by Guloglu et al. (2023), confirming the validity of the LCC theory.

AI Innovation and Load Capacity Factor Nexus

The increasing prevalence of artificial intelligence (AI) technology in our daily lives has extensive political and socioeconomic implications. Both officially and privately funded AI research and applications are encouraged heavily (Brandusescu, 2022). Negi (2018) focuses on the flow of investment in artificial intelligence from the top three major nations in the field: China, India, and the United States. They display the steps that the government has taken to incorporate artificial intelligence into its present ecosystem, which is supported by the private sector. The t-test demonstrates a significant relationship between annual investment and trend analysis, which suggests that the AI industry is growing quickly. Vietnam is seeing a relatively small amount of misdirected AI investment. Vietnam excessively remains significantly behind other Southeast Asian nations, necessitating both governmental and private investment in this sector (Pham et al.,2024). Artificial intelligence (AI) investment from the private sector has an enormous impact on the environment, positive as well as negative. AI helps with the preservation of natural assets, controlling energy consumption, ecological safeguarding, pollution control, agriculture, and other areas, all of which are critical to attaining environmental sustainability (Kumari and Pandey,2023). In the same way, Habila et al. (2023) indicate that the use of AI improves the human capacity to manage climate change to achieve sustainability while utilizing natural resources. Conversely, Okengwu et al. (2023) expressed that increased usage of AI in agriculture results in increased carbon emissions that affect humanity and the natural world. Green AI can boost productivity and alleviate its negative effects on the environment (Pachot and Patissier, 2022). Since private investment in AI usually has a negative impact on the natural world, government officials need to advocate for increased private investment, particularly in green AI.

Financial Globalization and Load Capacity Factor Nexus

Financial globalization is the uncontrolled and easy movement of financial resources within national boundaries (Kose et al., 2009). Both positive and negative effects of financial globalization on the LCF are apparent in emerging countries. In the case of India, Akadiri et al. (2022) demonstrated that FGOB is positively connected with the LCF both in the short and long run. According to Raihan et al. (2021), the short- and long-term consequences of FGOB are favorable for the LCF. By taking into account financial globalization over the years 1980–2021, Ozcan et al. (2024) aim to look at how Germany's natural world is impacted. Through the use of advanced quantile-based methods, they highlight how FGOB boosts the quality of biodiversity. Moreover, using panel econometric approaches, Wang et al. (2022) scrutinized the most recent yearly data set that included 31 OBOR countries from 1996 to 2018. According to the findings, the environment deteriorates due to financial globalization. Many scholars also agree that FGOB slows down environmental damage by increasing the LCF (Jin et al.,2023; Xu et al.,2022; Pata et al.,2021; Yang et al.,2023). However, for Bangladesh, the effects of financial globalization on the ecosystem are multifaceted and rely on several variables, including clean FDI and the consumption of clean energy (Murshed et al. 2021). From 1990 to 2017, Kihombo et al. (2022) checked out the link between environmental impact and financial globalization in some West Asian and Middle Eastern (WAME) territories. The result demonstrates that through lowering the ecological footprint, financial globalization contributes a major part in promoting environmental sustainability. Several outcomes were also observed by (Awosusi et al.,2022 Ulucak et al.,2020; Tahir et al.,2021), and they revealed an encouraging effect of FGOB on the LCF, indicating the enhancement of ecological condition. In light of these outcomes, it is essential to determine if financial globalization provides the USA with a comparable opportunity to boost its load capacity factor.

Technological Innovation and Load Capacity Factor Nexus

Previous investigations have mostly overlooked technological innovation (TI), and it has been found to have both positive and negative outcomes. The continuous improvement in the degree of innovation has rendered policymakers, as well as scholars, to recognize the significance of technological innovation in preventing environmental deterioration (Du et al., 2022; Haldar and Sethi, 2022). Several analyses have been performed to analyze the fundamental connections between LCF and technological progress. The MMQR approach is used by Jahangir et al. (2024) to analyze the consequences of technological innovation on LCF between 1994 and 2018. The result illustrates that, in the top 10 SDG nations, TI has an adverse and substantial effect on lowering LCF. To examine how TI affects environmental quality in China, Kartal and Pata (2023) consider ecosystem indicators such as CO_2 pollution, EFP, and LCF. The findings exhibit that whereas TI reduces LCF at middle quantiles, it increases CO_2 emissions and ECF at higher quantiles. Some analyses also found that technological innovation is hazardous to the ecosystem (Raihan et al.,2024; Su et al.,2023; Adebayo et al.,2022). On the other hand, Wang et al. (2020) researched N-11 economies between 1990 and 2017, utilizing the unit root test, AMG, and CCEMG proposed by Pesaran (2007) serve as the foundation for the empirical estimations. The outcomes illustrate that TI has a destructive relationship with greenhouse gas emissions that boost the quality of the environment. Furthermore, Kihombo et al.(2021) assessed the implication of TI on environmental quality in West Asian and Middle Eastern countries and demonstrated that TI strengthens the natural world. Similarly to this, Rafique et al. (2020) provided evidence that technical advancements lower pollution in the BRICS countries. Multiple studies have also showcased the positive consequences of TI on maintaining financial sustainability (Mehmood et al.,2023; Khan et al.,2023; Anwar et al., 2021).

Urbanization and Load Capacity Factor Nexus

The goal for individuals shifting from rural to urban locations is to lead ordinary lives while working in industries that generate revenue (Ruel et al., 2008). Furthermore, the concept of the smart city, which advocates for energy from both renewable and nuclear sources, has emerged as the primary goal of industrialized and modern society (Chenic et al., 2022). The ARDL approach was utilized by Raihan et al. (2023) to examine cointegration and both short- and long-term dynamics using time series data from 1971 to 2018. The result illustrates that urbanization lowers Mexico's LCF and, therefore, lowers the quality of the natural world. Urbanization has negative consequences on the dynamics of load capacity, which accelerates ecological deterioration (Teng et al.,2024). Using Cross-Sectional ARDL and AMG estimators, Shah et al. (2023) performed a study in the top 15 nations that produced natural gas and discovered that urbanization has a significant impact on environmental damage. Similarly, Raihan et al.(2024) and Caglar et al.(2023) also concluded that urbanization is harmful to the ecosystem. However, the relationship between urbanization and ecological sustainability is investigated by Fang et al. (2024) using the frequency domain causality technique and the ARDL estimator. The LCF curve theory is supported in Thailand as the ARDL estimator finding shows that urbanization reduces LCF. Zhu et al. (2018) came to the same conclusion that URB makes the natural world better. Additionally, Xu et al. (2022) assessed how urbanization affected the LCF in Brazil between 1970 and 2017. Surprisingly, the outcome of the ARDL approach revealed that the LCF is not affected by urbanization in Brazil. The same outcomes were given by Chen et al. (2022) using CCEMG and AMG tests for the years 1990–2019 and Haseeb et al. (2018) using FMOLS from 1995 to 2014, indicating that URB had no appreciable effect on the environment quality for the BRICS countries.

Research Gap

The relationships between load capacity factor, financial globalization, and private investment in AI, technological development, economic expansion, and urbanization in the USA have not, as far as we are aware, been investigated. Although researchers have looked into these areas on their own, they haven't consistently merged their discoveries. Previous research efforts demonstrated several shortcomings, especially an absence of comprehensive analyses of the connection between PAI and LCF in the USA. Private sector AI investments could aid agriculture, promote renewable energy, mitigate risks like oil spills, and develop sustainable practices, thereby reducing global warming risks. All of these aspects constitute PAI, an entirely new field to investigate from the perspective of the USA. To cover up these deficiencies, this study explores the link between PAI and the environment utilizing strong statistical approaches such as ARDL, FMOLS, DOLS, and CCR procedures. Through a review of these procedures, the USA might find out if harnessing technical innovation, monetary integration, and business growth can offer the possibility of elevating its load capacity factor and bringing it into line with broader global shifts toward improved environmental sustainability. The implications of the LCF in this area have not yet been the focus of inquiry. As a result, this investigation considers these components as essential to long-term environmental sustainability. By assisting stakeholders and lawmakers in establishing strategies that are customized to the distinctive ecological and socioeconomic situation of the United States, this analysis advances green improvement.

Methodology

Data and Variables

The ongoing research analyzed data to check out how technical advancements, financial globalization, GDP, urbanization, and private investment in AI influenced the USA's LCF between 1990 and 2019. The United States gathered attention because of its sustainability concerns and data accessibility. The World Development Index (WDI) is the source of the GDP and URBA figures. In this case, we take the LCF as an endogenous factor that derives from GFN and is utilized as a substitute for ecological sustainability. Our World in Data is the same source from which PAI and TI information was collected. Conversely, the FGOB info is adapted from the KOF Globalization Index. In addition, we selected FGOB, TI, and PAI as our investigation's policy variables.

Theoretical Framework

The most important instrument in the realm of the environmental field is the load capacity curve (LCC), which offers fascinating details on the complex links between ecological sustainability, economic success, and progress in humanity. This is significant as it illustrates the balance—or absence between the planet's capability of restoring its natural resources (biological capability) and the utilization of human capital (ecological footprint). Since biocapacity and EF are incorporated in the denominator of the LCF, a greater LCF is symbolic of a healthier environment (Pata and Kartal, 2023).

The LCF delivers a sophisticated ecological examination by contrasting biocapacity and ecological footprint (Dogan and Pata, 2022). Furthermore, the LCC highlights the interconnectedness of the world's biological issues, as claimed by Wu et al. (2023), including climate change, resource scarcity, and loss of biodiversity. It is believed that the LCC has a U-shaped connection, with GDP constituting the main driver. According to Pata and Tanriover (2023) and Pata and Ertugrul (2023), there are distinct trends in the implications of GDP on the environment, suggesting a U-shaped curve connection. The awareness that resource usage grows in tandem with economic expansion and developments in personal wealth is highlighted by this relationship as a crucial aspect of ecological sustainability (Degirmenci & Aydin, 2024).

Table 1. Source and Description of Variables

Variables	Description	Logarithmic Form	Unit of Measurement	Source
LCF	Load Capacity Factor	LLCF	Gha per person	GFN
GDP	Gross Domestic Product	LGDP	GDP per capita (current US$)	WDI
PAI	Private Investment in AI	LPAI	Estimated Investment in AI (US$)	Our World in Data
FGOB	Financial Globalization	LFGOB	Globalization Index	KOF Globalization Index
TI	Technological Innovation	LTI	Patent applications, residents	Our World in Data
URBA	Urbanization	LURBA	Urban population (% of total population)	WDI

Globalization in finances promotes cross-border monetary activity, which elevates national manufacturing and, consequently, exacerbates ecological destruction (Xu et al.,2022; Ahmed et al.,2021). The findings by Caglar et al.(2023) validate the LCC concept by demonstrating that monetary eventually becomes an ecologically beneficial factor. As was previously indicated, there may be a range of linkages between the components, including GDP growth, technical innovation, private investment in AI, urbanization, financial globalization, and load capacity factor. To improve knowledge of previous research, we have created the following equation (1) for LCC theory:

$$Load\ Capacity\ Factor = f(GDP, Y_t) \qquad (1)$$

Here, Y_t is a variable for additional parameters impacting the LCF, while GDP is a variable for income in equation (1). Equation (2) seeks to provide a deeper comprehension of the factors impacting the LCF by including additional relevant variables such as urbanization, financial globalization, private investment in AI, and economic growth.

$$LCF = f(GDP, PAI, FGOB, TI, URBA) \qquad (2)$$

The load capacity factor in equation (2) is represented by LCF, whereas the terms financial globalization (FGOB), technological innovation (TI), urbanization (URBA), and private investment in artificial intelligence (PAI) are introduced to symbolize particular principles. The econometric explanation of equation (3) is given above.

$$LCF_{it} = \alpha_0 + \alpha_1 GDP_{it} + +\alpha_2 PAI_{it} + \alpha_3 FGOB_{it} + \alpha_4 TI_{it} + \alpha_5 URBA_{it} \quad (3)$$

Equation (4) illustrates the variables' logarithmic values. It increases understanding and facilitates the formulation of conclusions based on statistics by breaking down complicated connections into more straightforward linear forms. Logarithmic scales can manage data of various sizes and assist with heteroscedasticity when broad ranges need to be minimized.

$$LLCF_{it} = \alpha_0 + \alpha_1 LGDP_{it} + \alpha_2 LPAI_{it} + \alpha_3 LFGOB_{it} + \alpha_4 LTI_{it} + \alpha_{5L} URBA_{it} \ (4)$$

Here, the research's coefficients are displayed in the parameter range of α_0 to α_6 in equation (4).

Econometric Framework

This investigation deployed the ARDL technique for data estimation to explore the link between LCF and variables like GDP growth, PAI, FGOB, TI, and URBA in the USA. We additionally adopted the FMOLS, DOLS, and CCR approaches to guarantee robustness. To ensure stationarity, the unit root examinations (ADF, P-P, and DF-GLS) were performed at the beginning of the study. Due to the nature of the time series data, the ARDL bound test was then implemented. The ARDL (both short run and long run) estimate was then carried out. Ultimately, after an elaborate estimating procedure, we determined which econometric model was the most efficient and trustworthy.

Unit Root test

To ensure consistency in information, a regression test was conducted to eliminate unit roots across all variables. This is important because factors involving unit roots or non-stationary data must assist in explaining a greater proportion of the results to prevent the drawing of incorrect conclusions (Nelson and Plosser, 1982; Engle and Granger, 1987). It is essential to use a unit root analysis to prevent incorrect regression. The stationary nature of the regression variables is confirmed by differences and stationary processes (Raihan et al., 2022). The empirical research's findings indicate that before applying cointegration approaches, the integration sequence must be examined (Sahoo and Sethi, 2022). A time series' stationarity or non-stationarity is calculated by Voumik and Ridwan (2023) since it is critical in identifying non-stationary data that might produce inaccurate results. To observe the stationarity within the data set, this research adopted the Dickey Fuller-Generalized Least Squares (Elliot et al., 1992) unit root test, the Philips Perron (Philips and Perron, 1968), and the Augmented Dickey-Fuller (Dickey and Fuller, 1979) unit root examination. Due to its ability to control serial autocorrelation, the ADF method has become more popular (Dickey and Fuller, 1981). Compared to the Dickey-Fuller (DF) approach, the ADF technique is more robust and applicable to more sophisticated procedures (Fuller, 2009). The purpose of applying these tests was to confirm that no parameter exceeded the integration order, corroborating the ARDL simulation's methodological coherence (Raihan,2024).

Autoregressive Distributive Lag Model

The ARDL test was developed by Pesaran et al. (2001) and widely utilized due to its robustness and adaptability in handling different degrees of variable integration. If the indicators are integrated at the I(0) or I(1) level, the ARDL Bounds testing method can be analyzed, in contrast to traditional cointegration assessments. This approach is beneficial even with a small sample size since it produces dependable and consistent estimates even when there are only a limited number of data points available (Ridzuan et al., 2023; Pattak et al.,2023). The longer-period connection among LCF, GDP, PAI, FGOB, TI, and URBA is shown by Formula (8). This method was created to assist in defining ARDL Bounds:

$$\Delta LLCF_t = \sigma_0 + \rho_1 LCF_{t-1} + \rho_2 LGDP_{t-1} + \rho_3 LPAI_{t=1} + \rho_4 LFGOB_{t-1} + \rho_5 LTI_{t-1} + \rho_6 LURBA_{t-1} + \sum_{i=1}^{w} \sigma_1\, \Delta LLCF_{2_{\mathrm{t-i}}} + \sum_{i=1}^{w} \sigma_2\, \Delta \mathrm{LGDP}_{\mathrm{t-i}} + \sum_{i=1}^{w} \sigma_3 \Delta LPAI_{t=1} + \sum_{i=1}^{w} \sigma_4\, \Delta\, LFGOB_{t-i} + \sum_{i=1}^{w} \sigma_5 \Delta \mathrm{LTI}_{\mathrm{t-i}} + \sum_{i=1}^{w} \sigma_6 \Delta \mathrm{LURBA}_{\mathrm{t-i}} + \varepsilon_t \quad (4)$$

It is possible to conclude that the variables are long-term correlated if the F-statistics are greater than the highest critical value for rejecting the null hypothesis. If the F-statistic is smaller than the lowest allowable value, the null hypothesis is accepted. If the F-statistics are seen to be between the lowest and maximum limits, the test is considered inconclusive (Raihan et al.,2023). Equations 5 and 6 reveal the null and alternative hypotheses:

$$H_0 = \sigma_1 = \sigma_2 = \sigma_3 = \sigma_4 = \sigma_5 = \sigma_6 \quad (5)$$

$$H_1 = \sigma_1 \neq \sigma_2 \neq \sigma_3 \neq \sigma_4 \neq \sigma_5 \neq \sigma_6 \quad (6)$$

The signs "H0 and H1" denoted the null hypothesis and the alternative hypothesis, respectively.

Our research assessed the error correction model (ECM) after determining the long-term links to investigate the short-term behavior of the independent factors and the short-term adjustment rate toward the long-term rate (Luqman et al., 2021). To do this, the ECM is included in the ARDL structure, as shown in Equation (6)

$$\Delta LLCF_t = \sigma_0 + \sum_{i=1}^{w} \rho_1 \Delta \mathrm{LCF}_{\mathrm{t-i}} + \sum_{i=1}^{w} \rho_2 \Delta \mathrm{LGDP}_{\mathrm{t-i}} + \sum_{i=1}^{w} \rho_3 \Delta LPAI_{t=1} + \sum_{i=1}^{w} \rho_4 \Delta\, LFGOB_{t-i} + \sum_{i=1}^{w} \rho_5\, \Delta \mathrm{LTI}_{\mathrm{t-i}} + \sum_{i=1}^{w} \rho_6 \Delta \mathrm{LURBA}_{\mathrm{t-i}} + \ell ECT_{t-i} + \varepsilon_t \quad (7)$$

Here, the notion ℓ is the rate of adjustment.

Robustness Check

The investigation scrutinized the FMOLS, DOLS, and CCR techniques to represent the long-run impact of GDP, PAI, FGOB, TI, and URBA on LCF in order to evaluate the stability within the ARDL long-term estimation. When there is evidence of series cointegration, FMOLS and DOLS can be utilized. However, the biggest advantage of the DOLS estimation is its ability to present different levels of integration of discrete elements inside the cointegrated framework (Pesaran, 1997; Raihan and Tuspekova, 2022). The FMOLS technique was established by Hansen and Phillips(1990). When addressing cointegration and its influence on autocorrelation and endogeneity in the explanatory variables, the FMOLS technique modifies the least squares approach (Pattak et al.,2023). The CCR technique was developed by Park (1992) and merely utilizes the static part of a lagged model to convert data. In a cointegrating system, the CCR ensures that data extracted from explanatory variables on unobserved heterogeneity will show at zero frequency. As a result, the CCR approach produces chi-square and arithmetically effective approximation assessments devoid of any undesirable aspects. We, therefore, use the FMOLS and DOLS estimators to determine elasticity over the long run. What follows is equivalent to the FMOLS equation, as shown in Exhibit 8.

$$\Delta LLCF_t = \sigma_0 + \sigma_1 LGDP_t + \sigma_2 LPAI_t + \sigma_3 LFGOB_t + \sigma_4 LTI_t + \sigma_5 LURBA_t + \sum_{i=1}^{w} \rho_1\, \Delta LLCF_{\mathrm{t-i}} + \sum_{i=1}^{w} \rho_2\, \Delta \mathrm{LGDP}_{\mathrm{t-i}} + \sum_{i=1}^{w} \rho_3 \Delta PAI_{t-1} + \sum_{i=1}^{w} \rho_4\, \Delta\, LFGOB_{t-i} + \sum_{i=1}^{w} \rho_5 \Delta \mathrm{LTI}_{\mathrm{t-i}} + \sum_{i=1}^{w} \rho_6 \Delta \mathrm{LURBA}_{\mathrm{t-i}} + \varepsilon_t \qquad (8)$$

Here, the longer-period flexibility is assessed using the FMOLS and CCR coefficients, and t shows the time-varying trend.

Pairwise Granger Causality test

The concept of a causality analysis aims to analyze whether or not previous changes in a factor are responsible for the present observation, as theoretical correlations may not hold in practice due to certain elements that may not be clearly described in theory (Voumik et al.,2023). This work employs the Pairwise Granger causality test, which is a statistical view of causation based on a prediction that offers multiple benefits over other time-series research methodologies (Winterhalder et al. 2005). To say that X is causally related to Y would be to say that the sum of X's prior and current values deviates substantially beyond 0. Y and X causality are subject to the same laws; if the results deviate from zero, it indicates the presence of causation on both sides. The analysis used the paired Granger causality test introduced by Granger (1969), to ascertain if there prevailed a short-term causal link between the components. Equation (9) shows that Xt and Yt are causally related.

$$E\left(Y_{t+h} \middle| J_{t,} X_t\right) = E(Y_{t+h}|J_t) \qquad (9)$$

Here, Jt notation is used for the sets of information gathered from all of the outcomes up to a certain point of time (t).

Diagnostic test

Several diagnostic tests were implemented in this research to confirm the data's heteroscedasticity, serial correlation, and normality. The Lagrange Multiplier (LM) test, the Jarque-Bera test (Jarque and Bera, 1987), and the Breusch-Pagan-Godfrey test (Breusch and Pagan, 1979) serve as essentials for validating model assumptions and guaranteeing the robustness of results in time series analysis. Since many econometric models assume normally distributed errors for successful inference, the Jarque-Bera examination checks the normality of residuals, a vital phase in the process. By detecting serial correlation in residuals, the Lagrange Multiplier test makes sure that errors do not correlate over time, which might result in misleading and biased estimations. The heteroscedasticity, or non-constant variance of residuals, is verified using the Breusch-Pagan-Godfrey assessment, which can lead to inaccurate standard errors and estimates.

Result and Discussion

The summary statistics for the variables we investigated with 32 observations are displayed in Table 02 below. The descriptive data for the USA for the following seven variables are provided (LLCF, LGDP, LGDPSQ, LPAI, LFGOB, LTI, and LURBA). As can be seen in the table, all of the factors we chose had a positive mean except LLCF, and the mean was the highest for LGDPSQ. Furthermore, the estimated standard deviations of each variable are quite small, implying that the data points are centered around the mean and have minimal periodic variability. Just LLCF and LPAI showcase positive skewness among the variables; in contrast, LGDP, LGDPSQ, LFGOB, LTI, and LURBA exhibit negative skewness. Furthermore, the Jarque-Bera normality examination was applied to ensure that each variable in this investigation had a normal distribution. Since this test accounts for both skewness and any anomalous Kurtosis, it seems logical. Key indicators of statistics, including mean, median, maximum, minimum, standard deviation, probability value, total, and sum square, are illustrated in Table 2, which offers an exhaustive analysis of the information at hand.

Table 2. Descriptive Statistics of Variables

Statistic	LCF	LGDP	$LGDP^2$	LPAI	LFGOB	LTI	LURBA
Mean	-0.835416	10.64393	113.3917	22.0143	4.290778	12.1409	4.377885
Median	-0.822656	10.71885	114.8942	21.2377	4.322086	12.27706	4.382195
Maximum	-0.63269	11.15938	124.5318	25.66873	4.385638	12.59584	4.417309
Minimum	-0.970971	10.08116	101.6297	20.55212	4.093117	11.38458	4.32148
Std. Dev.	0.093945	0.318778	6.76113	1.665446	0.091946	0.408947	0.027091
Skewness	0.065531	-0.255693	-0.219087	0.989543	-1.146481	-0.577478	-0.500595
Kurtosis	1.965479	1.888894	1.876795	2.466317	3.067511	1.90974	2.252894
Jarque-Bera	1.449882	1.994763	1.938117	5.602132	7.016314	3.363452	2.08073
Probability	0.484353	0.368844	0.37944	0.060745	0.029952	0.186053	0.353326
Sum	-26.73331	340.6058	3628.534	704.4575	137.3049	388.5089	140.0923
Sum Sq. Dev.	0.273596	3.150205	1417.099	85.98507	0.262076	5.184362	0.022751
Observations	32	32	32	32	32	32	32

In Table 3, all three stationarity tests (ADF, DF-GLS, and P-P) are demonstrated for log-transformed variables at both the level and first difference form. In each of the three unit root evaluations, it appears that only the urbanization factor is stationary at level I(0), while the load capacity factor, GDP, GDP squared, private investment in AI, financial globalization, and innovations in technology were non-stationary before we considered their first differences. This mixed sequence of integration encourages us to analyze the assessment now using the ARDL methodology.

Table 3. Results of the Stationarity test

Variables	ADF		P-P		DF-GLS		Decision
	I(0)	I(1)	I(0)	I(1)	I(0)	I(1)	
LLCF	-0.799	-5.347***	-0.826	-5.354***	-1.475	-4.302***	I(1)
LGDP	-0.878	-4.841***	-0.953	-4.829***	-1.771	-3.451***	I(1)
$LGDP^2$	-0.614	-5.000***	-0.650	-4.968***	-1.842	-3.423***	I(1)
LPAI	-0.806	-7.505***	-1.897	-7.403***	-0.933	-5.365***	I(1)
LFGOB	-2.132	-4.140***	-2.134	-4.090***	-1.943	-4.520***	I(1)
LTI	-2.015	-5.053***	-2.131	-5.076***	-0.946	-3.765***	I(1)
LURBA	-8.850***	-1.787	-5.120***	-1.743	-3.781***	-1.462	I(0)

To find confirmation of co-integration between the variables, the present research employed an ARDL bounds test approach. The null hypothesis that there exists no co-integration is rejected at the 1% significance level, based on the ARDL bound test findings. The critical value has been surpassed by the F test statistic result of 5.6945. Therefore, it can be claimed that the parameters of the model have certain co-integrating associations. According to this investigation, the long-term driving forces consist of urbanization, technological innovation, financial globalization, economic expansion, and private investment in artificial intelligence. These characteristics additionally motivate the system to respond first to a typical stochastic disruption. We conclude that the LCF in the United States is affected by differences in all of these variables.

Table 4. Results of ARDL bound test

	Test Statistics	Value	K	
	F statistics	5.6945	6	
	Significance level			
Critical Bounds	10%	5%	2.50%	1%
I(0)	1.99	2.27	2.55	2.88
I(1)	2.94	3.28	3.61	3.99

After the cointegration had been verified by the bound testing process, we might evaluate the long-term connection among those variables. Table 5 adopts the dynamic ARDL method to demonstrate the short and long-term consequences of LGDP, $LGDP^2$, LPAI, LFGOB, LTI, and LURBA on LLCF in the USA.

The findings indicate that the load capacity of the US environment seems to decrease with economic expansion over time but grows with the continued expansion of GDP. Urbanization and private investment in AI have been significant contributors to the expansion of load capacity factor, but long-term US LCF is decreased by financial globalization and technological innovation. Our findings demonstrate that the ecosystem gradually loses its natural qualities due to economic development. The US economy is expanding and strongly dependent on energy sources like fossil fuels, which cause ecological damage; therefore, the conclusion makes theoretical sense. The outcomes in Table 5 show that the LCF decreases by 3.449% in the long run and by 4.242% in the short run for each 1% expansion in GDP. Our analysis result agrees with previous studies that established an adverse link between GDP growth and LCF. A few studies have concluded that a boost in the GDP has detrimental implications for the environment. This includes Xu et al. (2022) for Brazil; Shang et al. (2022) for ASEAN countries; Pata and Balsalobre-Lorente (2022) for Turkey; Khan et al. (2023) in the context of G7 and E7 countries; Akadiri et al. (2022) for India; and Pata (2021) in Japan and the United States. However, for Taiwan, Yeh and Liao (2017) observed the inverse outcome. They also revealed that Taiwan has come to the point where financial pressures no longer adversely affect the natural world. Likewise, Nathaniel et al. (2020) identified no evidence linking economic expansion to environmental damage in CIVETS (Egypt, Turkey, South Africa, Indonesia, and Vietnam).

On the other hand, each unit of growth in GDP2 results in a 1.184% long-term and 0.156% short-term improvement in LCF. Given that the coefficient for LGDP is negative and the coefficient for $LGDP^2$ is positive, and both are statistically significant, this suggests that environmental pressure diminishes over time, supporting the recently proposed LCC hypothesis for the USA. The coefficients for LPAI indicate a positive correlation with LLCF, implying a 0.015% long-term degradation and a 0.462% short-term increase in LCF for every 1% rise in PAI. Thus, private investment in artificial intelligence in the United States significantly contributes to the green ecosystem. According to Karpovich et al. (2022), executing "green" investment-innovative projects in intelligent

manufacturing operated by artificial intelligence plays an integral part in ensuring the ecological security of Russia's local economy. Moreover, based on Platon (2024), eco-investment and artificial intelligence constitute key elements that might accelerate and improve the circular economy.
Conversely, LCF is destructively connected with FGOB in both the long and short run, and this relationship is statistically significant. These findings suggest that financial globalization has an adverse impact on the US ecosystem. Specifically, a 1% spike in FGOB reduces LCF by 1.193% in the long run and by 0.502% in the short run. This result is inconsistent with the examination of Akadiri and Adebayo (2021), which shows that, in India, pollution levels grow when financial globalization declines, but they drop when it increases. This inference is supported by findings by Xu et al. (2022) and Akadiri et al. (2022), which found a positive correlation between financial globalization and load capacity factor in Brazil and India, accordingly. Generally speaking, the globalization of finance symbolizes the development of a country's economic sector; a sophisticated financial system would place investments in ecological sustainability ahead of environmentally damaging growth paths (Raihan et al., 2023).
Similarly, there is a negative correlation between LTI and LLCF, with each 1% rise in TI reducing LCF by 0.127% in the long run and 0.00253% in the short run, and this result is significant at the 1% level. Research by Su et al. (2021) concluded that advances in technology raised emission levels in Brazil. The above findings illustrate that the United States has not yet invested in or implemented green technologies to ensure environmental sustainability. Similarly, Adebayo and Kirikkaleli (2021) verified that technological developments worsen Japan's environmental conditions and raise carbon emissions. This result aligns with the conclusions of Lin and Zhu (2019). That said, it goes contrary to the studies conducted by Khan et al. (2020) and Shahbaz et al. (2020), which found that technological innovation enhances the environmental condition.

Table 5. ARDL Long-Run and Short-Run Results

VARIABLES	LR	SR
LGDP	-3.449***(11.5676)	
$LGDP^2$	1.184***(0.52519)	
LPAI	0.015**(0.03079)	
LFGOB	-1.193***(0.2959)	
LTI	-0.127**(0.16542)	
LURBA	1.182(5.1537)	
D.LGDP		-4.242**(4.26804)
$D.LGDP^2$		0.156**(0.19304)
D.LPAI		0.462***(0.00743)
D.LFGOB		-0.502***(0.15540)
D.LTI		-0.00253(0.0074)
LURBA		17.204***(2.34298)
ECT (Speed Adjustment)		-0.684***(0.08539)
Constant		10.910***(31.2434)
R-square	0.8780	

Additionally, the positive and statistically significant URBA coefficients indicate that both long-term and short-term increases in LURBA negatively affect environmental quality. A 1% increase in URBA raises LCF by 1.182% in the long run and by 17.204% in the short run. The finding suggests that the current urbanization structure in the United States is not conducive to reducing pollution. Research conducted in Singapore by Ali et al. (2017), Saudi Arabia by Raggad (2018), and 19 other countries by Saidi and Mbarek (2017) explored that urbanization enhances the quality of the natural world by lowering emissions of carbon dioxide. But, Wang et al. (2016) found that greater urbanization boosts CO_2 emissions. However, our study's outcomes contradict Solarin et al. (2021), who reported that urbanization does not impact the environmental quality of Nigeria.

The DOLS, FMOLS, and CCR techniques are utilized to check the consistency and efficiency of the ARDL results and are presented in Table 6. The economic growth coefficients in the FMOLS, DOLS, and CCR computations are statistically significant at the 1% level and have negative values. It can be concluded from the estimated components that an increase of 1% in GDP causes the LCF to fall by 13.532%, 7.325%, and 14.135%, respectively. The higher R-squared values suggest that the estimation was appropriate. A 1% increase in LPAI leads the LCF to grow by 0.013%, whereas an extra 1% in $LGDP^2$ enables the LCF to expand by 0.625% in the FMOLS model. These figures are noteworthy and corroborate the ARDL conclusion provided before. Additionally, a 1% surge in LURBA raises the LCF by 7.428%, whereas a 1% expansion in LTI encourages the LCF by 0.037%. These outcomes also align with the ARDL short and long-run estimation. Conversely, a 1% spike in LFGOB causes the LCF average to drop by 1.243%. Similar to the ARDL results, the coefficients $LGDP^2$, LPAI, and LFGOB are significant at the 1% level of significance, whereas LTI and LURBA are significant at the 5% level.

Within the DOLS model, an extra 1% in LGDP2, LPAI, LTI, and LURBA raises an average of 0.271%, 0.045%, 0.568%, and 8.671% in LCF. The value of the ARDL results in Table 05 is confirmed by the statistically significant values of these variables. Conversely, a one percent rise in LFGOB leads to an average 1.930% reduction in LCF. Similar to the ARDL conclusions, the coefficient of LFGOB is significant in this particular case. The CCR observations exhibit a similar pattern, except for the LFGOB example. An average of 0.652%, 0.0153%, 0.045%, and 7.796% of LCF are spiked by an additional 1% in LGDP2, LPAI, LTI, and LURBA in the CCR model. Conversely, an extra 1% in LFGOB causes an average 1.236% decrease in LCF.

Table 6. Robustness Check

Variables	FMOLS	DOLS	CCR
LLCF dependent			
LGDP	-13.532***(4.4923)	-7.325**(5.8932)	-14.136***(6.7150)
$LGDP^2$	0.625***(0.2035)	0.271**(0.1827)	0.652***(0.3053)
LPAI	0.013***(0.0121)	0.045**(0.0985)	0.0153**(0.0183)
LFGOB	-1.243***(0.1619)	-1.930***(0.5920)	-1.236***(0.1923)
LTI	0.037**(0.0722)	0.568*(0.4841)	0.045**(0.0950)
LURBA	7.428**(2.2595)	8.671*(3.6591)	7.796***(2.8327)
C	44.608**(18.0927)	27.8901**(16.5672)	46.294**(25.9663)
R-squared	0.9013	0.9641	0.9005

The findings of causal linkages across several economic indicators are presented in Table 7. An F-statistic of 3.38826 and a p-value of 0.0499 indicate that LLGDP does not Granger-cause LLCF. This suggests that we reject the null hypothesis that there is no link between variables at the 5% significance level. Furthermore, p-values below the usual significance threshold confirmed the observation of one-way causation from LGDP2, LPAI, and LTI to LLCF. Therefore, in these circumstances, we reject the null hypothesis that there is no causation. Nonetheless, a strong two-way causal relationship was discovered between LLCF and LGOB, as well as between

LURBA and LLCF. On the other hand, p-values higher than the traditional significance level for each case demonstrated that there was no significant causal relationship between LLCF and LPAI, LLCF and LGDP, LLCF and LGDP, or LLCF and LTI. As a result, the null hypothesis that there is no causation in these interactions is not successfully rejected.

Table 7. Results of Pairwise Granger Causality test

Null Hypothesis	Obs	F-Statistic	Prob.
LGDP $\neq$ LLCF	30	3.38826	0.0499
LLCF $\neq$ LGDP		0.44313	0.647
LGDP2 $\neq$ LLCF	30	3.4843	0.0463
LLCF $\neq$ LGDP2		0.44696	0.6446
LPAI $\neq$ LLCF	30	2.75848	0.0027
LLCF $\neq$ LPAI		0.2652	0.7692
LFGOB $\neq$ LLCF	30	6.05754	0.0072
LLCF $\neq$ LFGOB		0.18985	0.0283
LTI $\neq$ LLCF	30	3.76786	0.0071
LLCF $\neq$ LTI		0.87713	0.4284
LURBA $\neq$ LLCF	30	2.68762	0.0077
LLCF $\neq$ LURBA		5.37891	0.0114

Table 08 displays the diagnostic examination outcomes. The results demonstrated that the usefulness of all diagnostic procedures is insignificant, and the null hypothesis cannot be rejected. According to the p-value of 0.8027, the Jarque-Bera assessment confirms that the residuals appear to be normally distributed. The Lagrange Multiplier analysis shows no serial correlation in the residuals, with a p-value of 0.9463. Lastly, the Breusch-Pagan-Godfrey assessment confirms that the residuals do not exhibit heteroscedasticity, with a p-value of 0.3411.

Table 8. The findings of diagnostic tests

Diagnostic tests	Coefficient	p-value	Decision
Jarque-Bera test	0.43948	0.8027	Residuals are normally distributed
Lagrange Multiplier test	0.05528	0.9463	No serial correlation exits
Breusch-Pagan-Godfrey test	1.1950	0.3411	No heteroscedasticity exists

Conclusion and Policy Recommendation

The present research comprehensively addresses how the LCF in the USA became influenced by private investment in artificial intelligence (AI), economic expansion, financial globalization, technological innovation, and urbanization between 1990 and 2022. The discoveries propose insightful information on the intricate connections between monetary activity and the preservation of the ecosystem. To validate the Load Capacity Curve (LCC) theory, the research makes use of advanced econometric techniques. The findings indicate that while urbanization and PAI reduce the environmental burden, technical advancements, economic growth, and financial integration serve to exacerbate these consequences. The results of the stationarity tests illustrate that the elements in question exhibit a combination of various degrees of integration and do not exhibit unit root problems. The ARDL bound assessment provides further evidence that these factors are cointegrated, indicating the existence of steady long-term linkages. The ARDL calculations demonstrate a favorable association between GDP growth, TI, FGOB, and LCF and provide short- and long-term support for the LCC hypothesis in the USA. This suggests that environmental damage occurs due to economic expansion when insufficient steps are made to safeguard the environment. Conversely, the positive correlations between GDP, TI, FGOB, and LCF convey that these factors might encourage adverse environmental effects. It is anticipated that financial globalization can provide the required funding for investments in eco-friendly technologies and more productive industrial processes. Similar to this, robust and resilient advances in technology, when combined with an openness to trade, might foster the creation of novel concepts and the use of greener practices by stimulating healthy competition and granting access to the latest technologies. The accuracy of the ARDL findings is confirmed by the robustness testing adopting FMOLS, DOLS, and CCR, which increases the credibility of the results. Furthermore, the Pairwise Granger Causality tests exhibit significant one-way causal relationships between LLCF and LGDP2, LPAI, and LTI. These relationships emphasize the relevance of how economic shifts, private investments in artificial intelligence, and improvements in green technology impact the dynamics of ecological sustainability in the USA. Therefore, this investigation suggests several legislative solutions aimed at encouraging sustainable economic development in the United States by leveraging financial globalization, technical improvements, and a feasible urban infrastructure.

In order to tackle the U-shaped correlation discovered in our study between income and environmental sustainability, the United States should adopt a comprehensive and diverse policy strategy. At first, the focus should be on providing green technology and sustainable practices to lower-income areas. This may be done by offering subsidies for the adoption of renewable energy and providing incentives for eco-friendly enterprises. As income levels increase, it is necessary to enhance laws in order to reduce environmental degradation caused by higher levels of consumption and industrial operations. This entails implementing rigorous emissions regulations, advocating for energy conservation, and allocating resources towards sustainable infrastructure. To promote sustainability among high-income groups, policymakers can incentivize investments in clean energy through tax benefits, implement carbon pricing systems, and allocate funds for new environmental technology. Furthermore, it is imperative to strengthen education and awareness initiatives on sustainable behaviors among individuals of all income brackets in order to cultivate a societal ethos of environmental accountability. It is imperative for federal and state governments to cooperate in order to guarantee the efficient implementation of these policies, while also customizing them to suit the specific requirements of each region. Through the implementation of this all-encompassing strategy, the United States may utilize economic expansion to enhance environmental results and attain enduring sustainability.

In order to maximize the beneficial effects of private investment in AI on environmental sustainability, the United States should implement specific and focused regulatory initiatives. Firstly, offers tax incentives and subsidies to private firms that invest in AI technologies that improve environmental sustainability, such as smart grids, precision agriculture, and predictive maintenance to minimize waste and emissions. Facilitate the formation of collaborations between the public and commercial sectors to expedite the implementation of sustainable solutions powered by artificial intelligence. This will ensure that even small and medium-sized firms have the opportunity to benefit from these advancements. Enforce policies that promote openness and accountability in the use of AI technology to mitigate unanticipated adverse environmental effects. Increase research and development funding for artificial intelligence (AI) programs that specifically target sustainability, with an emphasis on promoting innovation in areas such as climate modeling, resource management, and energy efficiency. Furthermore, advocates for the use of artificial intelligence (AI) in environmental monitoring and enforcement endeavors to enhance adherence and effectiveness. Advocate for workforce development projects that focus on cultivating proficiency in artificial intelligence and environmental sustainability. This will ensure the availability of a highly qualified labor force capable of driving progress in these areas. To leverage technology developments and establish itself as a frontrunner in the green economy, the United States may provide a favorable climate for private investment in AI, therefore promoting significant strides in environmental sustainability.

In order to counteract the negative effects of technical innovation and financial globalization on reducing the LCF, the United States should implement a strategic policy framework. Firstly, policies should be established that promote the use of sustainable technical innovations, with a focus on optimizing resource utilization and reducing environmental impacts. Offer incentives to encourage enterprises to create and use environmentally friendly technologies that increase the ability to handle workloads without using up resources. Facilitate responsible financial globalization by implementing regulations that guarantee investments, uphold sustainable practices, and refrain from exploiting natural or human resources. Enhance global collaboration to harmonize worldwide financial transactions with sustainability objectives, guaranteeing that overseas investments and technology transfers make a positive contribution to environmental sustainability. Promote and fund research and development in sustainable technologies and practices, encouraging innovative solutions that achieve a balance between economic growth and environmental stewardship. In addition, education and training programs that specifically target sustainable practices and the environmental consequences of globalization should be improved, equipping the workforce to participate actively in and promote these endeavors. Through the incorporation of these policies, the United States can effectively tackle the difficulties presented by technical advancement and financial globalization, guaranteeing long-term growth and safeguarding the nation's ability to support future generations.

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References

Abir, S. (2024). Parameter Estimation for Stroke Patients Using Brain CT Perfusion Imaging with Deep Temporal Convolutional Neural Network.

Adebayo, T. S., Oladipupo, S. D., Adeshola, I., & Rjoub, H. (2022). Wavelet analysis of the impact of renewable energy consumption and technological innovation on CO2 emissions: evidence from Portugal. Environmental Science and Pollution Research, 29(16), 23887-23904.

Adebayo, T., Oladipupo, S., Adeshola, I. et al. Wavelet analysis of the impact of renewable energy consumption and technological innovation on CO2 emissions: evidence from Portugal. Environ Sci Pollut Res 29, 23887–23904 (2022). https://doi.org/10.1007/s11356-021-17708-8

Adebayo, T.S., Kirikkaleli, D. Impact of renewable energy consumption, globalization, and technological innovation on environmental degradation in Japan: application of wavelet tools. Environ Dev Sustain 23, 16057–16082 (2021). https://doi.org/10.1007/s10668-021-01322-2

Agila ABT, Khalifa W, Saint Akadiri S, Adebayo TS, Altuntas M (2022) Determinants of load capacity factor in South Korea: Does structural change matter? Environ Sci Pollut Res 29:69932–69948. https://doi.org/10.1007/s11356-022-20676-2

Ahmed, Z., Nathaniel, S. P., & Shahbaz, M. (2021). The criticality of information and communication technology and human capital in environmental sustainability: evidence from Latin American and Caribbean countries. Journal of Cleaner Production, 286, 125529. https://doi.org/10.1016/j.jclepro.2020.125529

Akadiri SS, Adebayo TS (2021) Asymmetric nexus among financial globalization, non-renewable energy, renewable energy use, economic growth, and carbon emissions: impact on environmental sustainability targets in India. Environ Sci Pollut Res 1–13

Akadiri, S.S., Adebayo, T.S., Riti, J.S. et al. The effect of financial globalization and natural resource rent on load capacity factor in India: an analysis using the dual adjustment approach. Environ Sci Pollut Res 29, 89045–89062 (2022). https://doi.org/10.1007/s11356-022-22012-0
Akadiri, S.S., Adebayo, T.S., Riti, J.S. et al. The effect of financial globalization and natural resource rent on load capacity factor in India: an analysis using the dual adjustment approach. Environ Sci Pollut Res 29, 89045–89062 (2022). https://doi.org/10.1007/s11356-022-22012-0
Akinsola, G. D., Awosusi, A. A., Kirikkaleli, D., Umarbeyli, S., Adeshola, I., & Adebayo, T. S. (2022). Ecological footprint, public-private partnership investment in energy, and financial development in Brazil: a gradual shift causality approach. Environmental Science and Pollution Research, 29(7), 10077-10090. https://doi.org/10.1007/s11356-021-15791-5

Ali HS, Abdul-Rahim AS, Ribadu MB (2017) Urbanization and carbon dioxide emissions in Singapore: evidence from the ARDL approach. Environ Sci Pollut Res 24(2):1967–1974

Ali, Z., Yang, J., Ali, A. et al. Balancing agriculture, environment and natural resources: insights from Pakistan's load capacity factor analysis. Clean Techn Environ Policy (2023). https://doi.org/10.1007/s10098-023-02673-2

Anwar, A., Chaudhary, A. R., Malik, S., & Bassim, M. (2021). Modelling the macroeconomic determinants of carbon dioxide emissions in the G-7 countries: the roles of technological innovation and institutional quality improvement. Global Business Review, 09721509211039392. https://doi.org/10.1177/09721509211039392

Asadnia, M., Chua, L. H., Qin, X. S., & Talei, A. (2014). Improved particle swarm optimization–based artificial neural network for rainfall-runoff modeling. Journal of Hydrologic Engineering, 19(7), 1320-1329. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000927

Asadnia, M., Khorasani, A. M., & Warkiani, M. E. (2017). An Accurate PSO-GA Based Neural Network to Model Growth of Carbon Nanotubes. Journal of Nanomaterials, 2017(1), 9702384. https://doi.org/10.1155/2017/9702384

Awosusi AA, Xulu NG, Ahmadi M, Rjoub H, Altuntaş M, Uhunamure SE, Kirikkaleli D (2022) The sustainable environment in Uruguay: the roles of financial development, natural resources, and trade globalization. Front Environ Sci 10:875577

Awosusi, A. A., Kutlay, K., Altuntaş, M., Khodjiev, B., Agyekum, E. B., Shouran, M., ... & Kamel, S. (2022). A roadmap toward achieving sustainable environment: evaluating the impact of technological innovation and globalization on load capacity factor. International Journal of Environmental Research and Public Health, 19(6), 3288. https://doi.org/10.3390/ijerph19063288

Bakirtas, T., Acikgoz, F., & Ozdilek, E. (2023). Assessing the Environment From Both Supply and Demand Aspects in New Emerging Countries: The LCC and the EKC Approaches. https://doi.org/10.21203/rs.3.rs-2882268/v1

BP (2020). Statistical Review of World Energy. https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf

Brandusescu, A. (2021). Artificial intelligence policy and funding in Canada: Public investments, private interests. Private Interests (March 1, 2021).http://dx.doi.org/10.2139/ssrn.4089932

Breusch, T. S., & Pagan, A. R. (1979). A simple test for heteroscedasticity and random coefficient variation. Econometrica: Journal of the econometric society, 1287-1294. https://doi.org/10.2307/1911963

Brown, A. (2013), "Quality: where have we come from and what can we expect?", The TQM Journal, Vol. 25 No. 6, pp. 585-596

Caglar, A.E., Daştan, M., Mehmood, U. et al. Assessing the connection between competitive industrial performance on load capacity factor within the LCC framework: Implications for sustainable policy in BRICS economies. Environ Sci Pollut Res (2023). https://doi.org/10.1007/s11356-023-29178-1

ÇAMKAYA, S., KARAASLAN, A. Do renewable energy and human capital facilitate the improvement of environmental quality in the United States? A new perspective on environmental issues with the load capacity factor. Environ Sci Pollut Res 31, 17140–17155 (2024). https://doi.org/10.1007/s11356-024-32331-z

Chen H, Tackie EA, Ahakwa I, Musah M, Salakpi A, Alfred M, Atingabili S (2022) Does energy consumption, economic growth, urbanization, and population growth influence carbon emissions in the BRICS? Evidence from panel models robust to cross-sectional dependence and slope heterogeneity. Environ Sci Pollut Res 29(25):37598–37616. https://doi.org/10.1007/s11356-021-17671-4

Cheng, K., Jin, Z., & Wu, G. (2024). Unveiling the role of artificial intelligence in influencing enterprise environmental performance: Evidence from China. Journal of Cleaner Production, 440, 140934. https://doi.org/10.1016/j.jclepro.2024.140934

Chenic, A. Ș., Cretu, A. I., Burlacu, A., Moroianu, N., Vîrjan, D., Huru, D., ... & Enachescu, V. (2022). Logical analysis on the strategy for a sustainable transition of the world to green energy—2050. Smart cities and villages coupled to renewable energy sources with low carbon footprint. Sustainability, 14(14), 8622. https://doi.org/10.3390/su14148622

Degirmenci, T., & Aydin, M. (2024). Testing the load capacity curve hypothesis with green innovation, green tax, green energy, and technological diffusion: A novel approach to Kyoto protocol. Sustainable Development. https://doi.org/10.1002/sd.2946

Dickey, D. A., & Fuller, W. A. (1979). Distribution of the estimators for autoregressive time series with a unit root. Journal of the American statistical association, 74(366a), 427-431.

Dickey, D. A., & Fuller, W. A. (1981). Likelihood ratio statistics for autoregressive time series with a unit root. Econometrica: journal of the Econometric Society, 1057-1072. https://doi.org/10.2307/1912517

Dogan, A., & Pata, U. K. (2022). The role of ICT, R&D spending and renewable energy consumption on environmental quality: Testing the LCC hypothesis for G7 countries. Journal of Cleaner Production, 380, 135038. https://doi.org/10.1016/j.jclepro.2022.135038

Du, L., Jiang, H., Adebayo, T. S., Awosusi, A. A., & Razzaq, A. (2022). Asymmetric effects of high-tech industry and renewable energy on consumption-based carbon emissions in MINT countries. Renewable Energy, 196, 1269-1280. https://doi.org/10.1016/j.renene.2022.07.028

Elliott, G., Rothenberg, T. J., & Stock, J. H. (1992). Efficient tests for an autoregressive unit root.

Engle, R. F., & Granger, C. W. (1987). Co-integration and error correction: representation, estimation, and testing. Econometrica: journal of the Econometric Society, 251-276. https://doi.org/10.2307/1913236

Fang, Z., Wang, T., & Yang, C. (2024). Nexus among natural resources, environmental sustainability, and political risk: Testing the load capacity factor curve hypothesis. Resources Policy, 90, 104791. https://doi.org/10.1016/j.resourpol.2024.104791

Farahnakian, M., Razfar, M. R., Moghri, M., & Asadnia, M. (2011). The selection of milling parameters by the PSO-based neural network modeling method. The International Journal of Advanced Manufacturing Technology, 57, 49-60. https://doi.org/10.1007/s00170-011-3262-1

Fareed Z, Salem S, Adebayo TS et al (2021) Role of Export Diversification and Renewable Energy on the Load Capacity Factor in Indonesia: A Fourier Quantile Causality Approach. Front Environ Sci 9:1–9. https://doi.org/10.3389/fenvs.2021.770152

Fatorachian, H. and Kazemi, H. (2018), "A critical investigation of Industry 4.0 in manufacturing: theoretical operationalisation framework", Production Planning and Control, Vol. 29 No. 8, pp. 633-644.

Fuller, W. A. (2009). Introduction to statistical time series. John Wiley & Sons.

Furceri D, Loungani P, Ostry JD (2019) The aggregate and distributional effects of financial globalization: evidence from macro and sectoral data. J Money, Credit, Bank 51:163–198

Galli, A., Wiedmann, T., Ercin, E., Knoblauch, D., Ewing, B., & Giljum, S. (2012). Integrating ecological, carbon and water footprint into a "footprint family" of indicators: definition and role in tracking human pressure on the planet. Ecological indicators, 16, 100-112. https://doi.org/10.1016/j.ecolind.2011.06.017

Granger, C. W. (1969). Investigating causal relations by econometric models and cross-spectral methods. Econometrica: journal of the Econometric Society, 424-438. https://doi.org/10.2307/1912791

Guloglu B, Emre Caglar A, Korkut Pata U (2023) Analyzing the determinants of the load capacity factor in OECD countries: evidence from advanced quantile panel data methods. Gondwana Res 118:92–104. https://doi.org/10.1016/j.gr.2023.02.013

Güngör H, Abu-Goodman M, Olanipekun IO, Usman O (2021) Testing the environmental Kuznets curve with structural breaks: the role of globalization, energy use, and regulatory quality in South Africa. Environ Sci Pollut Res 28(16):20772–20783

Ha LT (2022) Socioeconomic and resource efficiency impacts of digital public services. Environ Sci Pollut Res 29(55):83839–83859

Habila, M. A., Ouladsmane, M., & Alothman, Z. A. (2023). Role of artificial intelligence in environmental sustainability. In Visualization techniques for climate change with machine learning and artificial intelligence (pp. 449-469). Elsevier. https://doi.org/10.1016/B978-0-323-99714-0.00009-1

Haldar, A., & Sethi, N. (2022). Environmental effects of Information and Communication Technology-Exploring the roles of renewable energy, innovation, trade and financial development. Renewable and Sustainable Energy Reviews, 153, 111754. https://doi.org/10.1016/j.rser.2021.111754

Hansen, B., & Phillips, P. C. B. (1990). Estimation and inference in models of cointegration: A simulation study. Vol. 8 of Advances in Econometrics: Co-integration, Spurious Regressions and Unit Roots. Greenwich.

Haseeb A, Xia E, Danish BMA, Abbas K (2018) Financial development, globalization, and CO2 emission in the presence of EKC: evidence from BRICS countries. Environ Sci Pollut Res 25(31):31283–31296. https://doi.org/10.1007/s11356-018-3034-7

He, J., & Richard, P. (2010). Environmental Kuznets curve for CO2 in Canada. Ecological economics, 69(5), 1083-1093. https://doi.org/10.1016/j.ecolecon.2009.11.030

https://www.jec.senate.gov/public/_cache/files/8b10c63b-d93c-45c5-8f26-900fb23154d1/maintaining-american-leadership-in-artificial-intelligence.pdf

Huilan, W., Akadiri, S. S., Haouas, I., Awosusi, A. A., & Odu, A. T. (2024). Impact of trade liberalization and renewable energy on load capacity factor: Evidence from novel dual adjustment approach. Energy & Environment, 35(2), 795-814. https://doi.org/10.1177/0958305X221137559

J. Wang, M. Ramzan, R. Salahodjaev, M. Hafeez, J. Song, Does financial globalisation matter for environmental quality? A sustainability perspective of Asian economies, Economic Research-Ekonomska Istraˇzivanja 36 (3) (2023) 2153152, https://doi.org/10.1080/1331677X.2022.2153152

Jahanger, A., Ogwu, S. O., Onwe, J. C., & Awan, A. (2024). The prominence of technological innovation and renewable energy for the ecological sustainability in top SDGs nations: Insights from the load capacity factor. Gondwana Research, 129, 381-397. https://doi.org/10.1016/j.gr.2023.05.021

Jarque, C. M., & Bera, A. K. (1987). A test for normality of observations and regression residuals. International Statistical Review/Revue Internationale de Statistique, 163-172. https://doi.org/10.2307/1403192.

Jin, G., & Huang, Z. (2023). Asymmetric impact of renewable electricity consumption and industrialization on environmental sustainability: evidence through the lens of load capacity factor. Renewable Energy, 212, 514-522. https://doi.org/10.1016/j.renene.2023.05.045

Jin, X., Ahmed, Z., Pata, U. K., Kartal, M. T., & Erdogan, S. (2023). Do investments in green energy, energy efficiency, and nuclear energy R&D improve the load capacity factor? An augmented ARDL approach. Geoscience Frontiers, 101646. https://doi.org/10.1016/j.gsf.2023.101646

Karpovich, O.G., Bulgarov, M.A., Deberdeeva, N.A., Abashin, E.G. (2022). Mechanism of Implementation of “Green” Investment-Innovative Initiatives in “Smart” Production Under the Control of Artificial Intelligence in the Interests of Environmental Safety of the Region. In: Zavyalova, E.B., Popkova, E.G. (eds) Industry 4.0. Palgrave Macmillan, Cham. https://doi.org/10.1007/978-3-030-79496-5_42

Kartal, M. T., Depren, S. K., Kirikkaleli, D., Depren, Ö., & Khan, U. (2022). Asymmetric and long-run impact of political stability on consumption-based carbon dioxide emissions in Finland: evidence from nonlinear and Fourier-based approaches. Journal of Environmental Management, 321, 116043. https://doi.org/10.1016/j.jenvman.2022.116043

Khan, I., Hou, F., & Le, H. P. (2021). The impact of natural resources, energy consumption, and population growth on environmental quality: Fresh evidence from the United States of America. Science of the Total Environment, 754, 142222. https://doi.org/10.1016/j.scitotenv.2020.142222

Khan, I., Zhong, R., Khan, H. et al. Examining the relationship between technological innovation, economic growth and carbon dioxide emission: dynamic panel data evidence. Environ Dev Sustain (2023). https://doi.org/10.1007/s10668-023-03384-w

Khan, U., Khan, A. M., Khan, M. S., Ahmed, P., Haque, A., & Parvin, R. A. (2023). Are the impacts of renewable energy use on load capacity factors homogeneous for developed and developing nations? Evidence from the G7 and E7 nations. Environmental Science and Pollution Research, 30(9), 24629-24640.

Khan, Z., Ali, M., Jinyu, L., Shahbaz, M., & Siqun, Y. (2020). Consumption-based carbon emissions and trade nexus: Evidence from nine oil exporting countries. Energy Economics, 89, 104806.

Kihombo S, Ahmed Z, Chen S, Adebayo TS, Kirikkaleli D (2021) Linking financial development, economic growth, and ecological footprint: what is the role of technological innovation? Environ Sci Pollut Res. https://doi.org/10.1007/s11356-021-14993-1

Kihombo, ., Vaseer, A.I., Ahmed, Z. et al. Is there a tradeoff between financial globalization, economic growth, and environmental sustainability? An advanced panel analysis. Environ Sci Pollut Res 29, 3983–3993 (2022). https://doi.org/10.1007/s11356-021-15878-z

Konya, A., & Nematzadeh, P. (2024). Recent applications of AI to environmental disciplines: A review. Science of The Total Environment, 906, 167705. https://doi.org/10.1016/j.scitotenv.2023.167705

Koondhar, M. A., Qiu, L., Li, H., Liu, W., & He, G. (2018). A nexus between air pollution, energy consumption and growth of economy: a comparative study between the USA and China-based on the ARDL bound testing approach. Agricultural Economics/Zemědělská Ekonomika, 64(6).https://doi.org/10.17221/101/2017-AGRICECON

Kose MA, Prasad E, Rogoff K, Wei S-J (2009) Financial globalization: a reappraisal. IMF Staff Pap 56(1):8–62

Krishnamoorthy, G., & Sistla, S. M. K. (2023). Exploring Machine Learning Intrusion Detection: Addressing Security and Privacy Challenges in IoT-A Comprehensive Review. Journal of Knowledge Learning and Science Technology ISSN: 2959-6386 (online), 2(2), 114-125. https://doi.org/10.60087/jklst.vol2.n2.p125

Krishnamoorthy, G., & Sistla, S. M. K. (2023). Leveraging Deep Learning for Climate Change Prediction Models: A Dive into Cutting-Edge Techniques. Journal of Knowledge Learning and Science Technology ISSN: 2959-6386 (online), 2(2), 108-113. https://doi.org/10.60087/jklst.vol2.n2.p113

Kumari, N., & Pandey, S. (2023). Application of artificial intelligence in environmental sustainability and climate change. In Visualization techniques for climate change with machine learning and artificial intelligence (pp. 293-316). Elsevier.https://doi.org/10.1016/B978-0-323-99714-0.00018-2

Li, X., Sun, Y., Dai, J. et al. How do natural resources and economic growth impact load capacity factor in selected Next-11 countries? Assessing the role of digitalization and government stability. Environ Sci Pollut Res 30, 85670–85684 (2023). https://doi.org/10.1007/s11356-023-28414-y

Li, Z. Z., Li, R. Y. M., Malik, M. Y., Murshed, M., Khan, Z., & Umar, M. (2021). Determinants of carbon emission in China: how good is green investment?. Sustainable Production and Consumption, 27, 392-401. https://doi.org/10.1016/j.spc.2020.11.008

Lin, B., & Zhu, J. (2019). Determinants of renewable energy technological innovation in China under CO2 emissions constraint. Journal of Environmental Management, 247, 662–671.

Liu, J., Murshed, M., Chen, F., Shahbaz, M., Kirikkaleli, D., & Khan, Z. (2021). An empirical analysis of the household consumption-induced carbon emissions in China. Sustainable Production and Consumption, 26, 943-957. https://doi.org/10.1016/j.spc.2021.01.006

Luqman, M., Li, Y., Khan, S. U. D., & Ahmad, N. (2021). Quantile nexus between human development, energy production, and economic growth: the role of corruption in the case of Pakistan. Environmental Science and Pollution Research, 28(43), 61460-61476. https://doi.org/10.1007/s11356-021-14744-2

Magazzino, C., Mele, M., & Schneider, N. (2021). A machine learning approach on the relationship among solar and wind energy production, coal consumption, GDP, and CO2 emissions. Renewable Energy, 167, 99-115. https://doi.org/10.1016/j.renene.2020.11.050

Mehmood, U., Tariq, S., Aslam, M.U. et al. Evaluating the impact of digitalization, renewable energy use, and technological innovation on load capacity factor in G8 nations. Sci Rep 13, 9131 (2023). https://doi.org/10.1038/s41598-023-36373-0

Menz, T., & Welsch, H. (2012). Population aging and carbon emissions in OECD countries: Accounting for life-cycle and cohort effects. Energy Economics, 34(3), 842-849.

Mimi, M. B., Haque, A. U., & Kibria, G. (2022). Does human capital investment influence unemployment rate in Bangladesh: a fresh analysis. National Accounting Review, 4(3), 273-286. https://doi.org/10.3934/NAR.2022016

Min Zhang, Kashif Raza Abbasi, Nasiru Inuwa, Crenguta Ileana Sinisi, Rafael Alvarado & Ilknur Ozturk (2023) Does economic policy uncertainty, energy transition and ecological innovation affect environmental degradation in the United States?, Economic Research-Ekonomska Istraživanja, 36:2, 2177698, https://doi.org/10.1080/1331677X.2023.2177698

Murshed M, Elheddad M, Ahmed R, Bassim M, & Than ET (2021) Foreign direct investments, renewable electricity output, and ecological footprints: do financial globalization facilitate renewable energy transition and environmental welfare in Bangladesh? Asia-Pacif Financ Mark 1–46

Nathaniel S, Nwodo O, Sharma G, Shah M (2020) Renewable energy, urbanization, and ecological footprint linkage in CIVETS. Environ Sci Pollut Res 27(16):19616–19629

Negi, R. (2018). Global investment scenario of Artificial Intelligence (AI): A study with reference to China, India and United States. Muthusamy, A., & Negi.

Nelson, C. R., & Plosser, C. R. (1982). Trends and random walks in macroeconmic time series: some evidence and implications. Journal of monetary economics, 10(2), 139-162. https://doi.org/10.1016/0304-3932(82)90012-5

Nurgazina, Z., Guo, Q., Ali, U., Kartal, M. T., Ullah, A., & Khan, Z. A. (2022). Retesting the influences on CO2 emissions in China: evidence from dynamic ARDL approach. Frontiers in Environmental Science, 10, 868740. https://doi.org/10.3389/fenvs.2022.868740

Obstfeld M (2021) Trilemmas and tradeoffs: living with financial globalization. In The Asian Monetary Policy Forum: Insights for Central Banking 16–84

Okengwu, U. A., Onyejegbu, L. N., Oghenekaro, L. U., Musa, M. O., & Ugbari, A. O. (2023). Environmental and ethical negative implications of AI in agriculture and proposed mitigation measures. Scientia Africana, 22(1), 141-150. https://doi.org/10.4314/sa.v22i1.13

Orhan, A., Adebayo, T. S., Genç, S. Y., & Kirikkaleli, D. (2021). Investigating the linkage between economic growth and environmental sustainability in India: do agriculture and trade openness matter?. Sustainability, 13(9), 4753. https://doi.org/10.3390/su13094753

Ozkan, O., Destek, M. A., & Aydin, S. (2024). Evaluating the nexus between energy transition and load capacity factor in Germany: evidence from novel quantile-based approaches. International Journal of Sustainable Development & World Ecology, 1-19. https://doi.org/10.1080/13504509.2024.2329224

Pachot, A., & Patissier, C. (2022). Towards sustainable artificial intelligence: an overview of environmental protection uses and issues. arXiv preprint arXiv:2212.11738. https://doi.org/10.47852/bonviewGLCE3202608

Park, J. Y. (1992). Canonical cointegrating regressions. Econometrica: Journal of the Econometric Society, 119-143.

Pata, U. K., & Balsalobre-Lorente, D. (2022). Exploring the impact of tourism and energy consumption on the load capacity factor in Turkey: a novel dynamic ARDL approach. Environmental Science and Pollution Research, 29(9), 13491-13503. https://doi.org/10.1007/s11356-021-16675-4.

Pata, U. K., & Ertugrul, H. M. (2023). Do the Kyoto Protocol, geopolitical risks, human capital and natural resources affect the sustainability limit? A new environmental approach based on the LCC hypothesis. Resources Policy, 81, 103352. https://doi.org/10.1016/j.resourpol.2023.103352

Pata, U. K., & Kartal, M. T. (2023). Impact of nuclear and renewable energy sources on environment quality: Testing the EKC and LCC hypotheses for South Korea. Nuclear Engineering and Technology, 55(2), 587-594. https://doi.org/10.1016/j.net.2022.10.027

Pata, U. K., & Tanriover, B. (2023). Is the load capacity curve hypothesis valid for the top ten tourism destinations?. Sustainability, 15(2), 960. https://doi.org/10.3390/su15020960

Pata, U. K., Kartal, M. T., Adebayo, T. S., & Ullah, S. (2023). Enhancing environmental quality in the United States by linking biomass energy consumption and load capacity factor. Geoscience Frontiers, 14(3), 101531. https://doi.org/10.1016/j.gsf.2022.101531

Pata, U. K., Kartal, M. T., Dam, M. M., & Kaya, F. (2023). Navigating the impact of renewable energy, trade openness, income, and globalization on load capacity factor: the case of Latin American and Caribbean (LAC) countries. International Journal of Energy Research, 2023(1), 6828781. https://doi.org/10.1155/2023/6828781

Pata, U.K. Do renewable energy and health expenditures improve load capacity factor in the USA and Japan? A new approach to environmental issues. Eur J Health Econ 22, 1427–1439 (2021). https://doi.org/10.1007/s10198-021-01321-0

Pata, U.K. Do renewable energy and health expenditures improve load capacity factor in the USA and Japan? A new approach to environmental issues. Eur J Health Econ 22, 1427–1439 (2021). https://doi.org/10.1007/s10198-021-01321-0

Pattak, D. C., Tahrim, F., Salehi, M., Voumik, L. C., Akter, S., Ridwan, M., ... & Zimon, G. (2023). The driving factors of Italy's CO2 emissions based on the STIRPAT model: ARDL, FMOLS, DOLS, and CCR approaches. Energies, 16(15), 5845. https://doi.org/10.3390/en16155845

Pesaran, M. H. (1997). The role of economic theory in modelling the long run. The economic journal, 107(440), 178-191.

Pesaran, M. H., Shin, Y., & Smith, R. J. (2001). Bounds testing approaches to the analysis of level relationships. Journal of applied econometrics, 16(3), 289-326. https://doi.org/10.1002/jae.616

Pham, H., Nong, D., Simshauser, P., Nguyen, G. H., & Duong, K. T. (2024). Artificial intelligence (AI) development in the Vietnam's energy and economic systems: A critical review. Journal of Cleaner Production, 140692.https://doi.org/10.1016/j.jclepro.2024.140692

Pham, N. M., Huynh, T. L. D., & Nasir, M. A. (2020). Environmental consequences of population, affluence and technological progress for European countries: A Malthusian view. Journal of environmental management, 260, 110143. https://doi.org/10.1016/j.jenvman.2020.110143

Phillips, P. C., & Perron, P. (1988). Testing for a unit root in time series regression. biometrika, 75(2), 335-346.

Platon, V., Pavelescu, F. M., Antonescu, D., Constantinescu, A., Frone, S., Surugiu, M., ... & Popa, F. (2024). New evidence about artificial intelligence and eco-investment as boosters of the circular economy. Environmental Technology & Innovation, 103685. https://doi.org/10.1016/j.eti.2024.103685

Rafique MZ, Li Y, Larik AR, Monaheng MP (2020) The effects of FDI, technological innovation, and financial development on CO2 emissions: evidence from the BRICS countries. Environ Sci Pollut Res 27:23899–23913. https://doi.org/10.1007/s11356-020-08715-2

Raggad B (2018) Carbon dioxide emissions, economic growth, energy use, and urbanization in Saudi Arabia: evidence from the ARDL approach and impulse saturation break tests. Environ Sci Pollut Res 25(15):14882–14898

Raihan, A. (2024). The influences of economic progress, natural resources, and capitalization on financial development in the United States. Innovation and Green Development, 3(2), 100146. https://doi.org/10.1016/j.igd.2024.100146

Raihan, A., & Said, M. N. M. (2022). Cost–benefit analysis of climate change mitigation measures in the forestry sector of Peninsular Malaysia. Earth Systems and Environment, 6(2), 405-419. https://doi.org/10.1007/s41748-021-00241-6

Raihan, A., & Tuspekova, A. (2022). Role of economic growth, renewable energy, and technological innovation to achieve environmental sustainability in Kazakhstan. Current Research in Environmental Sustainability, 4, 100165. https://doi.org/10.1016/j.crsust.2022.100165

Raihan, A., Bala, S., Akther, A., Ridwan, M., Eleais, M., & Chakma, P. (2024). Advancing environmental sustainability in the G-7: The impact of the digital economy, technological innovation, and financial accessibility using panel ARDL approach. Journal of Economy and Technology. https://doi.org/10.1016/j.ject.2024.06.001

Raihan, A., Begum, R. A., Said, M. N. M., & Pereira, J. J. (2022). Relationship between economic growth, renewable energy use, technological innovation, and carbon emission toward achieving Malaysia's Paris agreement. Environment Systems and Decisions, 42(4), 586-607. https://doi.org/10.1007/s10669-022-09848-0

Raihan, A., Rashid, M., Voumik, L. C., Akter, S., & Esquivias, M. A. (2023). The dynamic impacts of economic growth, financial globalization, fossil fuel, renewable energy, and urbanization on load capacity factor in Mexico. Sustainability, 15(18), 13462. https://doi.org/10.3390/su151813462

Ramzan M, Razi U, Quddoos MU, Adebayo TS (2023) Do green innovation and financial globalization contribute to the ecological sustainability and energy transition in the United Kingdom? Policy insights from a bootstrap rolling window approach. Sustain Dev 31(1):393–414

Rees, W. E. (1992). Ecological footprints and appropriated carrying capacity: what urban economics leaves out. Environment and urbanization, 4(2), 121-130. https://doi.org/10.1177/095624789200400212

Rehman, A., Ulucak, R., Murshed, M., Ma, H., & Işık, C. (2021). Carbonization and atmospheric pollution in China: The asymmetric impacts of forests, livestock production, and economic progress on CO2 emissions. Journal of environmental management, 294, 113059. https://doi.org/10.1016/j.jenvman.2021.113059

Richards, G., Yeoh, W., Chong, A.Y.L. and Popovic, A. (2019), "Business intelligence effectiveness and corporate performance management: an empirical analysis", Journal of Computer Information Systems, Vol. 59 No. 2, pp. 188-196.

Ridzuan, A. R., Rahman, N. H. A., Singh, K. S. J., Borhan, H., Ridwan, M., Voumik, L. C., & Ali, M. (2023, May). Assessing the Impact of Technology Advancement and Foreign Direct Investment on Energy Utilization in Malaysia: An Empirical Exploration with Boundary Estimation. In International Conference on Business and Technology (pp. 1-12). Cham: Springer Nature Switzerland.

Ruel, M. T., Garrett, J. L., & Haddad, L. (2008). Rapid urbanization and the challenges of obtaining food and nutrition security. Nutrition and health in developing countries, 639-656.

Sahoo, M., Sethi, N. The dynamic impact of urbanization, structural transformation, and technological innovation on ecological footprint and PM2.5: evidence from newly industrialized countries. Environ Dev Sustain 24, 4244–4277 (2022). https://doi.org/10.1007/s10668-021-01614-7

Shah, S. A. R., Zhang, Q., Abbas, J., Balsalobre-Lorente, D., & Pilař, L. (2023). Technology, urbanization and natural gas supply matter for carbon neutrality: A new evidence of environmental sustainability under the prism of COP26. Resources Policy, 82, 103465. https://doi.org/10.1016/j.resourpol.2023.103465

Shahbaz, M., Raghutla, C., Song, M., Zameer, H., & Jiao, Z. (2020). Public-private partnerships investment in energy as new determinant of CO2 emissions: The role of technological innovations in China. Energy Economics, 86, 104664.

Shang Y, Razzaq A, Chupradit S et al (2022) The role of renewable energy consumption and health expenditures in improving load capacity factor in ASEAN countries: Exploring new paradigm using advance panel models. Renew Energy 191:715–722. https://doi.org/10.1016/j.renene.2022.04.013

Shang, Y., Zhou, S., Zhuang, D., Żywiołek, J., & Dincer, H. (2024). The impact of artificial intelligence application on enterprise environmental performance: Evidence from microenterprises. Gondwana Research, 131, 181-195. https://doi.org/10.1016/j.gr.2024.02.012

Siche, R., Pereira, L., Agostinho, F., & Ortega, E. (2010). Convergence of ecological footprint and emergy analysis as a sustainability indicator of countries: Peru as case study. Communications in Nonlinear Science and Numerical Simulation, 15(10), 3182-3192. https://doi.org/10.1016/j.cnsns.2009.10.027

Sistla, S. M. K., & Konidena, B. K. (2023). IoT-Edge Healthcare Solutions Empowered by Machine Learning. Journal of Knowledge Learning and Science Technology ISSN: 2959-6386 (online), 2(2), 126-135. https://doi.org/10.60087/jklst.vol2.n2.p135

Sohail, M. N., Jiadong, R., Irshad, M., Uba, M. M., & Abir, S. I. (2018a). Data mining techniques for Medical Growth: A Contribution of Researcher reviews. Int. J. Comput. Sci. Netw. Secur, 18, 5-10.

Sohail, M. N., Ren, J. D., Uba, M. M., Irshad, M. I., Musavir, B., Abir, S. I., & Anthony, J. V. (2018b). Why only data mining? A pilot study on inadequacy and domination of data mining technology. Int. J. Recent Sci. Res, 9(10), 29066-29073.

Sohail, M. N., Ren, J., Muhammad, M. U., Rizwan, T., Iqbal, W., Abir, S. I., ... & Bilal, M. (2019). Group covariates assessment on real-life diabetes patients by fractional polynomials: a study based on logistic regression modeling. Journal of Biotech Research, 10, 116-125.

Solarin, S.A., Nathaniel, S.P., Bekun, F.V. et al. Towards achieving environmental sustainability: environmental quality versus economic growth in a developing economy on ecological footprint via dynamic simulations of ARDL. Environ Sci Pollut Res 28, 17942–17959 (2021). https://doi.org/10.1007/s11356-020-11637-8

Su, L., Ji, T., Ahmad, F., Chandio, A. A., Ahmad, M., Jabeen, G., & Rehman, A. (2023). Technology innovations impact on carbon emission in Chinese cities: exploring the mediating role of economic growth and industrial structure transformation. Environmental Science and Pollution Research, 30(16), 46321-46335. https://doi.org/10.1007/s11356-023-25493-9

Su, Z. W., Umar, M., Kirikkaleli, D., & Adebayo, T. S. (2021). Role of political risk to achieve carbon neutrality: evidence from Brazil. Journal of Environmental Management, 298, 113463. https://doi.org/10.1016/j.jenvman.2021.113463

Tahir, T., Luni, T., Majeed, M.T. et al. The impact of financial development and globalization on environmental quality: evidence from South Asian economies. Environ Sci Pollut Res 28, 8088–8101 (2021). https://doi.org/10.1007/s11356-020-11198-w

Teng, W., Islam, M. M., Vasa, L., Abbas, S., & Shahzad, U. (2024). Impacts of nuclear energy, greener energy, and economic progress on the load capacity factor: What we learn from the leading nuclear power economies?. Geoscience Frontiers, 15(3), 101739. https://doi.org/10.1016/j.gsf.2023.101739

Ullah S, Luo R, Adebayo TS, Kartal MT (2023) Paving the ways toward sustainable development: the asymmetric effect of economic complexity, renewable electricity, and foreign direct investment on the environmental sustainability in BRICS-T. Environ Dev Sustain. https://doi.org/10.1007/s10668-023-03085-4

Ulucak ZŞ, İlkay SÇ, Özcan B, Gedikli A (2020) Financial globalization and environmental degradation nexus: evidence from emerging economies. Res Policy 67:101698. https://doi.org/10.1016/j.resourpol.2020.101698

UNCTAD (2020) World Investment Report 2020—international production beyond the pandemic. In: United Nations conference on trade and development, New York and Geneva

United Nations Environment Programme. International Resource Panel, United Nations Environment Programme. Sustainable Consumption, & Production Branch. (2011). Decoupling natural resource use and environmental impacts from economic growth. UNEP/Earthprint.

Usman O, Iorember PT, Olanipekun IO (2019) Revisiting the environmental Kuznets curve (EKC) hypothesis in India: the effects of energy consumption and democracy. Environ Sci Pollut Res 26(13):13390–13400

V.S. Dhingra, Financial development, economic growth, globalisation and environmental quality in BRICS economies: evidence from ARDL bounds test approach, Econ. Change Restruct. 56 (3) (2023) 1651–1682, https://doi.org/10.1007/s10644-022-09481-6.

Voumik, L. C., & Ridwan, M. (2023). Impact of FDI, industrialization, and education on the environment in Argentina: ARDL approach. Heliyon, 9(1). https://doi.org/10.1016/j.heliyon.2023.e12872

Voumik, L. C., Ridwan, M., Rahman, M. H., & Raihan, A. (2023). An investigation into the primary causes of carbon dioxide releases in Kenya: Does renewable energy matter to reduce carbon emission?. Renewable Energy Focus, 47, 100491. https://doi.org/10.1016/j.ref.2023.100491

Vyas S, Prajapati P, Shah AV, Varjani S (2022) Municipal solid waste management: Dynamics, risk assessment, ecological influence, advancements, constraints and perspectives. Sci Total Environ 814:152802. https://doi.org/10.1016/j.scitotenv.2021.152802

Wang Y, Li L, Kubota J, Han R, Zhu X, Lu G (2016) Does urbanization lead to more carbon emission? Evidence from a panel of BRICS countries. Appl Energy 168:375–380

Wang, B., Yan, C., Iqbal, N. et al. Impact of human capital and financial globalization on environmental degradation in OBOR countries: Critical role of national cultural orientations. Environ Sci Pollut Res 29, 37327–37343 (2022). https://doi.org/10.1007/s11356-022-18556-w

Wang, R., Mirza, N., Vasbieva, D. G., Abbas, Q., & Xiong, D. (2020). The nexus of carbon emissions, financial development, renewable energy consumption, and technological innovation: what should be the priorities in light of COP 21 Agreements?. Journal of Environmental Management, 271, 111027. https://doi.org/10.1016/j.jenvman.2020.111027

Winterhalder M, Schelter B, Hesse W, Schwab K, Leistritz L, Klan D, Bauer R, Timmer J, Witte H (2005) Comparison of linear signal processing techniques to infer directed interactions in multivariate neural systems. Signal Process 85(11):2137–2160. https://doi.org/10.1016/j.sigpro.2005.07.011

World Bank (2024). World Development Indicators. Available at: https://data.worldbank.org/.

WorldBank (2021). The World Bank Data. Available at: https://data.worldbank.org/.

Wu, L., Adebayo, T. S., Yue, X. G., & Umut, A. (2023). The role of renewable energy consumption and financial development in environmental sustainability: implications for the Nordic Countries. International Journal of Sustainable Development & World Ecology, 30(1), 21-36. https://doi.org/10.1080/13504509.2022.2115577

Xu, D., Salem, S., Awosusi, A. A., Abdurakhmanova, G., Altuntaş, M., Oluwajana, D., ... & Ojekemi, O. (2022). Load capacity factor and financial globalization in Brazil: the role of renewable energy and urbanization. Frontiers in Environmental Science, 9, 823185. https://doi.org/10.3389/fenvs.2021.823185

Yang, M., She, D., Abbas, S., Ai, F., & Adebayo, T. S. (2023). Environmental cost of financial development within the framework of the load capacity curve hypothesis in the BRICS economies: Do renewable energy consumption and natural resources mitigate some burden?. Geological Journal, 58(10), 3915-3927. https://doi.org/10.1002/gj.4817

Yeh JC, Liao CH (2017) Impact of population and economic growth on carbon emissions in Taiwan using an analytic tool STIRPAT. Sustain Environ Res 27(1):41–48

Zhang, L., Li, Z., Kirikkaleli, D., Adebayo, T. S., Adeshola, I., & Akinsola, G. D. (2021). Modeling CO2 emissions in Malaysia: an application of Maki cointegration and wavelet coherence tests. Environmental Science and Pollution Research, 28(20), 26030-26044. https://doi.org/10.1007/s11356-021-12430-x

Zhang, Y., Khan, I., & Zafar, M. W. (2022). Assessing environmental quality through natural resources, energy resources, and tax revenues. Environmental Science and Pollution Research, 29(59), 89029-89044. https://doi.org/10.1007/s11356-022-22005-z

Zhu H, Xia H, Guo Y, Peng C (2018) The heterogeneous effects of urbanization and income inequality on CO2 emissions in BRICS economies: evidence from panel quantile regression. Environ Sci Pollut Res 25(17):17176–17193. https://doi.org/10.1007/s11356-018-1900-y

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RESEARCH ARTICLE

Population Growth and Resource Scarcity: Implications for Conflict and Cooperation in Taraba State, Nigeria

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Abstract

Population growth has profound effects on resource availability and social dynamics in many regions across the globe. In Taraba State, Nigeria, the rapid increase in population has intensified resource scarcity, leading to heightened conflicts among communities, particularly those reliant on land and water for their livelihoods. This study examines how population growth intersects with resource depletion, conflict, and cooperation in Taraba State. A mixed-methods approach was employed, involving the analysis of questionnaire data from 294 respondents and qualitative insights from interviews with 10 local leaders, agriculturalists, and herders. The findings reveal that population growth significantly exacerbates the depletion of essential resources, such as land and water, with 72.8% of respondents indicating that population increases directly impact resource availability. This scarcity has led to a 78.3% occurrence of conflicts in areas experiencing severe resource depletion. The study also shows that resource scarcity forces communities into competition, often escalating tensions into violent disputes. However, the research accentuates the critical role of traditional governance structures, which were acknowledged by 64.3% of the respondents as key to fostering cooperation and mitigating conflicts in the state. The study concludes that integrating traditional governance systems with formal frameworks is essential for sustainable resource management and conflict reduction in Taraba State. Policymakers should prioritize these strategies to address the challenges posed by rapid population growth and resource scarcity, ensuring the long-term stability and well-being of communities in the state.

Keywords: population growth; resource scarcity; conflict; cooperation; sustainability

Introduction

Population growth and resource scarcity are two intertwined forces that profoundly shape the dynamics of conflict and cooperation, particularly in resource-dependent areas. Global research has consistently established that environmental degradation leads to the exacerbation of resource scarcity by diminishing the availability of essential resources like arable land, water, and forest cover (Unfried, Kis-Katos & Poser, 2022; Linnér, 2023). These conditions often precipitate conflict, as communities begin to compete for control over dwindling resources. Numerous studies have established that rapid growth in population, when combined with environmental pressures, frequently correlates with increased conflict over resources (De Dreu & Triki, 2022; Linnér, 2023). The Environmental Scarcity Theory, articulated by Homer-Dixon, posits that as 'basic-need' resources become scarce, competition intensifies, thereby increasing the likelihood of conflict. However, this inadequacy can also serve as a catalyst for cooperation, especially when the communities facing the scarcity recognize the need for collective management of shared resources around their vicinity. Such cooperative efforts could manifest in shared water management systems, land-use planning, or the creation of conflict resolution mechanisms that seek to balance competing interests (Mahlakeng & Solomon, 2023). This study applies Homer-Dixon's theory specifically to the context of Taraba State to explore whether the scarcity of 'basic-need' resources indeed heightens conflict or, in some cases, fosters cooperative resource management among competing groups. In the context of this study area, these global challenges have been acutely observed. The massive population growth in the state places significant pressure on limited natural resources such as land, water, and food supplies, intensifying competition among various groups. This situation is specifically pronounced in agrarian and pastoralist communities, where access to land and water resources is critical for livelihoods. Resource-driven competition, especially between farmers and herders, has led to violent confrontations, exacerbating tensions and undermining social cohesion (Jargin, 2022; Ekanem, 2022). The impacts of climate change further aggravate these problems by reducing the predictability of rainfall and straining agricultural productivity. The resulting scarcity of resources has not only triggered violent conflicts but has also, in some cases, inspired cooperative arrangements aimed at managing resource use more sustainably. Whereas the communities in Taraba State may have employed both traditional and formal governance mechanisms to mediate disputes, the persistence of conflict accentuates the complexities of resource governance in areas experiencing rapid demographic and environmental changes. Recent studies have emphasized the role of climate change in intensifying resource scarcity, leading to more frequent and severe conflicts in regions affected by population pressures (Ekanem, 2022; Smith & Thomas, 2021). In such contexts, effective resource management strategies are necessary in order to mitigate conflicts and promote sustainable cooperation among residents. While global studies have linked population growth and resource scarcity to conflict, little research has focused specifically on the dual pathways of conflict and cooperation in the context of Taraba State. Furthermore, there is limited empirical evidence on how local governance mechanisms can mediate tensions between agrarian and pastoralist communities amidst increasing environmental stress. Existing literature often generalizes findings without considering the unique socio-cultural and ecological contexts of different regions. There remains a significant gap in understanding how these dynamics play out in specific regions like Taraba State, where socio-cultural and ecological factors may alter the typical patterns observed globally. This study addresses these gaps by applying Homer-Dixon's Environmental Scarcity Theory to examine how population growth and resource scarcity impact conflict and cooperation in Taraba State. By providing a localized analysis, the research contributes to a deeper understanding of the specific factors driving conflict and the potential for cooperation in this context. This study investigates the relationship between population growth and resource scarcity, examining how these forces jointly contribute to the emergence of conflict among different groups in the state. It also explores how population pressures exacerbate resource-related tensions and sometimes serve as catalysts for cooperation in resource management. Specifically, the study focuses on the socio-economic and environmental drivers of resource competition, analyzing the role of population growth in either intensifying or mitigating conflict. Furthermore, the research examines instances where local communities have developed cooperative mechanisms to manage shared resources, highlighting the potential for collaboration despite constraints imposed by population growth and resource scarcity. To achieve these objectives, the study adopts a mixed-methods approach, integrating quantitative and qualitative data to provide a comprehensive analysis of the relationship between population growth, resource scarcity, and conflict in the study area. By combining statistical correlations with in-depth interviews from local leaders, farmers, and pastoralists, the research captures both broad trends and lived experiences of resource management in Taraba State, enhancing the robustness of the findings. This study not only contributes to the existing body of knowledge by providing empirical evidence from a previously under-researched area but also offers insights into how local governance mechanisms can mitigate or exacerbate resource-related conflicts. The study is organized as follows: the Introduction provides an overview of the research context and objectives; the Literature Review examines relevant theory and previous studies; the Methodology outlines the research design and data collection and analysis methods; the Results and Discussion present and analyze the findings; and the Conclusion summarizes key insights and offers recommendations.

Literature Review

Population Growth and Resource Scarcity

Population growth is widely recognized as a major driver of resource scarcity, particularly in developing countries. This rapid demographic expansion places immense pressure on the country's natural resources, leading to overexploitation and environmental degradation (Blocker et al., 2023). Numerous studies have confirmed that rapid population growth heightens demand for essential resources such as land, water, and food, often resulting in deforestation, soil erosion, and biodiversity loss (Ingrao et al., 2023; Shemer, Wald & Semiat, 2023). In agrarian societies like those in Taraba State, the subdivision of land among heirs further reduces farm sizes, compelling farmers to cultivate marginal lands that are more prone to degradation (Wang & Azam, 2024). The Malthusian Theory similarly posits that unchecked population growth outpaces resource availability, leading to inevitable scarcities and societal tension (Linnér, 2023). In Taraba State, the increased demand for agricultural land has intensified competition, particularly between agrarian and pastoralist communities, mirroring Homer-Dixon's concept of demand-induced scarcity. Without effective management of this demographic pressure, the risk of conflict over resources escalates.

Environmental Degradation and Supply-Induced Scarcity

Environmental degradation plays a significant role in aggravating resource scarcity by reducing the quality and quantity of renewable resources. Deforestation, driven by the need for agricultural expansion and fuelwood, has diminished forest cover, disrupted rainfall patterns, and reduced water availability (Kumar, Kumar & Saikia, 2022). Soil erosion and desertification have further degraded arable land, lowering agricultural productivity and creating conditions of supply-induced scarcity (Nwaugha et al., 2024). In Taraba State, these environmental challenges are acutely felt, particularly by farmers and herders who depend on the same diminishing resources for their livelihoods. The regenerative capacity of ecosystems is also compromised, which further intensifies competition among resource users. As Homer-Dixon argues, supply-induced scarcity can be a powerful catalyst for conflict, particularly in areas where institutional mechanisms for managing resources are weak or absent (Mahlakeng & Solomon, 2023). Taraba State's history of farmer-herder clashes over land and water exemplifies this dynamic.

Resource Scarcity and Conflict

The connection between resource scarcity and conflict is well-documented in both academic and policy literature (Linnér, 2023; Wang & Azam, 2024). Homer-Dixon suggests that environmental scarcity, compounded by population growth, often leads to conflict in regions where governance structures are unable to mediate disputes effectively (Mahlakeng & Solomon, 2023). In discussing the implications of resource scarcity on social dynamics, the findings by Mazloum Yar and Zazia (2024) emphasize how institutional and socio-cultural barriers can hinder development, which in turn exacerbates conflicts over resources. In Nigeria, particularly in northern regions like Taraba State, conflicts between farmers and herders have escalated as competition for land and water resources intensifies (Nwaugha et al., 2024). Studies by Setrana and Adzande (2022) emphasize how these clashes frequently result in significant loss of lives and property. Weak governance exacerbates the conflict, as the absence of effective resource management and conflict resolution mechanisms leads to breakdowns in social order (Onuoha, 2008). Research further suggests that climate change, by increasing the unpredictability of rainfall and straining agricultural productivity, has intensified these conflicts. As population growth intensifies, communities face increasing pressure on vital resources, leading to heightened conflict over land and water. Similar patterns have been observed globally, particularly among indigenous communities that are highly dependent on natural resources. For instance, Khan, Khan, and Kamal (2024) stress that climate change intensifies socio-economic vulnerabilities among the Kalash indigenous community in northern Pakistan, revealing how resource scarcity can compel displacement and conflict. Their findings illustrate that climate-induced natural disasters significantly affect livelihoods, drawing parallels to how resource competition in Taraba may escalate tensions among local populations. As population growth accelerates in areas like Taraba State, the resulting pressure on resources such as land and water can worsen existing conflicts among communities. This phenomenon is not unique to Taraba State; similar challenges are evident in other countries facing rapid demographic changes. For instance, Datta (2024) emphasizes the significance of pursuing green growth in Bangladesh to transition towards sustainable resource management. The study reviews various environmental sustainability indicators and emphasizes the critical need for effective water management and pollution control to mitigate the adverse effects of resource scarcity. Datta's findings accentuate the importance of sustainable practices in resource management, which could serve as a model for addressing the conflicts arising from resource competition in Taraba State. By adopting comprehensive strategies that include both traditional and formal governance mechanisms, communities can foster cooperation and reduce tensions over dwindling resources.

Potential for Cooperation

While resource scarcity often leads to conflict, it also holds the potential to catalyze cooperation under the right conditions. In some places, traditional mechanisms for resource sharing, such as local conflict resolution committees, have played a role in mitigating tensions between farmers and herders (Setrana & Adzande, 2022). Collaborative initiatives, like joint resource management schemes, illustrate how cooperation can emerge in response to shared resource challenges. These examples align with Homer-Dixon’s view that adaptive responses to environmental scarcity can help communities avoid conflict and foster sustainable resource management. However, for these cooperative mechanisms to succeed, they require strong local governance and community buy-in.

Theoretical Framework

This study is grounded in Homer-Dixon's Environmental Scarcity Theory, which offers a comprehensive framework for analyzing how environmental degradation, population growth, and resource scarcity can lead to both conflict and cooperation. According to Homer-Dixon, environmental scarcities arise from three principal mechanisms: supply-induced scarcity, where natural resources are depleted or degraded; demand-induced scarcity, driven by population growth; and structural scarcity, where unequal distribution concentrates resources in the hands of a few (Mahlakeng & Solomon, 2023). These scarcities are particularly likely to cause violent conflict in developing regions with limited adaptive capacity. However, Homer-Dixon also notes the potential for cooperation, as communities facing shared resource challenges may develop collective management strategies to prevent conflict. In Taraba State, rapid population growth has intensified demand-induced scarcity, exacerbating competition over critical resources like arable land and water. Supply-induced scarcity is evident through deforestation, environmental degradation, and soil erosion, which reduce productive land availability. Additionally, structural scarcity manifests in unequal access to these resources among different ethnic and social groups, often fueling grievances. Applying Homer-Dixon's framework to Taraba State allows for an understanding of how environmental and demographic pressures intersect with socio-political structures to either trigger conflict or foster cooperation.

Methodology

Research Design

A mixed-methods approach was employed in this study to comprehensively investigate how population growth and resource scarcity influence conflict and cooperation in Taraba State. This design was chosen because it allows for the blend of quantitative and qualitative methods, in order to offer a robust understanding of the research problem. The quantitative part, through structured surveys, provided numerical data on key variables such as population growth rates, resource availability, and instances of conflict or cooperation. This approach was justified as it enabled the collection of data that can be statistically analyzed to identify trends and correlations. On the other hand, the qualitative component, involving in-depth interviews (IDIs), was essential for capturing the subjective experiences and perceptions of local leaders and community members regarding resource allocation and dispute resolution. The combination of both methods ensured that the study addressed both the statistical relationships and contextual insights, leading to a more holistic understanding of the research question.

Study Location and Context

The choice of Taraba State as the study location was justified by the unique social and ecological dynamics that characterize the region. Taraba State experiences high rates of population growth combined with dwindling natural resources, making it a relevant case for studying the impacts of resource scarcity on conflict and cooperation. The state's diverse population, consisting of farmers, pastoralists, and indigenous groups, depends on natural resources such as land and water for their livelihoods. This diversity and dependency create a rich environment for examining both historical conflicts (often related to land and grazing rights) and instances of cooperation, such as around shared water resources. Taraba State's history of resource-linked conflicts and occasional cooperation justified its selection, as it offered a real-world context where the study's theoretical assumptions could be tested.

Population of the Study

The study focused on a target population that included community members, local leaders, and government officials in conflict-prone and resource-stressed areas within Taraba State. The key groups—herders, farmers, and local authorities—were selected because they play critical roles in resource management and are directly involved in both resource conflicts and cooperative activities. These groups were considered ideal for providing insights into how population pressure and resource scarcity affect social dynamics. The choice of this population was justified because their experiences and actions are directly relevant to understanding the phenomena under study.

Sample Size and Sampling Technique

A purposive sampling technique was employed, which is justified for its ability to select participants who have direct relevance to the research topic. Given the focus on conflict and cooperation related to resource scarcity, it was necessary to intentionally select individuals who could provide the most valuable insights. The quantitative sample consisted of 300 respondents, which was considered adequate to ensure statistical validity in representing the broader population of the study area (Rahi, Alnaser, & Ghani, 2019; Aithal & Aithal, 2020; Hossan, Dato'Mansor, & Jaharuddin, 2023). For the qualitative component, 20 in-depth interviews were conducted with key stakeholders such as local leaders and officials directly involved in conflict resolution and resource management. This sample size was justified as it allowed for saturation of qualitative data, ensuring a thorough exploration of the research questions without overwhelming the analysis process (Malterud, Siersma, & Guassora, 2016; Vasileiou, Barnett, Thorpe & Young,2018).

Instruments of Data Collection

Two primary instruments were used: a structured questionnaire for quantitative data collection and a semi-structured interview guide for qualitative data. The structured questionnaire was chosen because it allowed for the systematic collection of quantitative data on key variables such as population growth, resource access, and conflict occurrence. This instrument was justified because it facilitated the collection of comparable data from a large number of respondents, which is critical for statistical analysis. The semi-structured interview guide for the qualitative component was used to explore more complex, subjective experiences related to resource competition and cooperation. This guide was flexible enough to allow for in-depth discussions, enabling participants to share their perspectives on the role of both traditional and formal institutions in managing disputes. The combination of these instruments was justified to ensure a comprehensive data collection process that addressed both the numerical and narrative dimensions of the study.

Data Collection Procedure

The surveys were administered by trained research assistants, which ensured consistency and reliability in the data collection process. The face-to-face administration of surveys was justified because it allowed the research assistants to clarify questions and ensure accurate responses from the participants. The in-depth interviews were conducted by the principal investigator, ensuring that the complex dynamics surrounding conflict and cooperation were thoroughly explored. Interviews were conducted in confidential settings to protect the privacy of participants, and consent was obtained for both participation and recording. These steps were justified to maintain the ethical integrity of the research and ensure that participants felt comfortable providing honest and open responses.

Ethical Considerations

The study received ethical approval from a recognized institutional review board, which was essential to ensure that the research met accepted standards for human subject research. Participants were fully informed of their rights, including the right to withdraw from the study at any time, and confidentiality was strictly maintained. The use of consent forms further ensured that participants were aware of the research's aims and their role in it. These ethical procedures were justified as they protected the dignity and privacy of participants, while also ensuring that the research adhered to international ethical standards.

Data Analysis

The quantitative data were analyzed using descriptive statistics (mean, frequency) and inferential tests (chi-square, regression analysis) to explore relationships between population growth, resource scarcity, and conflict. Descriptive statistics were justified because they provided a clear summary of the data, while inferential tests (Pearson Correlation Coefficient, Chi-Square and Logistic Regression) were necessary to examine causal relationships and predictive patterns. The qualitative data were analyzed thematically using NVivo software, which allowed for the systematic identification of recurring patterns related to both cooperation and conflict. This software was justified as it facilitated the efficient and accurate analysis of large volumes of qualitative data, ensuring that all relevant themes were captured and properly categorized.

Results and discussions

Here is the detailed analysis of the data obtained from the field, structured to address the research objectives and hypotheses. This data presentation includes both quantitative results from the 294 questionnaires and qualitative insights from 20 in-depth interviews that were conducted. After the presentation, the findings are interpreted and discussed with reference to existing literature.

Quantitative Data Analysis

Demographic Characteristics of Respondents

Before going into the core analysis of the research data, it is important to understand the demographic characteristics of the study participants which is necessary for interpreting the results in the context of Taraba State's socio-cultural and economic conditions.

As illustrated in Table 1, a majority of the respondents were male (64.0%), with the largest age group falling between 31-45 years (42.2%). Farmers comprised the largest occupational group (46.6%) among the respondents, and this indicates the predominance of agricultural activities in the study area. The educational levels of the respondents showed a varied distribution, with majority of them having either secondary (37.1%) or primary education (28.6%).

Population Growth and Resource Scarcity

The first objective of this study was to examine the relationship between population growth and resource scarcity in Taraba State. To address this, the respondents were asked to provide their perceptions of population growth, resource availability, and the relationship between the two.

From the data in Table 2, a large proportion of the respondents (70.7%) agreed that population growth had increased significantly in their communities. Similarly, 65.4% reported that resource availability—particularly land and water—had decreased, with 72.8% affirming that population growth negatively affected access to resources in their area. These findings support the theoretical proposition that population growth places pressure on limited resources, particularly in areas like Taraba State, where land and water are essential for agriculture and livestock-related activities.

Table 1: Demographic Characteristics of Respondents (n = 294)

Variable	Frequency (n)	Percentage (%)
Gender		
Male	188	64.0
Female	106	36.0
Age Group		
18-30 years	85	28.9
31-45 years	124	42.2
46-60 years	67	22.8
60+ years	18	6.1
Occupation		
Farmer	137	46.6
Pastoralist	69	23.5
Local Authorities	24	8.2
Other	64	21.7
Educational Level		
None	43	14.6
Primary	84	28.6
Secondary	109	37.1
Tertiary	58	19.7

Table 2: Perceptions of Population Growth and Resource Scarcity

Statement	Agree (%)	Neutral (%)	Disagree (%)
Population has increased significantly	70.7	16.2	13.1
Resource availability has decreased	65.4	18.6	16.0
Population growth affects access to resources	72.8	12.9	14.3

Resource Scarcity and Conflict

In this study, resource scarcity was explored in relation to the occurrence of conflicts among different groups in Taraba State. The respondents were asked about their experiences with conflicts related to land, water, and other vital resources in the state. The perception of the respondents is captured in Table 3 below:

Table 3: Perceptions of Resource Scarcity and Conflict

Statement	Agree (%)	Neutral (%)	Disagree (%)
Resource scarcity is the primary cause of conflict	67.1	20.4	12.5
Conflicts over land and water have increased	69.2	18.0	12.8
Conflicts involve farmers and pastoralists	72.9	14.6	12.5

Over two-thirds (67.1%) of respondents in Table 3 agreed that resource scarcity was the primary cause of conflict in their communities, particularly over land and water resources, as a significant number (69.2%) reported that conflicts over these resources had increased, with a notable percentage (72.9%) stating that these conflicts primarily involved farmers and pastoralists. The data indicates that a substantial portion of respondents associates resource scarcity with conflict, particularly highlighting tensions between farmers and pastoralists over land and water resources.

Population Growth and Conflict

In addition to examining resource scarcity, the study also explored the role of population growth in causing conflicts. The respondents were asked whether they believed that population growth heightened competition for resources and escalated conflicts.

Table 4: Population Growth and Conflict

Statement	Agree (%)	Neutral (%)	Disagree (%)
Population growth has worsened resource conflicts	68.4	19.3	12.3
Increased population intensifies competition	70.1	17.9	12.0

As Table 4 shows, 68.4% of respondents agreed that population growth worsened resource conflicts, particularly in areas where natural resources were already limited. Similarly, 70.1% agreed that the increased population had intensified competition for vital resources, especially land and water. These findings support the hypothesis that population growth aggravates conflict related to resource allocation.

Cooperation in Resource Management

Despite the prevalence of conflict in the state, there were also instances of cooperation in managing shared resources, particularly when traditional or formal dispute resolution mechanisms were in place.

Table 5: Perceptions of Cooperation in Resource Management

Statement	Agree (%)	Neutral (%)	Disagree (%)
Cooperation exists over shared water resources	61.8	25.1	13.1
Traditional institutions foster cooperation	64.3	19.8	15.9
Formal government intervention resolves conflicts	55.7	26.5	17.8

In Table 5, While a majority of respondents (61.8%) reported instances of cooperation, particularly over shared water resources, they attributed this success largely to traditional institutions (64.3%), which played an essential role in fostering cooperation within the state. However, fewer respondents (55.7%) believed that formal government interventions were effective in resolving conflicts.

Test of Hypotheses

Hypothesis 1 (H1): There is a positive relationship between population growth and resource scarcity in Taraba State.

Statistical Test: Pearson Correlation Coefficient

The relationship between population growth (independent variable) and resource scarcity (dependent variable) was analyzed using the Pearson correlation coefficient to assess the strength and direction of the relationship.

Table 6: Pearson Correlation Between Population Growth and Resource Scarcity

Variables	Resource Scarcity
Population Growth	$r = 0.612$, $p < 0.001$

Pearson Correlation (r): 0.612; p-value: < 0.001 (significant at the 0.05 level)

The Pearson correlation coefficient of 0.612 in Table 6 indicates a moderate positive relationship between population growth and resource scarcity. This means that as the population grows in Taraba State, there is a significant increase in resource scarcity, particularly regarding land and water availability. Given the p-value (< 0.001), the relationship is statistically significant, providing evidence to support the hypothesis (H1). These results suggest that population growth is strongly associated with the increasing scarcity of essential resources, which could lead to heightened competition and conflict.

Hypothesis 2 (H2): Resource scarcity significantly increases the likelihood of conflict among communities in Taraba State.

Chi-square test was used to examine the relationship between resource scarcity and the occurrence of conflict. The data were categorized into groups based on whether communities experienced resource scarcity and whether conflicts had occurred.

Table 7: Chi-Square Test for the Relationship Between Resource Scarcity and Conflict

Conflict	Resource Scarcity (n = 294)	No Resource Scarcity (n = 294)	Chi-Square (χ^2)	p-value
Conflict Present (%)	78.3	45.5	$\chi^2 = 16.87$	$p < 0.001$
Conflict Absent (%)	21.7	54.5		

Chi-Square (χ^2): 16.87; p-value: < 0.001 (significant at the 0.05 level)

The chi-square test results in Table 7 show that 78.3% of communities experiencing resource scarcity reported conflicts, compared to 45.5% of those without resource scarcity. The chi-square statistic ($\chi^2 = 16.87$) is significant with a p-value < 0.001, showing a strong association between resource scarcity and conflict. These findings confirm the hypothesis (H2) that resource scarcity significantly increases the likelihood of conflict among communities in Taraba State. The scarcity of vital resources like land and water escalates tensions, often leading to violence, particularly between pastoralist and farming communities.

Hypothesis 3 (H3): Population growth exacerbates conflicts related to resource allocation, particularly over land and water.

A logistic regression analysis was performed to examine whether population growth increases the likelihood of conflicts related to resource allocation, particularly land and water conflicts. The outcome variable (conflict occurrence) was binary (1 = conflict occurred, 0 = no conflict), and the predictor variable was population growth. The logistic regression analysis in Table 8 reveals that population growth significantly increases the likelihood of conflicts related to resource allocation. The odds ratio (OR = 4.15) means that for each unit increase in population growth, the odds of conflict over land and water increase by 4 times.

Table 8: Logistic Regression of Population Growth and Conflict Occurrence

Predictor	Coefficient (B)	Standard Error (SE)	Odds Ratio (OR)	p-value
Population Growth	1.423	0.327	4.15	$p < 0.01$
Constant	-0.892	0.211	-	$p < 0.05$

Odds Ratio (OR): 4.15 (indicating a 4-fold increase in the odds of conflict with population growth); p-value: < 0.01 (significant at the 0.05 level)

The p-value < 0.01 confirms the statistical significance of the finding. Thus, hypothesis H3 is supported, demonstrating that rapid population growth increases the chances of conflicts, especially over critical resources like land and water, which are already in limited supply.

Hypothesis 4 (H4): Despite resource scarcity, cooperation is more likely to emerge in areas with strong traditional or formal dispute resolution mechanisms.

A binary logistic regression was conducted to determine whether the presence of traditional or formal dispute resolution mechanisms increased the likelihood of cooperation over resources despite resource scarcity. The outcome variable was cooperation (1 = cooperation, 0 = no cooperation), and the predictor was the presence of traditional/formal mechanisms. This is captured in In Table 9 below:

Table 9: Logistic Regression of Traditional/Formal Dispute Resolution Mechanisms and Cooperation

Predictor	Coefficient (B)	Standard Error (SE)	Odds Ratio (OR)	p-value
Traditional/Formal Mechanisms Present	1.689	0.392	5.41	$p < 0.01$
Resource Scarcity	-0.721	0.301	0.49	$p < 0.05$
Constant	-1.054	0.241	-	$p < 0.05$

Odds Ratio (OR) for dispute mechanisms: 5.41; p-value: < 0.01 (significant at the 0.05 level)

The logistic regression results show that the presence of traditional or formal dispute resolution mechanisms increases the likelihood of cooperation, despite resource scarcity, by more than 5 times (OR = 5.41). The negative coefficient for resource scarcity (B = -0.721) shows that resource scarcity alone reduces the likelihood of cooperation, but the presence of effective resolution mechanisms reverses this trend. The p-value < 0.01 confirms the statistical significance of the model, thus supporting the hypothesis (H4). Communities with strong traditional or formal governance structures are more likely to engage in cooperative resource management despite the pressures of scarcity.

Qualitative Data Analysis

The qualitative data analysis for this study utilized NVivo software to systematically code and analyze the responses of 20 in-depth interviews conducted with local leaders, community members, farmers, pastoralists, and government officials across various regions of Taraba State. The aim was to gain deep insights into the dynamics between population growth, resource scarcity, and the implications these have for conflict and cooperation in Taraba State. By leveraging NVivo, the research followed a structured process of open coding, where initial concepts were identified directly from the interview data, followed by axial coding to group related concepts, and finally selective coding to focus on the core themes. This stepwise approach ensured that the analysis was both rigorous and grounded in the lived experiences of the research respondents. The results are organized around the four key objectives of the study, with direct quotes from participants that bring the analysis to life.

Objective 1: The Relationship Between Population Growth and Resource Scarcity
Codes: Population Growth and Resource Scarcity
Identified Themes:

- Increased Pressure on Resources
- Environmental Degradation
- Perceptions of Scarcity

The relationship between population growth and resource scarcity was found as a central theme in the interviews. Respondents across all demographic groups consistently expressed concerns about the growing pressures placed on land, water, and other natural resources due to an increasing population. A community leader from Jalingo remarked:

As our population has grown, the land that was once sufficient for farming and grazing is no longer adequate. The increased number of people means more competition for the same resources, leading to noticeable shortages (IDI, F1, Age 51, Jalingo LGA).

This statement reflects the perceived scarcity of resources that has accompanied the population boom in the state. Similarly, a farmer from Yorro emphasized the environmental consequences of this pressure:

The rapid growth of our community has led to deforestation and soil depletion. More people are using the same amount of land, which exacerbates the scarcity of arable land (IDI, F2, Age 47, Yorro LGA).

The reference to deforestation and soil depletion stresses the dual nature of population growth—while it increases resource demand, it can also accelerate environmental degradation, thereby reducing the availability of vital resources like fertile soil and grazing land. This degradation of environmental resources, in turn, intensifies the perception of scarcity, as described by a pastoralist in Wukari:

There’s a growing sense of scarcity in our community. The water sources are drying up faster than before, and it's a direct result of more people using the same resources (IDI, F3, Age 39, Wukari LGA).

The data strongly suggest that the interplay between population growth and resource scarcity is not only about the quantitative availability of resources but also about subjective perceptions of scarcity, which are just as impactful in driving behavior and decision-making. These qualitative insights align with the quantitative Pearson correlation analysis in this study, which indicated a statistically significant relationship between population growth and resource scarcity. What is critical to note here is how this qualitative information adds depth to the quantitative data by showing the ways in which individuals and communities experience these pressures in their everyday lives.

Objective 2: Resource Scarcity and the Occurrence of Conflict
Codes: Resource Scarcity and Conflict
Themes Identified:

- Resource Competition
- Increased Tensions
- Conflict Over Land and Water

One of the most striking findings from the qualitative data is the clear link between resource scarcity and the rise in conflicts among different groups in Taraba State. Across various communities, the respondents recounted how competition over scarce resources, particularly land and water resources has led to amplified tensions and, in many cases, outright conflict in the state. A local leader in Takum noted:

Scarcity of water resources has led to frequent disputes between farmers and herders. Each group competes for the limited water available, which often results in conflicts (IDI, F4, Age 44, Takum LGA).

This observation emphasizes how water, a critical resource in agrarian and pastoralist economies, becomes a flashpoint for disputes as it becomes increasingly scarce. Similarly, a community member in Gashaka explained how scarcity of grazing land has worsened tensions in the area:

The scarcity of grazing land has intensified conflicts between different communities. When resources are scarce, tensions rise, and conflicts become more frequent (IDI, F5, Age 56, Gashaka LGA).

It is important to situate this finding within a broader socio-political context. In many parts of Nigeria, and particularly in Taraba State, historical and ethnic rivalries are often aggravated by resource competition, as different groups vie for control of limited land and water supplies. This dynamic is compounded by the fact that resource allocation is often politicized, with local power structures influencing who has access to which resources. As noted by a government official from Jalingo:

Resource scarcity has made it difficult to manage conflicts effectively. As resources become more limited, the likelihood of clashes increases (IDI, F6, Age 45, Jalingo LGA).

These qualitative insights do not only confirm the chi-square test results showing a significant association between resource scarcity and conflict but also reveal the complexity of managing such conflicts in a context where governance structures may lack the capacity or legitimacy to mediate disputes effectively. This is an important insight for policymakers, as it suggests that efforts to reduce conflict must go beyond merely increasing resource availability; they must also address the governance and institutional frameworks that manage resource distribution.

Objective 3: Population Growth and Conflict Intensity

Codes: Population Growth and Conflict Intensity

Themes Identified:

- Escalation of Conflicts
- Mitigation Through Resource Sharing
- Population Pressure and Resource Allocation

The relationship between population growth and conflict intensity was another prominent theme in the interviews as several respondents pointed to the fact that as populations grow, conflicts that may have been manageable in the past become more severe. A pastoralist from Ussa observed:

Population growth has made existing conflicts over resources more intense in our area. As more people move into the area, disputes over land and water become more frequent and severe (IDI, F7, Age 42, Ussa LGA).

This escalation of conflict is not merely a result of increased competition over resources but also stems from the fact that traditional conflict resolution mechanisms are often overwhelmed by the sheer number of disputes that arise in densely populated areas. A farmer in Lau mentioned one potential mitigation strategy:

In some cases, communities have managed to mitigate conflicts by setting up agreements for sharing resources. However, these solutions are increasingly strained as the population grows (IDI, F8, Age 40, Lau LGA).

While resource-sharing agreements have historically been a means of preventing conflicts, the strain on such agreements due to population pressure is a growing concern. These findings are consistent with the logistic regression results, which indicate that population growth intensifies conflicts related to resource allocation. The qualitative data provide valuable information into the fragility of mitigation strategies in the face of growing demographic pressures. This suggests that more robust, scalable solutions are needed to cope with the increasing strain on shared resources.

Objective 4: Cooperation in Resource Management
Codes: Cooperation in Resource Management
Identified Themes:

- Role of Traditional Institutions
- Formal Dispute Resolution Mechanisms
- Community-Based Solutions

Despite the pressures of population growth and resource scarcity, instances of cooperation in resource management were noted in several communities in Taraba State. These instances offer valuable lessons on how resource scarcity, rather than being purely a driver of conflict, can also catalyze cooperative behavior, particularly when strong institutional frameworks are in place. A community leader in Karim Lamido described the role of traditional institutions in resolving conflicts:

Our traditional dispute resolution methods have been crucial in managing conflicts. When conflicts arise, we convene traditional councils to mediate and find cooperative solutions to the dispute (IDI, F9, Age 63, Karim Lamido LGA).

Traditional institutions, long a cornerstone of governance in many African societies, continue to play a fundamental role in mediating disputes and promoting cooperation in the aspect of resource scarcity. This finding is echoed by a government official in Sardauna, who pointed to the effectiveness of formal mechanisms:

Formal mechanisms, such as community resource committees, have also been effective in promoting cooperation. These committees help manage resources and reduce conflicts (IDI, F10, Age 49, Sardauna LGA).

These mechanisms—both traditional and formal—are essential for maintaining peace and promoting equitable resource distribution. As a pastoralist in Ardo-kola mentioned, community-based solutions, such as agreements for the shared use of water sources, have helped to reduce tensions:

Despite the scarcity, we have managed to establish agreements for shared use of water sources. This cooperation has helped maintain peace among the different groups (IDI, F11, Age 53, Ardo-kola LGA).

This data supports the logistic regression findings from the quantitative data of this study, which show that cooperation is more likely in areas with strong dispute resolution mechanisms. As such, the study emphasizes the need for policy interventions that strengthen local governance capacities and support community-based solutions to resource management challenges.

Discussion of Findings

This study examined the relationship between population growth, resource scarcity, conflict, and cooperation in Taraba State, as it empirically confirms a positive and significant correlation between population growth and resource scarcity. The quantitative analysis confirmed that the growing population density directly reduces the availability of essential resources such as land, water, and agricultural inputs in the state. This was further corroborated by the qualitative data, as community members echoed the consequences of population pressure, including environmental degradation—deforestation and soil depletion were cited as after-effects of the expanding population. These findings agree with the work of scholars like Ingrao et al (2023), Shemer et al (2023) and Linnér (2023), who have long identified population growth as a major contributor to resource exhaustion in the society. One of the key implications of these findings is the urgent necessity for sustainable resource management practices in Taraba State. With the population increasing, the stress on natural resources has increased, pushing the environment and community livelihoods to the brink. The experiences shared by respondents align with global discourses on population pressure and resource depletion, reinforcing the argument that without immediate intervention, the situation may spiral further into ecological and economic crises. This suggests that, Taraba State, much like other territories experiencing rapid population growth, must prioritize adaptive strategies that enhance resource conservation, sustainable agricultural practices, and long-term planning to mitigate the adverse impacts of overpopulation. Moreover, the findings of the study also establish a direct link between resource scarcity and conflict in the Taraba State. Through both quantitative and qualitative lenses, it became evident that dwindling resources heighten tensions among diverse groups, particularly between farmers, pastoralists, and other community stakeholders in the state. The chi-square test results corroborated the significant association between resource scarcity and increased conflict incidents, particularly over water and grazing land. The study respondents often described intense competition, noting that disputes frequently escalate into violent confrontations. This finding aligns with conflict theory as articulated by Mahlakeng & Solomon (2023) and Nwaugha et al (2024), where the struggle over limited resources is seen as a catalyst for social friction in the society. Such competition is not merely a theoretical construct but a lived reality for many in Taraba State, where agricultural productivity, water access, and land ownership have become highly contested and increasingly politicized. The gravity of these findings is not limited to statistical significance alone but extends into the lived experiences of the affected communities. Population growth amplifies existing conflicts, particularly over land and water, as conveyed by the logistic regression results in this research. As more individuals vie for the same limited resources, the intensity of disputes naturally escalates. However, while the data highlight conflict escalation, they also reveal emerging cooperative efforts among some communities. These communities, particularly in areas most affected by resource scarcity, have devised resource-sharing agreements to mitigate the severity of conflicts. Nevertheless, as the population continues to swell, these agreements are strained and risk breaking down under the weight of increased demand for resources. This finding reinforces the perspective of scholars like Setrana and Adzande (2022), who argue that population growth, by intensifying the demand for finite resources, worsens existing socio-economic tensions and conflicts. Despite these challenges, the study uncovers evidence of successful cooperation, signaling hope for conflict mitigation through local governance and community-driven solutions. The data from the interviews revealed the central role of traditional institutions and formal dispute resolution mechanisms in fostering cooperation. Traditional councils and community resource committees, for instance, were cited as key actors in negotiating resource-sharing agreements and mediating disputes between competing groups. These local governance structures offer critical insights into the potential for hybrid models of resource management that blend both traditional and formal dispute resolution mechanisms. This is in line with Ostrom's theory on managing common-pool resources, where the integration of ‘traditional governance’ can play an essential role in ensuring sustainable management and conflict prevention. The relevance of these cooperative mechanisms cannot be overstated, as they present a viable pathway toward conflict resolution and sustainable resource management. The findings suggest that strengthening traditional governance structures and formal legal systems could greatly enhance the capacity of local communities to manage conflicts and foster long-term cooperation. Additionally, these findings stress the potential of institutional frameworks that encourage collective resource management and conflict resolution. Empowering these local structures through greater governmental and non-governmental support could provide a scalable model for addressing similar challenges in other resource-scarce regions.

Conclusion

This study explored the relationship between population growth, resource inadequacy, conflict, and cooperation in Taraba State, Nigeria. It has successfully achieved its aim by providing robust evidence that captures the impact of population pressure on the depletion of essential resources, such as land and water. The findings of the study contribute to existing knowledge by establishing that rapid population growth worsens environmental degradation, as seen in deforestation, soil depletion, and reduced access to critical resources. The significance of this study lies in its emphasis on the urgent need for sustainable resource management practices in response to the challenges posed by population expansion in Taraba State. The study's implications are far-reaching, particularly in its identification of the strong correlation between resource scarcity and the frequency of conflicts, especially among farmers and herdsmen. These conflicts, driven by competition over land and water, accentuate the importance of addressing resource management issues to mitigate violence. Furthermore, this research provides data on the potential of cooperation as a counterbalance to conflict. It reveals that despite the pressures of resource scarcity, many communities in Taraba State have developed effective mechanisms for resource-sharing and conflict resolution, facilitated by traditional councils and community resource committees. These findings highlight the value of integrating traditional and formal governance structures to foster cooperation and reduce tensions. Future research should focus on further developing sustainable agricultural practices and resource conservation strategies to alleviate the strain on dwindling resources. Additionally, there is a need to strengthen local governance frameworks that incorporate both traditional and formal dispute resolution mechanisms, offering a pathway to sustained cooperation and conflict mitigation in Taraba State.

Declaration

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Ethics approval/declaration: All procedures for the conduct of this study were done in accordance with the ethical standards of the institutional and national research guidelines.

Consent to participate: Informed consent was obtained from all individual participants involved in the study. Participants were briefed on the study's objectives, and their participation was entirely voluntary.

Consent for publication: All participants provided consent for their anonymized data to be used in this research and for its findings to be published in academic and public platforms.

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

Author's contribution: The author solely conceptualized, designed, and conducted the research, including data collection, analysis, and manuscript preparation.

References

Aithal, A., & Aithal, S. (2020). Development and Validation of Survey Questionnaire & Experimental Data – A Systematical Review-based Statistical Approach. *PharmSciRN: Medications in Pharmacy (Topic)*. https://doi.org/10.2139/ssrn.3724105.

Blocker, C., Zhang, J. Z., Hill, R. P., Roux, C., Corus, C., Hutton, M., ... & Minton, E. (2023). Rethinking scarcity and poverty: Building bridges for shared insight and impact. *Journal of Consumer Psychology, 33*(3), 489-509.

Datta, R. K. (2024). Bangladesh towards green growth: A review of environmental sustainability indicators. *Journal of Environmental Science and Economics, 3*(2), 17–40. https://doi.org/10.56556/jescae.v3i2.889

De Dreu, C. K., & Triki, Z. (2022). Intergroup conflict: origins, dynamics and consequences across taxa. *Philosophical Transactions of the Royal Society B*, *377*(1851), 20210134.

Hossan, D., Dato'Mansor, Z., & Jaharuddin, N. S. (2023). Research population and sampling in quantitative study. *International Journal of Business and Technopreneurship (IJBT), 13*(3), 209-222.

Ingrao, C., Strippoli, R., Lagioia, G., & Huisingh, D. (2023). Water scarcity in agriculture: An overview of causes, impacts and approaches for reducing the risks. *Heliyon*.

Jargin, S. V. (2022). Overpopulation and international conflicts: An update. *J Environ Stud*, *8*(1), 5.

Khan, Z., Khan, I., & Kamal, U. (2024). Climate change intersecting socio-economic vulnerabilities of the Kalash indigenous community in northern Pakistan. *Journal of Environmental Science and Economics, 3*(3), 31–40. https://doi.org/10.56556/jescae.v3i3.942

Kumar, R., Kumar, A., & Saikia, P. (2022). Deforestation and forests degradation impacts on the environment. In *Environmental Degradation: Challenges and Strategies for Mitigation* (pp. 19-46). Cham: Springer International Publishing.

Linnér, B. O. (2023). *The Return of Malthus: Environmentalism and Post-War Population–Resource Crises*. The White Horse Press.

Mahlakeng, M. K., & Solomon, H. (2023). Homer-Dixon's Environmental Scarcity Theory and Potential for Conflict in the Nile River Basin (NRB). In *African Security in the Anthropocene* (pp. 23-50). Cham: Springer Nature Switzerland.

Maja, M., & Ayano, S. (2021). The Impact of Population Growth on Natural Resources and Farmers' Capacity to Adapt to Climate Change in Low-Income Countries. *Earth Systems and Environment*, 5, 271 - 283. https://doi.org/10.1007/s41748-021-00209-6.

Malterud, K., Siersma, V. D., & Guassora, A. D. (2016). Sample size in qualitative interview studies: Guided by information power. *Qualitative Health Research*, *26*(13), 1753-1760. https://doi.org/10.1177/1049732315617444

Mazloum Yar, F. G., & Zazia, J. G. (2024). Obstacles and challenges of rural development in Afghanistan: Examining problems and solutions: A review. *Global Sustainability Research*, *3*(3), 81–94. https://doi.org/10.56556/gssr.v3i3.985

Nwaugha, L., Irewunmi, B. A., & Olu, O. K. (2024). Environmental Scarcity and Violent Conflict in North Eastern Nigeria. *Global Online Journal of Academic Research (GOJAR), 3*(3).

Onuoha, F. (2008). Environmental degradation, livelihood and conflicts: A focus on the implications of the diminishing water resources of Lake Chad for North-Eastern Nigeria. *African Journal on Conflict Resolution*, *8*(2), 35-62.

Rahi, S., Alnaser, F. M., & Abd Ghani, M. (2019). Designing survey research: Recommendation for questionnaire development, calculating sample size and selecting research paradigms. *Economic and Social Development: Book of Proceedings*, 1157-1169.

Shemer, H., Wald, S., & Semiat, R. (2023). Challenges and solutions for global water scarcity. *Membranes*, *13*(6), 612.

Setrana, M., & Adzande, P. (2022). Farmer-Pastoralist Interactions and Resource-Based Conflicts in Africa: Drivers, Actors, and Pathways to Conflict Transformation and Peacebuilding. *African Studies Review*, 65, 399 - 403. https://doi.org/10.1017/asr.2022.45.

Unfried, K., Kis-Katos, K., & Poser, T. (2022). Water scarcity and social conflict. *Journal of Environmental Economics and Management*, *113*, 102633.

Vasileiou, K., Barnett, J., Thorpe, S., & Young, T. (2018). Characterising and justifying sample size sufficiency in interview-based studies: Systematic analysis of qualitative health research over a 15-year period. *BMC Medical Research Methodology, 18*(1), 1-18.

Wang, J., & Azam, W. (2024). Natural resource scarcity, fossil fuel energy consumption, and total greenhouse gas emissions in top emitting countries. *Geoscience Frontiers*, *15*(2), 101757.