Information Sciences and Technological Innovations

www.isti.reapress.com

Inf. Sci. Technol. Innov. Vol. 2, No. 1 (2025) 57–71.

Paper Type: Original Article

# Unlocking Load Capacity Potential: The Synergy of Financial Technology and ICT in the United States

**Abdullah Al Abrar Chowdhury[1], Sheikh Shoaib Uddin Sayem[2], Tasneem Hossain[3], Asif Khan Emon[3,*], Azizul Hakim Rafi[1], Sahariar Alam[4]**

[1] Department of Information Technology, National University of America, United States; abdullahalabrarchy@gmail.com. rafiazizul96@gmail.com.

[2] Department of Information Technology, Chittagong University of Science and Technology, Bangladesh; shoaibsheikhstk@gmail.com.

[3] New York City College of Technology, New York, United States; tasneemhossain14@gmail.com; asif.k.emon@gmail.com.

[4] China West Normal University, China; shariarimon78926@gmail.com.

**Citation:**

| | |
|---|---|
| *Received: 11 June 2024*<br>*Revised: 17 September 2024*<br>*Accepted: 25 October 2024* | Al Abrar Chowdhury, A., Uddin Sayem, Sh. Sh., Hossain, T., Emon, A. Kh., Rafi, A. H., & Alam, S. (2025). Unlocking load capacity potential: The synergy of financial technology and ICT in the united states. *Information Sciences and Technological Innovations,* 2(1), 57-71. |

## Abstract

This research analyses the influence of FinTech and the Digital Economy (DGE) on environmental sustainability in the United States (US) over the period from 1990 to 2021, using the Load Capacity Curve (LCC) hypothesis as a theoretical framework. The primary objective is to assess how technological advancements in financial services and digital infrastructure influence the Load Capacity Factor (LCF), a key indicator of ecological longevity. The analysis employs several econometric approaches, including Autoregressive Distributive Lag Model estimation, Fully Modified OLS, Dynamic OLS, and Canonical Cointegration Regression, to explore both short-run and long-run relationships among the factors. The outcomes reveal that GDP has a substantial negative link with LCF, confirming the U-shaped relationship described by the LCC hypothesis, where higher economic growth initially reduces sustainability but eventually improves it as a country's development progresses. GDP Squared ($GDP^2$) shows a positive impact on LCF, further validating the LCC hypothesis. Moreover, the study demonstrates that FinTech and the DGE favorably promote the ecosystem health. A 1% increase in FinTech activity significantly raises LCF in both the short and long run, indicating that monetary technological innovations contribute to more sustainable economic practices. Similarly, DGE development has an encouraging implication on LCF, suggesting that digital infrastructure facilitates long-term prosperity. Conversely, Urbanization (URBA) negatively affects LCF, highlighting the environmental challenges associated with rapid urban growth. Overall, the study underscores the relevance of integrating growing economies, technological innovation, and urban development to promote long-term environmental sustainability in an increasingly DGE.

**Keywords:** FinTech, Load capacity factor, Digital economy, ARDL, United states.

## 1 | Introduction

Over the past few decades, technology, economic development and environmental sustainability has become a rapidly growing research domain [1]. Perhaps one of the most interesting intersections is the convergence

Corresponding Author: Asif.k.emon@gmail.com

regarding the ascent of FinTech, the Digital Economy (DGE) and metrics of ecological sustainability, including the Load Capacity Factor (LCF) [2]. In this study, we examine the intersection of these variables in the United States (US), specifically focusing on how FinTech developments and the DGE more broadly affect the LCF — An indices of ecosystem quality that measures the ratio between a nation's bio capacity and its environmental footprint [3]. FinTech – Is the application of digital technologies to support, develop or automate financial products and functions. This includes technologies such as online payments, mobile banking, peer-to-peer lending, and cryptocurrency [4], [5]. In the last few years, the FinTech sector has experienced rapid development. The global FinTech market for instance, grew from $179 billion in 2019 to $512 billion by 2024 at a CAGR of 24.8% [6]. FinTech investments in the US alone are at an all-Time high — $22 billion poured into US FinTech startups in 2021, which is over twice as much as it was just five years ago [6]. The same time FinTech was exploding, so too was the DGE, defined as the economic activities spawned by the widespread adoption of digital tools (Especially internet, e-commerce, and digital services). In 2020, the DGE accounted for about 9.3% of the GDP of the US, with its momentum driven by the digital revolution in the industrial sector [7]. This DGE does not only involve financial technologies, but also industries such as e-commerce, digital marketing, and the emergence of platform businesses. With increasing numbers of services being connected to the internet, demand for energy and tech infrastructure has risen, prompting concerns about its impact on the environment [8].

The LCF is a number used to measure the sustainability of a country — That is, the balance between its biocapacity and its environmental impact. While biocapacity describes the capacity of an ecosystem to replenish natural resources, ecological footprint describes the human pressure on the Earth's ecosystems [9]. The LCF is calculated by dividing the per-capita biocapacity by the per-capita ecological footprint. A LCF greater than 1 means that a country is living within its limits on nature whereas a LCF lower than 1 indicates that the country is crossing over its ecological boundaries, leading to excessive use of assets and loss of biodiversity [10]. In the US, the environmental footprint has been expanding quickly thanks to consumption and carbon emissions. As of 2020, the US had an ecological footprint of approximately 8.1 hectares per person and a biocapacity of approximately 3.5 hectares per person, with an LCF of 0.43 [11]. It's a sign that the US is using up more resources than the Earth can replenish and thus is a driver of environmental problems such as climate change and resource depletion. Given this, it is important for policymakers and entrepreneurs to understand what determines LCF to ensure that they are on the path to meeting SDGs [12]–[14].

Although the DGE has been linked to higher energy usage, most of which stems from data centers and cloud computing, it also offers great opportunities for sustainability [15]. FinTech in particular, has already introduced several technologies that might reduce the ecological footprint and boost the LCF. The Green finance sector is just one field in which FinTech has impacted. Both green bond and blockchain-based systems for transparent management of carbon credits are becoming increasingly popular over the past few years [16], [17]. The Climate Bonds Initiative estimated that green bond issuance reached a new record $500 billion in 2022, and green bonds issued globally exceeded $1 trillion by 2023. Furthermore, the digitization of energy markets — Through smart grids and IoT solutions — has the potential to dramatically improve electricity conservation [18], [19]. These technologies make it possible to track energy usage in real time, better integrate renewable energy, and control electricity consumption. With the global smart grid market in the US projected to rise from $24.3 billion in 2020 to $60.4 billion by 2028, it's clear that the digitalization of the energy industry will be a key contributor to increasing sustainability and minimizing our environmental impact [20], [21].

This evaluation aims to explore the consequences of FinTech and the DGE on environmental sustainability in the US during 1990-2021 by introducing the Load Capacity Curve (LCC) hypothesis as a theoretical framework. In particular, the research aims to examine how improvements in financial technology and digital infrastructure affect the LCF. The study uses a variety of econometric tools such as ARDL estimation, FMOLS, DOLS, and CCR to check out the short- And long-run interplay of the selected factors. The motivation behind this study stems from the growing need to understand how technological advancements, particularly in FinTech and the DGE, contribute to environmental sustainability. As digitalization accelerates globally, this research aims to uncover how these innovations can be leveraged to balance economic growth with ecological resilience, addressing a critical gap in sustainability literature.

This study is significant as it bridges the gap between financial technology, DGE, and environmental sustainability by applying the LCC hypothesis within the context of the US. Its novelty lies in integrating FinTech and digital infrastructure as key drivers of ecological resilience, a relatively underexplored area in existing literature. While previous studies have largely focused on economic growth or isolated environmental factors, this research uniquely highlights how technological advancements in financial services and digitalization can enhance sustainability, as measured by the LCF. By employing a range of econometric techniques to capture both short- and long-term effects, the study offers robust evidence supporting the positive role of FinTech and digital infrastructure in promoting sustainable development, while also identifying Urbanization (URBA) as a key challenge. This contribution is valuable as it not only validates the U-shaped relationship proposed by the LCC hypothesis but also extends it by incorporating modern technological dimensions. In doing so, the study fills a critical gap by offering a comprehensive understanding of how the DGE and financial innovations collectively influence ecological longevity, providing actionable insights for policymakers, financial sectors, and sustainability advocates.

# 2 | Literature Review

The relationship within environmental sustainability and FD is complex, as financial growth can sometimes contribute to environmental degradation. However, strong regulatory frameworks and ongoing green policies can improve environmental standards and support a more sustainable economy [22]. While many studies indicate a negative correlation between environmental sustainability and financial growth, several others highlight a positive connection, influenced by factors such as industry type, national categorization, and the existing banking framework [23]–[25]. Shahbaz [26] noted that in Pakistan, financial instability can exacerbate environmental harm. Nasreen and Anwar [27] found that in low-income countries, FD tends to worsen environmental damage, while in high-income nations, it has a mitigating effect. Sharma et al. [28] suggested that financial growth in emerging Asian economies positively impacts the environment. Similarly, FD raises environmental degradation in emerging economies by increasing the ecological footprint. In contrast, some studies argued that financial growth can improve environmental quality by reducing Greenhouse Gas (GHG) emissions [29]–[31]. Ali et al. [32] employed various methodologies and concluded that FD in the E-7 countries has worsened environmental deterioration. On the other hand, Lv and Li [33] contend that financial growth can improve biodiversity, particularly in regions with higher levels of development. Shoaib et al. [34] found that monetary expansion positively influenced $CO_2$ emissions in the G8 and D8 regions, while Dogan and Turkekul [35] noted that FD has not been a significant driver of ecological degradation in the US. Gharbi et al. [36] examined the relationship between financial development and environmental quality in Tunisia, employing the ARDL approach. Their findings revealed a significant positive effect of financial development on environmental quality. Similarly, Kurniawati et al. [37] concluded that financial inclusion enhances environmental quality in major tourist regions.

The DGE represents a transformative segment of global economic activity, characterized by transactions and interactions facilitated through online platforms and advanced digital technologies. These include mobile devices, big data analytics, the internet, and various forms of ICT [38], [39]. As this domain expands, researchers have increasingly focused on its financial, social, and environmental implications. On a microeconomic scale, the DGE offers tools to mitigate information asymmetry and alleviate economic constraints for businesses by leveraging cutting-edge technologies. For instance, Liu [40] highlights that the DGE may also play a crucial role in environmental management, particularly in reducing pollution emissions. A growing body of research examines this interplay between digital transformation and environmental sustainability. Raihan et al. [41], in their analysis of G-7 nations spanning 1990 to 2019, concluded that a digitalized society greatly improves environmental sustainability. Jiang et al. [42] provided additional evidence, estimating that DGE could contribute to reducing emissions by as much as 0.092%. Similarly, Yuan et al. [43], utilizing a spatial econometric paradigm with panel data from 267 Chinese cities between 2012 and 2021, demonstrated that DGE is instrumental in curbing harmful emissions. These findings are echoed in various studies that affirm the beneficial ecological impacts of the modern age, such as reducing $CO_2$ emissions intensity and fostering greener practices [44]–[46]. Despite its advantages, the environmental implication of the DGE is multifaceted and not without its challenges. Jin et al. [47] emphasize that the overall effects of the shared DGE on environmental pollution remain ambiguous. On one hand, Zha et al. [45] assessed that the DGE can mitigate $CO_2$ outputs in targeted areas while enhancing sustainability in neighboring areas. On the other hand, Kuntsman and Rattle [44] argue that the production, restoration, and eventual recycling of digital devices come with significant environmental costs, such as e-waste and resource depletion. Furthermore, Danish et al. [46], in their analysis of 73 developing countries using an adjusted OLS approach, revealed that the DGE in these contexts might exacerbate $CO_2$ releases, signifying an intricate interaction involving growing economies, technology adoption, and environmental stewardship. Overall, while the DGE holds promise for advancing sustainability and reducing harmful emissions, its broader environmental impact requires careful consideration. Policymakers and researchers must address the challenges posed by digital infrastructure development, energy consumption, and waste management to ensure that the benefits of the DGE are not offset by its potential ecological drawbacks.

URBA profoundly impacts environmental health, as the increasing concentration of people in urban areas drives greater demand for energy, natural resources, and services. This surge often leads to ecological degradation, contributing to challenges such as resource depletion, pollution, and GHG emissions. The link within URBA and ecosystem outcomes has been the focus of extensive research across various regions, yielding diverse findings. Studies have explored this dynamic in a range of contexts. For instance, Arshad et al. [48] analyzed Asian regions, while Nathaniel et al. [49] focused on Latin American and Caribbean nations, and van Delden et al. [50] investigated URBA's effects in Australia. A common theme across these studies is that urban population growth often degrades the natural world. Arslan et al. [51] argue that expanding urban populations exacerbate pressures on natural systems, leading to higher pollution levels and resource consumption. Specific metrics such as the EFP have been used to gauge URBA's environmental impact. Nathaniel and Khan [52], studying ASEAN economies from 1990 to 2016, illustrated that URBA correlates with a rise in the EFP, which diminishes overall environmental sustainability.

Conversely, some findings indicate that URBA can have favorable consequences on the ecosystem under certain conditions. For example, Xue et al. [53] employed the ARDL methodology to data from France between 1987 and 2019, discovering that URBA contributed to reduced pollution during this period. Similarly, Ahmad et al. [54] explored that URBA can enhance natural health by reducing the EFP. Their research, employing FMOLS and DOLS methodologies, provides evidence of URBA's potential to align with greener outcomes. Mehmood [55] also noted positive effects, finding that URBA in the SAARC region improved air quality between 1996 and 2015. The complexity of URBA's environmental impacts becomes even more apparent when examined across different countries and time frames. Azam and Khan [56] explored its effects on ecological damage in Bangladesh, India, Sri Lanka, and Pakistan between 1982 and 2013. Their findings underscore regional variations: URBA negatively impacted environmental conditions in Bangladesh and India, while it had an encouraging effect in Sri Lanka and Pakistan. This nuanced picture highlights that the environmental consequences of URBA are influenced by factors such as governance, technological adoption, resource management, and regional socioeconomic contexts.

Despite significant analysis on the link involving FD, ecosystem quality, and DGE, several gaps remain in the literature. First, while many studies explore the destructive implications of financial development on the natural world, there is limited consensus on the conditions under which FD can actually contribute to ecological improvement, especially in emerging economies. The findings are often context-specific, and the function of legal structures and green financial initiatives in mitigating negative environmental conclusions requires further investigation. Additionally, while studies on the DGE's environmental effects suggest both positive and negative outcomes, the impact of a "Shared" DGE (i.e., collaborative platforms and digital services) on environmental pollution remains underexplored. Most studies focus on individual technological innovations or macro-level digital economic activities, but the environmental impact of digital transformation on different sectors or regions is not well understood. Another gap exists in URBA studies, where research often focuses on large, high-income countries or regions. Less is known about how URBA affects the environment in developing economies or smaller cities with rapid urban growth. Furthermore, the interplay between DGE growth, URBA, and environmental sustainability in emerging markets remains insufficiently addressed, particularly how digitalization in urban contexts influences local environmental outcomes. This research will aim to bridge these gaps by examining the combined effects of FD, DGE and URBA on environmental sustainability, with a focus on developing economies.

# 3 | Methodology

The analysis examined data to evaluate the influence of different chosen factors on the USA's LCF from 1990 to 2022. The USA received focus due of its environmental challenges, economic stability, and data availability. The World Bank supplies data on GDP, GDP per capita, the DGE, and URBA metrics. We consider LCF as a dependent variable derived from GFN, utilised as a proxy for environment quality. In contrast, fintech data is obtained from credible organizations like the IMF. Furthermore, we recognized access to financing, energy use, and URBA as the policy elements for our inquiry. The variables were selected for their direct relevance to the study's objectives. FinTech and the DGE are key drivers of technological innovation and sustainable economic practices, making them essential to this analysis. The LCF is used as a reliable measure of environmental sustainability. GDP and GDP Squared ($GDP^2$) are included to test the LCC hypothesis and capture the non-linear relationship between growth and sustainability. URBA is added due to its well-documented environmental impact. Together, these variables offer a well-rounded framework to explore the links between digitalization, financial innovation, and ecological resilience. *Table 1* presents details about study variables.

**Table 1. Sources and description of data.**

| Variables | Description | Logarithmic Form | Unit of Measurement | Source |
|---|---|---|---|---|
| LCF | LCF | LLCF | Gha per person | GFN |
| GDP | Gross domestic product | LGDP | GDP per capita (Current US$) | WDI |
| $GDP^2$ | GDP square | $LGDP^2$ | GDP per capita (Current US$) | WDI |
| DGE | DGE | LDGE | ICT goods imports (% of GDP) | WDI |
| LFNT | FinTech | LFNT | Financial development index | IMF |
| LURBA | LURBA | LURBA | Urban population (% of total ) | WDI |

The LCF in the context of biocapacity and ecological footprint is a measure of how sustainable a given area's resources are relative to its consumption [57]. It is calculated by dividing the biocapacity (The ability of an area to regenerate resources and absorb waste) by the ecological footprint (The demand placed on the environment by human activity). An LCF greater than 1 indicates that an area is operating sustainably, with resources exceeding consumption [58], [59]. A value less than 1 signals ecological overshoot, where human demands exceed the environment's capacity to regenerate. The *Eq. (1)* can be write as:

$$\mathrm{LCF} = \mathrm{f}(\mathrm{GDP}, \mathrm{GDP}^2, \mathrm{M_t}). \tag{1}$$

GDP and $GDP^2$ used as income variable, but the parameter for additional factors influencing the LCF is $\mathrm{M_t}$. *Eq. (2)* aims to offer a comprehensive perspective on the elements influencing the LCF by incorporating additional pertinent aspects, including URBA, financial technology, GDP, and DGE.

$$\mathrm{LCF_{it}} = \delta_0 + \delta_1 \mathrm{GDP_{it}} + \delta_2 \mathrm{GDP_{it}^2} + \delta_3 \mathrm{DGE_{it}} + \delta_4 \mathrm{FNT_{it}} + \delta_5 \mathrm{URBA_{it}}. \tag{2}$$

Logarithmic multiplication effectively strengthens volatility, making it an extremely useful modification for integrating wide ranges in scientific and economic study. It enhances comprehension and aids in making decisions from statistics by simplifying complex situation. *Eq. (3)* demonstrates the logarithmic values of the variables.

$$LLCF_{it} = \delta_0 + \delta_1 LGDP_{it} + \delta_2 LGDP_{it}^2 + \delta_3 LDGE_{it} + \delta_4 LFNT_{it} + \delta_5 LFNT_{it} + \delta_6 LURBA_{it}. \quad \textbf{(3)}$$

The unit root test is essential in evaluating the stationarity of a time series, a key assumption for many time series models, including ARDL. Stationarity guarantees the core patterns in the data maintain stability across time, enabling reliable analysis [60], [61]. When data are non-stationary, often indicated by the existence of a unit root, it may end up in erroneous conclusions and inaccurate predictions if not appropriately addressed. In this study, the stationarity of the statistics was evaluated utilizing the ADF, P-P, and DF-GLS unit root examinations.

The ARDL approach is outperforms to other cointegration methods owing to its versatility and durability. Unlike methods such as Engle-Granger or Johansen, the ARDL can be adopted to parameters that are stationary (I(0)) or have a unit root (I(1)), eliminating the need for pre-testing unit roots [62]–[65]. It simultaneously estimates both sustained relationships and immediate dynamics, providing a comprehensive view of variable interactions. The ARDL approach also performs well with small sample sizes and is more adaptable to datasets with structural breaks [66]–[68]. These advantages make it a popular choice for analyzing economic relationships across different contexts.

We employ the ARDL bound assessment to investigate the enduring relationships among the selected variables, as outlined below:

$$\Delta LLCF_t = \varphi_0 + \rho_1 LCF_{t-1} + \rho_2 LGDP_{t-1} + \rho_3 LGDP^2{}_{t=1} + \rho_4 LENU_{t-1} + \rho_5 LFA_{t-1} + \rho_6 LURBA_{t-1} + \sum_{i=1}^{w} \varphi_1\, \Delta LLCF_{2_{t-i}} + \sum_{i=1}^{w} \varphi_2\, \Delta LGDP_{t-i} + \sum_{i=1}^{w} \varphi_3 \Delta LGDP^2{}_{t=1} + \sum_{i=1}^{w} \varphi_4\, \Delta\, LENU_{t-i} + \sum_{i=1}^{w} \varphi_5 \Delta LFA_{t-i} + \sum_{i=1}^{w} \varphi_6 \Delta LURBA_{t-i} + \varepsilon_t \quad \textbf{(5)}$$

*Eq. (6)* demonstrates the incorporation of the ECM into the ARDL framework:

$$\Delta LLCF_t = \varphi_0 + \sum_{i=1}^{w} \rho_1 \Delta LCF_{t-i} + \sum_{i=1}^{w} \rho_2 \Delta LGDP_{t-i} + \sum_{i=1}^{w} \rho_3 \Delta LGDP^2{}_{t=1} + \sum_{i=1}^{w} \rho_4 \Delta\, LENU_{t-i} + \sum_{i=1}^{w} \rho_5\, \Delta LFA_{t-i} + \sum_{i=1}^{w} \rho_6 \Delta LURBA_{t-i} + ¥ECT_{t-i} + \varepsilon_t \quad \textbf{(6)}$$

Here, ¥ indicates the coefficient of the ECT.

The utilization of FMOLS, DOLS and CCR in conjunction with the ARDL technique strengthens the reliability of cointegration analysis. These methods are crucial since they address serial correlation and endogeneity concerns that may impact ordinary least squares estimates in cointegrated systems [69–72]. FMOLS accounts for both endogeneity and serial correlation in the error term, whereas DOLS incorporates leads and lags to reflect the dynamic character of the connection. CCR enhances the cointegration relationship by refining the estimation of long-term parameters [30], [73–75]. The combined application of these methodologies enhances the verification of the validity and consistency of the ARDL results.

# 4 | Results and Discussion

The *Table 2* illustrates descriptive statistics for seven variables, each with 32 observations. The variable "T" (Likely representing time) has a mean of 2005.5, with a Standard Deviation (SD) of 9.381, ranging from 1990 to 2021. "LLCF" has a mean of -0.835, with a SD of 0.094, and values ranging from -0.971 to -0.633. "LGDP" has a mean of 10.644, a SD of 0.319, and ranges from 10.081 to 11.159, indicating moderate variation in GDP levels. "$LGDP^2$" (Possibly a squared GDP term) has a mean of 113.392, with a larger SD of 6.761, ranging from 101.63 to 124.532. "LDGE" has a mean of 7.506, with a SD of 1.036, spanning from 6.321 to 9.724. "LFNT" shows a mean of -0.129, with a small SD of 0.033, ranging from -0.183 to -0.065. Finally, "LURBA" has a mean of 4.378, with a very low SD of 0.027, ranging from 4.321 to 4.417, indicating little variation in URBA levels across the observations.

**Table 2. Summary statistics.**

| Variable | Obs | Mean | Std. Dev. | Min | Max |
|---|---|---|---|---|---|
| T | 32 | 2005.5 | 9.381 | 1990 | 2021 |
| LLCF | 32 | -0.835 | 0.094 | -0.971 | -0.633 |
| LGDP | 32 | 10.644 | 0.319 | 10.081 | 11.159 |
| LGDP$^2$ | 32 | 113.392 | 6.761 | 101.63 | 124.532 |
| LDGE | 32 | 7.506 | 1.036 | 6.321 | 9.724 |
| LFNT | 32 | -0.129 | 0.033 | -0.183 | -0.065 |
| LURBA | 32 | 4.378 | 0.027 | 4.321 | 4.417 |

This study used three unit root assessments—ADF, P-P, and DF-GLS—to evaluate the factors' stationarity characteristics. *Table* 3 presents the results, which show a mixed pattern of stationarity. Specifically, the variables LLCF, LGDP, and LGDP$^2$ were found to be non-stationary at their levels, as evidenced by the inability to reject the null hypothesis of a unit root. However, these variables became stationary upon first differencing, indicating they are integrated of order one, or I(1). Conversely, the parameters LDGE, LFNT, and LURBA were determined to be stationary at I(0), signifying they are free of unit roots and are integrated of order zero. This combination of integration orders—some variables being I(0) and others I(1)—Provides a solid rationale for utilizing the ARDL structure in the analysis. Thus, the findings strongly endorse the suitability of the ARDL framework for investigating the connections among the factors in this inquiry.

**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 | -0.245 | -4.248*** | -0.271 | -4.317*** | -0.189 | -4.981*** | I(1) |
| LGDP | -0.372 | -3.891*** | -0.31 | -3.981*** | -0.401 | -3.984*** | I(1) |
| LGDP$^2$ | -0.37 | -3.951*** | -0.381 | -3.968*** | -0.483 | -3.343** | I(1) |
| LFNT | -3.084** | -4.721*** | -3.187** | -4.673*** | -3.198** | -4.541*** | I(0) |
| LDGE | -3.043** | -4.415*** | -3.210** | -4.014*** | -3.761** | -4.571*** | I(0) |
| LURBA | -4.280*** | -7.571*** | -4.550*** | -6.112*** | -3.229** | -4.549*** | I(0) |

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

The conclusions of the ARDL bound examination, outlined in *Table 4*, imply a significant long-term relationship across the factors. With an F-statistic value of 7.78192, which surpasses the upper bound critical values for I(1) at all conventional significance thresholds—1%, 5%, and 10%—the results are compelling. Notably, the F-statistic exceeds the upper bound critical value of 3.99 at the 1% significance level, providing robust evidence to reject the null hypothesis of no cointegration. This confirms that the variables are cointegrated, indicating a stable and consistent sustained association between them. Consequently, the use of the ARDL model is validated, as it is well-equipped to analyze the established long-term relationships among the selected parameters.

**Table 4. Results of ARDL bound test.**

| Test statistic | Value | Significance | I(0) | I(1) |
|---|---|---|---|---|
| F-statistic | 7.78192 | 10% | Asymptotic: n=1000 | 1.99 |
| K=5 | | 6% | 2.27 | 3.28 |
| | | 2.50% | 2.55 | 3.61 |
| | | 1% | 2.88 | 3.99 |

*Table 5* presents the ARDL results for both the short-run and long-run links within the dependent variable, LLCF, and several independent variables. The findings reveal important insights into how key factors affect LLCF. First, GDP (LGDP) is negatively related to LLCF, demonstrating that as GDP rises, the LCF tends to fall. Specifically, a 1% increase in GDP (LGDP) reduces LLCF by 0.251% in the short run and by 0.240% in the long run. In contrast, $GDP^2$ ($LGDP^2$) has a positive relationship with LLCF, implying that higher levels of GDP initially reduce LLCF, but at a certain threshold, further increases in GDP lead to higher LLCF. The results show that a 1% increment in $LGDP^2$ raises LLCF by 0.231% over time and by 0.182% in the immediate term. This U-shaped connection between LLCF and GDP supports the LCC hypothesis, which posits that there is an optimal level of economic growth that maximizes LLCF.

Additionally, the analysis reveals that FinTech (LFIN) has a significant encouraging relationship with LLCF in both time periods. A 1% expansion in FinTech activity increases LLCF by 0.342% in the short run and 0.221% in the long run, highlighting the role of technological innovations in enhancing load capacity. Similarly, the LDGE shows a favorable and substantial correlation with LLCF. A 1% improvement in DGE activity boosts LLCF by 0.084% in the short run and 0.431% in the long run, suggesting that the growth of digital platforms and online services positively impacts LLCF. Lastly, URBA (LURBA) shows a significant destructive connection with LLCF. A 1% increase in URBA results in a 0.231% decrease in LLCF in the long run and a 0.134% decrease in the short run. This suggests that rapid URBA may place additional strain on infrastructure, reducing its load capacity over time. Overall, the ARDL outcomes illustrate the complex interrelations among economic, technological, and demographic factors in influencing load capacity, with both short-term and long-term implications varying across different variables.

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

| Variables | Long-run | Short-run |
|---|---|---|
| LGDP | -0.251***(0.2483) | |
| LGDP2 | 0.231***(0.2871) | |
| LFIN | 0.221***(0.4321) | |
| LDGE | 0.084***(0.0817) | |
| LURBA | -0.231**(0.4351) | |
| D.LGDP | | -0.240***(0.1324) |
| D.$LGDP^2$ | | 0.182**(0.4310) |
| D.LFIN | | 0.342***(0.0345) |
| D.LDGE | | 0.431***(0.2317) |
| D.LURBA | | -0.134**(0.1023) |
| ECT (Speed Adjustment) | | -0.451***(0.0212) |
| Constant | | 10.167***(7.8091) |
| R-square | 0.9061 | |

*Note: ***p < 0.01, **p < 0.05. Standard errors are in brackets

*Table 6* illustrates the results of the robustness checks using three alternative cointegration estimation methods: FMOLS, DOLS, and CCR. These methods were adopted to check the reliability of the ARDL conclusions and they are aligned with the ARDL results, confirming the relationships identified in the initial assessment. Specifically, GDP (LGDP) remains negatively associated with LLCF, while $GDP^2$ ($LGDP^2$) continues to show a positive relationship with LLCF. This reinforces the earlier conclusion that LLCF follows a U-shaped pattern in response to changes in GDP, thereby supporting the existence of the LCC hypothesis. Further, the robustness checks reveal that FinTech (LFIN) and the (LDGE) have significant positive relationships with LLCF, which aligns with the ARDL results, suggesting that advancements in financial technology and digital infrastructure enhance the LCF. In contrast, URBA (LURBA) maintains a significant inverse link with LLCF in all three methods, confirming the earlier finding that increased URBA tends to reduce LLCF. These consistent results across different estimation techniques provide strong validation for the original ARDL findings, ensuring the robustness of the relationships identified between LLCF and the study's independent variables. The robustness checks affirm the reliability as well as validity of the ARDL methodology employed in this study.

**Table 6. Result of robustness check.**

| Variables | FMOLS | DOLS | CCR |
|---|---|---|---|
| **LLCF Dependent** | | | |
| LGDP | -0.230***(0.2084) | 0.284**(0.2765) | 0.272***(0.2987) |
| $LGDP^2$ | 0.265***(0.2054) | 0.289*(0.2543) | 0.249**(0.1385) |
| LFIN | 0.243***(0.2783) | 0.304***(0.3024) | -0.276***(0.3134) |
| LDGE | 0.062**(0.6723) | 0.077**(0.4301) | 0.055**(0.2455) |
| LURBA | -0.372**(0.6503) | -0.270***(0.2065) | -0.285***(0.3011) |
| C | 10.723**(4.0841) | 10.291**(4.0387) | 10.652**(7.8099) |
| R-squared | 0.9101 | 0.9324 | 0.9591 |

*Note: ***p < 0.01, **p < 0.05. Standard errors are in brackets

*Table 7* presents the results of several diagnostic tests performed to verify the statistical framework and ensure the reliability of the estimated relationships. The diagnostic tests indicate that there is no evidence of serial correlation and heteroscedasticiy which are common issues that can lead to biased or inconsistent estimates if left unaddressed. Specifically, the lack of serial correlation means that the residuals from the model do not exhibit patterns of autocorrelation, suggesting that the error terms are independent across time.

Similarly, the absence of heteroscedasticity indicates that the variance of the residuals is constant, ensuring that the assumptions of homoscedasticity are met and the standard errors of the calculations are unbiased. In addition to these tests, *Fig. 1* presents the results of the Cumulative Sum (CUSUM) and Cumulative Sum of Squares (CUSUMSQ) examinations, which are commonly used to explore the relaibility of the estimated coefficients over time. The CUSUM test examines whether the cumulative sum of the residuals stays within the critical bounds, while the CUSUMSQ test does so by evaluating the cumulative sum of the squared residuals. The results from both tests observe that the parameters of the model remain consistent throughout the sample period, further validating the robustness of the model and confirming that the projected coefficients do not exhibit any significant structural breaks.

**Table7. The findings of diagnostic test.**

| Diagnostic Tests | Coefficient | P-value |
|---|---|---|
| J-B test for normality | 0.13452 | 0.1042 |
| LM test for serial correlation | 0.19621 | 0.2431 |
| BPG test for heterocedasticity | 1.14321 | 0.2134 |

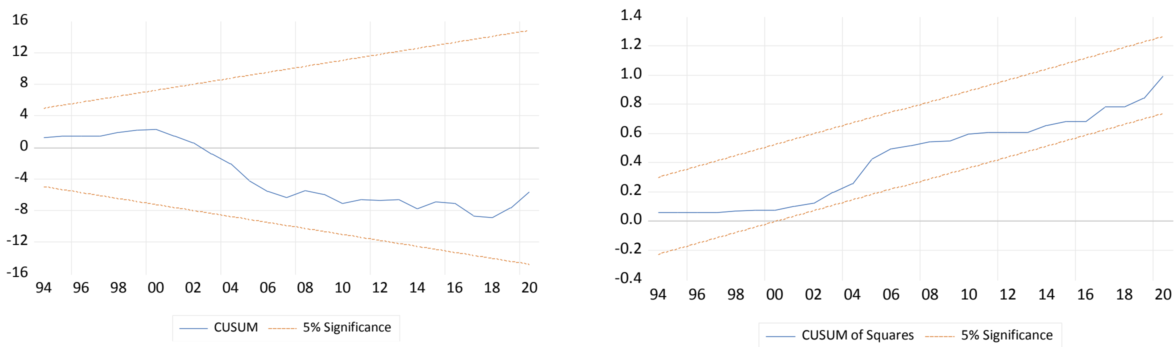


**Fig. 1. CUSUM and CUSUMSQ tests.**

# 5 | Conclusion and Policy Implications

This research examined the impact of FinTech and the DGE on ecosystem health in the US over the period from 1990 to 2021, using the LCC hypothesis as a framework. The analysis employed a range of econometric techniques, including the ARDL structure, FMOLS, DOLS, and CCR, to explore the short-run and long-run correlations among the chosen factors. The outcomes consistently indicate that both FinTech and the DGE have a significant beneficial consequence on environmental sustainability, measured by the LCF, across different model specifications. The study found that GDP has a negative relationship with LLCF, supporting the LCC hypothesis, which suggests that as economic growth increases beyond a certain point, environmental sustainability may begin to decline.

Conversely, $GDP^2$ demonstrates a positive relationship with LCF, reflecting the U-shaped relationship described by the LCC hypothesis—Where initial economic growth reduces environmental sustainability, but at higher levels of economic development, technological and institutional advancements help restore and improve sustainability. Additionally, the conclusions illustrate the positive aspect of FinTech and the DGE in improving the natural world. A 1% increment in FinTech activity (LFIN) causes a substantial rise in LLCF, both in the short and long run, suggesting that technological innovations in finance help to boost improved and green economic activities. Similarly, the growth of the (LDGE) is positively associated with LLCF, indicating that the expansion of digital infrastructure and services supports sustainable economic development. However, this investigation also observed that URBA (LURBA) has a negative implication on LLCF, suggesting that rapid urban development may strain environmental resources.

Policymakers should leverage the positive role of FinTech and the DGE in promoting environmental sustainability by encouraging technological innovation in finance and expanding digital infrastructure to support green economic activities. Given the U-shaped relationship between economic growth and ecosystem health, regulatory frameworks should foster sustainable economic policies that integrate advanced technologies and institutional reforms to mitigate the environmental costs of early-stage growth. Additionally, policies should address the negative environmental impact of URBA by promoting smart city initiatives, green urban planning, and resource-efficient infrastructure.

Incentivizing eco-friendly FinTech solutions, such as digital payment systems that support carbon trading and green investment platforms, can further enhance sustainability. Governments should also implement policies that balance economic expansion with environmental protection, ensuring that digital transformation does not contribute to ecological degradation. Strengthening collaborations between financial institutions, technology firms, and environmental agencies can help create an integrated approach to sustainable development. Moreover, education and awareness campaigns on digital finance and sustainability should be promoted to encourage responsible financial behavior. Overall, a comprehensive policy strategy that harmonizes economic growth, technological innovation, and environmental conservation will be crucial in shaping a sustainable and resilient DGE.

While this study provides valuable insights, it does have some limitations that open the door for further research. Since it focuses only on the US, the findings may not fully apply to other countries with different economic structures and environmental challenges. Future research could benefit from comparing multiple countries to gain a broader perspective. Also, the study looks at FinTech and the DGE in general terms, without breaking down specific areas like mobile banking or blockchain, which could have unique effects on sustainability. Exploring these specific components would add more depth. Even though the study uses strong econometric models, they may not fully capture complex dynamics or hidden biases; Future work could apply more advanced techniques like structural equation modeling or machine learning to refine the results. Finally, factors like government policies, consumer behavior, or green finance initiatives were not included but could play a big role in shaping the relationship between digital innovation and environmental sustainability. Including these aspects in future research could help create a more complete picture of how technology and institutions work together to support a greener future.

# Author Contributaion

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

# Data Availability

Available on request.

# References


[1] Abdulmagid Basheer Agila, T., Khalifa, W. M. S., Saint Akadiri, S., Adebayo, T. S., & Altuntaş, M. (2022). Determinants of load capacity factor in South Korea: Does structural change matter? *Environmental science and pollution research*, *29*(46), 69932–69948. https://doi.org/10.1007/s11356-022-20676-2

[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

[3] Chandra Voumik, L., Ridwan, M., Hasanur Rahman, M., & 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

[4] Acheampong, A. O. (2019). Modelling for insight: Does financial development improve environmental quality? *Energy economics*, *83*, 156–179. https://doi.org/10.1016/j.eneco.2019.06.025

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

[6] Achuo, E. D., Miamo, C. W., & Kouhomou, C. Z. (2024). Resource rents and environmental pollution in developing countries: Does the quality of institutions matter? *Review of development economics*, *28*(1), 360–387. https://doi.org/10.1111/rode.13060

[7] 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

[8] Voumik, L. C., Rahman, M. H., Rahman, M. M., Ridwan, M., Akter, S., & Raihan, A. (2023). 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

[9] 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

[10] Raihan, A., Tanchangya, T., Rahman, J., & Ridwan, M. (2024). The influence of agriculture, renewable energy, international trade, and economic growth on India's environmental sustainability. *Journal of environmental and energy economics*, *3*(1), 37–53. https://doi.org/10.56946/jeee.v3i1.324

[11] Ahmad, M., Jan, D., Ali, S., & Khan, U. U. (2024). Empowering Asia's sustainable future: Unraveling renewable energy dynamics with trade, carbon emission, governance, and innovative interactions. *Renewable energy*, *229*, 120716. https://doi.org/10.1016/j.renene.2024.120716

[12] 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

[13] Raihan, A., Ridwan, M., Tanchangya, T., Rahman, J., & Ahmad, S. (2023). 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*(2), 1–16. http://dx.doi.org/10.56946/jeee.v2i1.346

[14] 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

[15] Raihan, A., Hasan, M. A., Voumik, L. C., Pattak, D. C., Akter, S., & Ridwan, M. (2024). Sustainability in vietnam: Examining economic growth, energy, innovation, agriculture, and forests' impact on CO2 emissions. *World development sustainability*, *4*, 100164. https://doi.org/10.1016/j.wds.2024.100164

[16] 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

[17] 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

[18] Raihan, A., Rahman, J., Tanchangya, T., Ridwan, M., & Bari, A. B. M. M. (2024). Influences of economy, energy, finance, and natural resources on carbon emissions in Bangladesh. *Carbon research*, *3*(1), 1–16. https://doi.org/10.1007/s44246-024-00157-6

[19] Raihan, A., Ridwan, M., & Rahman, M. S. (2024). An exploration of the latest developments, obstacles, and potential future pathways for climate-smart agriculture. *Climate smart agriculture*, *1*(2), 100020. https://doi.org/10.1016/j.csag.2024.100020

[20] Atasoy, F. G., Atasoy, M., Raihan, A., Ridwan, M., Tanchangya, T., & Rahman, J. (2022). Factors affecting the ecological footprint in the United States: The influences of natural resources, economic conditions. *Renewable energy sources, and advancements in technology. journal of environmental and energy economics*, *1*(1), 35–52. http://dx.doi.org/10.56946/jeee.v1i1.483

[21] Ridwan, M., Akther, A., Tamim, M. A., Ridzuan, A. R., Esquivias, M. A., & Wibowo, W. (2024). Environmental health in BIMSTEC: The roles of forestry, urbanization, and financial access using LCC theory, DKSE, and quantile regression. *Discover sustainability*, *5*(1), 429. https://doi.org/10.1007/s43621-024-00679-4

[22] Ridwan, M., Akther, A., Al Absy, M. S. M., Tahsin, M. S., Bin Ridzuan, A. R., Yagis, O., & Mukhta, K. P. (2024). The role of tourism, technological innovation, and globalization in driving energy demand in major tourist regions. *International journal of energy economics and policy*, *14*(6), 675–689. https://doi.org/10.32479/ijeep.17344

[23] Ahmed, Z., Asghar, M. M., Malik, M. N., & Nawaz, K. (2020). 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

[24] Rahman, J., Foisal, M. Z. U., Mohajan, B., & Islam, S. (2022). Nexus between agriculture, economy, energy use, and ecological footprint toward sustainable development in Bangladesh. *Journal of environmental and energy economics*, *1*(2), 18–31. https://doi.org/10.56946/jeee.v1i2.486

[25] Raihan, A., Atasoy, F. G., Coskun, M. B., Tanchangya, T., Rahman, J., Ridwan, M., … .m & Yer, H. (2024). Fintech adoption and sustainable deployment of natural resources: Evidence from mineral management in Brazil. *Resources policy*, *99*, 105411. https://doi.org/10.1016/j.resourpol.2024.105411

[26] Shahbaz, M. (2013). Does financial instability increase environmental degradation? Fresh evidence from Pakistan. *Economic modelling*, *33*, 537–544. https://doi.org/10.1016/j.econmod.2013.04.035

[27] Nasreen, S., & Anwar, S. (2015). The impact of economic and financial development on environmental degradation. *Studies in economics and finance*, *32*(4), 485–502. https://doi.org/10.1108/SEF-07-2013-0105

[28] Sharma, R., Sinha, A., & Kautish, P. (2021). Does financial development reinforce environmental footprints? Evidence from emerging Asian countries. *Environmental science and pollution research*, *28*(8), 9067–9083. https://doi.org/10.1007/s11356-020-11295-w

[29] Onwe, J. C., Ridzuan, A. R., Uche, E., Ray, S., Ridwan, M., & Razi, U. (2024). Greening Japan: Harnessing energy efficiency and waste reduction for environmental progress. *Sustainable futures*, *8*, 100302. https://doi.org/10.1016/j.sftr.2024.100302

[30] Raihan, A., Voumik, L. C., Ridwan, M., Akter, S., Ridzuan, A. R., Wahjoedi, … ., & Ismail, N. A. (2024). Indonesia's path to sustainability: Exploring the intersections of ecological footprint, technology, global trade, financial development and renewable energy. In *Opportunities and risks in ai for business development* (pp. 1–13). Cham: Springer, Cham. https://doi.org/10.1007/978-3-031-65203-5_1

[31] Islam, S., Raihan, A., Paul, A., Ridwan, M., & Rahman, M. S. (2024). Dynamic impacts of sustainable energies, technological innovation, economic growth, and financial globalization on load capacity factor in the top nuclear energy-consuming countries. *Journal of environmental and energy economics*, *3*(2), 1–14. https://doi.org/10.56946/jeee.v3i1.448

[32] Ali, S. S. S., Razman, M. R., & Awang, A. (2020). The nexus of population, GDP growth, electricity generation, electricity consumption and carbon emissions output in Malaysia. *International journal of energy economics and policy*, *10*(3), 84–89. http://dx.doi.org/10.32479/ijeep.8987

[33] Lv, Z., & Li, S. (2021). How financial development affects CO2 emissions: A spatial econometric analysis. *Journal of environmental management*, *277*, 111397. https://doi.org/10.1016/j.jenvman.2020.111397

[34] Shoaib, H. M., Rafique, M. Z., Nadeem, A. M., & Huang, S. (2020). Impact of financial development on CO2 emissions: A comparative analysis of developing countries (D8) and developed countries (G8). *Environmental science and pollution research*, *27*(11), 12461–12475. https://doi.org/10.1007/s11356-019-06680-z

[35] Dogan, E., & Turkekul, B. (2016). CO2 emissions, real output, energy consumption, trade, urbanization and financial development: Testing the EKC hypothesis for the USA. *Environmental science and pollution research*, *23*(2), 1203–1213. https://doi.org/10.1007/s11356-015-5323-8

[36] Gharbi, I., Rahman, M. H., Muryani, M., Esquivias, M. A., & Ridwan, M. (2025). Exploring the influence of financial development, renewable energy, and tourism on environmental sustainability in Tunisia. *Discover sustainability*, *6*(1), 127. https://doi.org/10.1007/s43621-025-00896-5

[37] Kurniawati, T., Rahmiza, M., Ridwan, M., Aspy, N. N., Mahjabin, T., Eleais, M., & Ridzuan, A. R. (2025). Reassessing the load capacity curve hypothesis in ASEAN-5: Exploring energy intensity, trade, and financial inclusion with advanced econometric techniques. *International journal of energy economics and policy*, *15*(2), 195–208. http://dx.doi.org/10.32479/ijeep.17328

[38] Ridwan, M., Aspy, N. N., Bala, S., Hossain, M. E., Akther, A., Eleais, M., & Esquivias, M. A. (2024). Determinants of environmental sustainability in the United States: Analyzing the role of financial development and stock market capitalization using LCC framework. *Discover sustainability*, *5*(1), 319. https://doi.org/10.1007/s43621-024-00539-1

[39] Ridwan, M. (2023). Unveiling the powerhouse: Exploring the dynamic relationship between globalization, urbanization, and economic growth in Bangladesh through an innovative ARDL approach. *Asian journal of economics and business management*, *2*(2), 283–291. https://doi.org/10.53402/ajebm.v2i2.352

[40] Liu, W. (2023). The digital economy and environmental pollution: New evidence based on the support of logistics development. *Journal of cleaner production*, *427*, 139210. https://doi.org/10.1016/j.jclepro.2023.139210

[41] 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

[42] Jiang, H., Elahi, E., Gao, M., Huang, Y., & Liu, X. (2024). Digital economy to encourage sustainable consumption and reduce carbon emissions. *Journal of cleaner production*, *443*, 140867. https://doi.org/10.1016/j.jclepro.2024.140867

[43] Yuan, H., Liu, J., Li, X., & Zhong, S. (2024). The impact of digital economy on environmental pollution: Evidence from 267 cities in China. *Plos one*, *19*(1), e0297009. https://doi.org/10.1371/journal.pone.0297009

[44] Kuntsman, A., & Rattle, I. (2019). Towards a paradigmatic shift in sustainability studies: A systematic review of peer reviewed literature and future agenda setting to consider environmental (Un) sustainability of digital communication. *Environmental communication*, *13*(5), 567–581. https://doi.org/10.1080/17524032.2019.1596144

[45] Zha, Q., Huang, C., & Kumari, S. (2022). The impact of digital economy development on carbon emissions - Based on the Yangtze River Delta urban agglomeration. *Frontiers in environmental science*, *10*, 1028750. https://doi.org/10.3389/fenvs.2022.1028750

[46] Zhang, J., Wang, B., & Latif, Z. (2019). Towards cross-regional sustainable development: The nexus between information and communication technology, energy consumption, and CO 2 emissions. *Sustainable development*, *27*(5), 990–1000. https://doi.org/10.1002/sd.2000

[47] Jin, M., Feng, Y., Wang, S., Chen, N., & Cao, F. (2024). Can the development of the rural digital economy reduce agricultural carbon emissions? A spatiotemporal empirical study based on China's provinces. *Science of the total environment*, *939*, 173437. https://doi.org/10.1016/j.scitotenv.2024.173437

[48] Arshad, Z., Robaina, M., Shahbaz, M., & Veloso, A. B. (2020). The effects of deforestation and urbanization on sustainable growth in Asian countries. *Environmental science and pollution research*, *27*(9), 10065–10086. https://doi.org/10.1007/s11356-019-07507-7

[49] Nathaniel, S. P., Nwulu, N., & Bekun, F. (2021). Natural resource, globalization, urbanization, human capital, and environmental degradation in Latin American and Caribbean countries. *Environmental science and pollution research*, *28*(5), 6207–6221. https://doi.org/10.1007/s11356-020-10850-9

[50] van Delden, L., Rowlings, D. W., Scheer, C., de Rosa, D., & Grace, P. R. (2018). Effect of urbanization on soil methane and nitrous oxide fluxes in subtropical Australia. *Global change biology*, *24*(12), 5695–5707. https://doi.org/10.1111/gcb.14444

[51] Arslan, H. M., Khan, I., Latif, M. I., Komal, B., & Chen, S. (2022). Understanding the dynamics of natural resources rents, environmental sustainability, and sustainable economic growth: new insights from China. *Environmental science and pollution research*, *29*(39), 58746–58761. https://doi.org/10.1007/s11356-022-19952-y

[52] Nathaniel, S., & Khan, S. A. R. (2020). The nexus between urbanization, renewable energy, trade, and ecological footprint in ASEAN countries. *Journal of cleaner production*, *272*, 122709. https://doi.org/10.1016/j.jclepro.2020.122709

[53] Xue, C., Shahbaz, M., Ahmed, Z., Ahmad, M., & Sinha, A. (2022). Clean energy consumption, economic growth, and environmental sustainability: What is the role of economic policy uncertainty? *Renewable energy*, *184*, 899–907. https://doi.org/10.1016/j.renene.2021.12.006

[54] Ahmad, S., Raihan, A., & Ridwan, M. (2024). Role of economy, technology, and renewable energy toward carbon neutrality in China. *Journal of economy and technology*, *2*, 138–154. https://doi.org/10.1016/j.ject.2024.04.008

[55] Mehmood, U. (2021). Transport energy consumption and carbon emissions: The role of urbanization towards environment in SAARC region. *Integrated environmental assessment and management*, *17*(6), 1286–1292. https://doi.org/10.1002/ieam.4463

[56] Azam, M., & Khan, A. Q. (2016). Urbanization and environmental degradation: Evidence from four SAARC countries—Bangladesh, India, Pakistan, and Sri Lanka. *Environmental progress & sustainable energy*, *35*(3), 823–832. https://doi.org/10.1002/ep.12282

[57] Bala, S., Al Shiam, S. A., Arefeen, S. S., Abir, S. I., & Hossain, H. (2024). Measuring how AI innovations and financial accessibility influence environmental sustainability in the G-7: The role of globalization with panel ARDL and quantile regression analysis. https://doi.org/10.56556/gssr.v3i4.974

[58] Abir, S., Shoha, S., Abdulla, S., Shiam, S., Dolon, M., Bala, S., … ., & Bibi, R. (2024). Enhancing load capacity factor: The influence of financial accessibility, AI innovation, and institutional quality in the United States. *Journal of environmental science and economics*, *3*(4), 12–36. http://dx.doi.org/10.56556/jescae.v3i4.979

[59] Akhter, A., Al Shiam, S. A., Ridwan, M., Abir, S. I., Shoha, S., Nayeem, M. B., & Bibi, R. (2024). Assessing the impact of private investment in AI and financial globalization on load capacity factor: Evidence from United States. *Journal of environmental science and economics*, *3*(3), 99–127. https://doi.org/10.56556/jescae.v3i3.977

[60] Hossain, M. S., Ridwan, M., Akhter, A., Nayeem, M. B., Choudhury, M. T. H., Asrafuzzaman, M., & Shoha, S. (2024). Exploring the LCC hypothesis in the nordic region: The role of AI innovation, environmental Taxes, and financial accessibility via panel ARDL. *Global sustainability research*, *3*(3), 54–80. https://doi.org/10.56556/gssr.v3i3.972

[61] Islam, S., Raihan, A., Ridwan, M., Rahman, M. S., Paul, A., Karmakar, S., … ., & Jubayed, A. A. (2023). The influences of financial development, economic growth, energy price, and foreign direct investment on renewable energy consumption in the BRICS. *Journal of environmental and energy economics*, *2*(2), 17–28. https://doi.org/10.56946/jeee.v2i2.419

[62] Ridzuan, A. R., Rahman, N. H. A., Singh, K. S. J., Borhan, H., Ridwan, M., Voumik, L. C., & Ali, M. (2024). Assessing the impact of technology advancement and foreign direct investment on energy utilization in malaysia: An empirical exploration with boundary estimation. *Technology and business model innovation: Challenges and opportunities* (pp. 1–12). Cham: Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-55911-2_1

[63] 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), e27095. https://doi.org/10.1016/j.heliyon.2024.e27095

[64] Tanchangya, T., Raihan, A., Rahman, J., Ridwan, M., & Islam, N. (2024). A bibliometric analysis of the relationship between corporate social responsibility (CSR) and firm performance in Bangladesh. *Frontiers of finance*, *2*(2), 6287. https://doi.org/10.59429/ff.v2i2.6550

[65] Guneysu Atasoy, F., Atasoy, M., Raihan, A., Khayruzzaman, S., Rahman, Ridwan, M., … ., & Jubayed, A. Al. (2022). An econometric investigation of how the usage of non-renewable energy resources affects the load capacity factor in the United States. *Journal of environmental and energy economics*, *1*(2), 32–44. http://dx.doi.org/10.56946/jeee.v1i2.482

[66] Voumik, L. C., Akter, S., Ridwan, M., Ridzuan, A. R., Pujiati, A., Handayani, B. D., … ., & Razak, M. I. M. (2023). 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

[67] Fakher, H. A., Nathaniel, S. P., Ahmed, Z., Ahmad, M., & Moradhasel, N. (2024). The environmental repercussions of financial development and green energy in BRICS economies: From the perspective of new composite indices. *Energy & environment*, 0958305X241270216. https://doi.org/10.1177/0958305X241270216

[68] Nathaniel, S. P., Solomon, C. J., Khudoykulov, K., & Fakher, H. A. (2025). Linking resource richness, digital economy, and clean energy to ecological footprint and load capacity factor in emerging markets. *Natural resources forum*. https://doi.org/10.1111/1477-8947.12590

[69] Fakher, H.-A., Panahi, M., Emami, K., Peykarjou, K., & Zeraatkish, S. Y. (2021). New insights into development of an environmental – Economic model based on a composite environmental quality index: A comparative analysis of economic growth and environmental quality trend. *Environmental energy and economic research*, *5*(3), 1–24. https://doi.org/10.22097/eeer.2021.280746.1192

[70] Fakher, H. A., & Idroes, G. M. (2025). Room for improving the ecological sustainability gap in g20 economies through the lens of load capacity factor: The role of green energy initiatives as moderators. *Innovations in environmental economics*, *1*(1), 1–18. https://www.iee.reapress.com/journal/article/view/33

[71] Raihan, A., Zimon, G., Ridwan, M., Rahman, M. M., & Salehi, M. (2025). Role of mineral resource rents, renewable energy, and energy efficiency toward carbon neutrality in China. *Energy nexus*, *17*, 100394. https://doi.org/10.1016/j.nexus.2025.100394

[72] Raihan, A., Ridwan, M., Sarker, T., Atasoy, F. G., Zimon, G., Bari, A. B. M. M., …., & Mohajan, B. (2025). The influence of different environmental factors toward Vietnam's net-zero emissions goal. *Innovation and green development*, *4*(3), 100229. https://doi.org/10.1016/j.igd.2025.100229

[73] Ridwan, M., Tahsin, M. S., Al-Absy, M. S. M., Eleais, M., Ridzuan, A. R., & Mukthar, K. P. J. (2025). Economic Alchemy: Unraveling the nexus between trade openness, inflation, exchange rates, and economic growth in bangladesh. *International journal of economics and financial issues*, *15*(3), 244–253. https://doi.org/10.32479/ijefi.17779

[74] Urbee, A. J., Hasan, M. A., Ridwan, M., & Dewan, M. F. (2025). Adaptation and resilience in the face of climate-induced migration: exploring coping strategies in the urban economy of barishal metropolitan city. *Environment, innovation and management*, *1*, 2550005. https://doi.org/10.1142/S306090112550005X

[75] Raihan, A., Ridwan, M., Salehi, M., & Zimon, G. (2025). Influences of financial development and energy price on renewable energy: An Italian case. *Energy engineering*, *122*(2), 493–514. http://dx.doi.org/10.32604/ee.2025.059016