Innovations in Environmental Economics

www.iee.reapress.com

Innov. Environ. Econ. Vol. 1, No. 2 (2025) 155–170.

Paper Type: Original Article

Economic Growth, Renewable Energy Consumption, Financial Development, and Ecological Sustainability in European Union Countries: Does Digital Economy Matter?

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Citation:

Received: 29 November 2024 *Revised: 02 February 2025* *Accepted: 03 April 2025*	Kaviani, M., Martinho, F., & Fakhrhosseini, S. F. (2025). Economic growth, renewable energy consumption, financial development, and ecological sustainability in European union countries: Does the digital economy matter? *Innovations in environmental economics, 1*(2), 155- 170.

Abstract

This study explores the role of Economic Growth (EG), Renewable Energy Consumption (REC), Financial Development (FD), and the Digital Economy (DE) in shaping environmental sustainability, measured by the Load Capacity Factor (LCF), in European Union (EU) countries. Given the increasing policy focus on green transition and digital transformation, understanding both direct and indirect effects of these factors has become essential. Using panel data for EU countries over the period 2010-2025, the study applies the Method of Moments Quantile Regression (MMQR) to capture heterogeneous effects across different levels of environmental performance. The findings indicate that EG exerts a negative effect on environmental sustainability, while REC and FD contribute positively, particularly at higher quantiles. The DE also shows a significant positive impact across the distribution of LCF. Importantly, the interaction results reveal that digitalization mitigates the environmental cost of EG and strengthens the beneficial effects of renewable energy and FD. These findings highlight the pivotal role of the DE as both a direct and moderating driver of sustainability. Therefore, policymakers should integrate digital transformation strategies with renewable energy expansion and green financial systems to enhance environmental performance across EU countries.

Keywords: Economic growth, Renewable energy consumption, Financial development, Ecological sustainability, Digital economy.

1 | Introduction

1.1 | Background and Theoretical Motivation

Environmental sustainability has become a critical concern in modern economic systems, particularly in regions such as the European Union (EU), where strong policy frameworks have been established to achieve carbon neutrality. Theoretical and empirical studies emphasize that economic systems operate within ecological limits, requiring a balance between Economic Growth (EG) and environmental preservation [1],

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https://doi.org/10.48313/iee.vi.50

[2]. The EU has taken a leading role in this transition through initiatives such as the European Green Deal, which promotes renewable energy adoption, resource efficiency, and technological innovation [3], [4]. However, despite progress, environmental degradation persists due to rising consumption, industrialization, and resource exploitation [5], [6]. These dynamics highlight the need for a comprehensive understanding of sustainability drivers within heterogeneous economic systems.

EG is a central determinant of environmental outcomes, though its effects are often ambiguous. According to the environmental Kuznets curve hypothesis, economic expansion initially leads to environmental degradation but may improve environmental quality at higher income levels [7–9]. Empirical evidence suggests that EG increases energy demand and resource use, thereby intensifying environmental pressure [10–12]. However, economic development can also facilitate technological innovation and efficiency improvements, which may reduce emissions in the long run [13–15]. In the EU context, these mixed effects are further complicated by structural and institutional heterogeneity, making it necessary to examine additional moderating factors.

Renewable energy consumption (REC) is widely recognized as a key mechanism for improving environmental sustainability. The transition from fossil fuels to renewable energy sources significantly reduces carbon emissions and ecological degradation [1], [16]. Empirical studies confirm that renewable energy plays a crucial role in mitigating environmental damage, particularly when supported by technological innovation and policy frameworks [17–19]. However, the effectiveness of renewable energy varies across regions and may exhibit nonlinear patterns, especially in the presence of rebound effects or structural inefficiencies [20], [21]. These findings suggest that renewable energy must be analyzed within a broader economic and technological framework.

Financial Development (FD) plays a dual role in shaping environmental sustainability by influencing investment allocation and economic activity. On one hand, developed financial systems can facilitate investments in green technologies and renewable energy, thereby improving environmental quality [22], [23]. On the other hand, financial expansion may increase environmental degradation by promoting industrialization and energy consumption [6], [24], [25]. Empirical evidence indicates that the environmental impact of FD depends largely on institutional quality, technological innovation, and policy frameworks. In the EU, where financial markets are relatively advanced, FD can act as both a driver of sustainability and a source of environmental pressure.

The Digital Economy (DE) has recently emerged as a significant factor influencing environmental sustainability. Digital technologies can enhance energy efficiency, optimize production processes, and promote green innovation, thereby reducing environmental degradation [26]. At the same time, digital infrastructure and data-intensive activities may increase energy consumption and environmental pressure [27], [28]. Furthermore, digitalization may influence the effectiveness of other factors, such as EG, renewable energy, and FD, through efficiency gains and technological diffusion. This highlights the importance of examining the DE not only as a direct determinant but also as a moderating factor in environmental sustainability.

1.2 | Why EU Countries

The selection of EU countries is justified by their unique combination of economic integration, technological advancement, and environmental policy leadership. The EU has implemented comprehensive sustainability strategies aimed at reducing emissions and improving resource efficiency [3]. However, despite these common policy frameworks, member states exhibit substantial heterogeneity in terms of economic structure, energy consumption patterns, and environmental performance [29–31]. This diversity provides a valuable context for examining heterogeneous environmental effects. Additionally, the availability of consistent panel data across EU countries enhances the robustness of empirical analysis. Previous studies also highlight that the effects of renewable energy, technological innovation, and EG differ across EU regions, reinforcing the relevance of this sample [17].

1.3 | Why Load Capacity Factor (LCF)

The Load Capacity Factor (LCF) is adopted as a comprehensive indicator of environmental sustainability because it captures the balance between ecological demand and environmental capacity. Unlike traditional indicators such as CO2 emissions, which focus only on environmental pressure, LCF provides a more holistic measure by incorporating both resource consumption and ecological regeneration capacity; [32], [33]. Environmental sustainability is a multidimensional concept that cannot be fully captured by single indicators [34–36]. Therefore, LCF offers a more accurate representation of sustainability by integrating ecological constraints with economic activity. This makes it particularly suitable for EU countries, where sustainability policies aim to achieve both emission reduction and long-term ecological balance.

1.4 | Contributions of the study

Although considerable progress has been made in understanding the drivers of environmental sustainability, the existing literature still exhibits several shortcomings that limit a comprehensive understanding of the issue. Much of the empirical work tends to assess the effects of EG, REC, and FD separately, thereby overlooking the potential interdependencies among these factors. In addition, while the DE has increasingly been recognized as an influential factor, its broader role, particularly in shaping the relationships between key economic variables and environmental outcomes, remains insufficiently examined. Furthermore, the dominant reliance on traditional proxies such as CO2 emissions and ecological footprint may not adequately reflect the dynamic balance between ecological pressure and regenerative capacity. In this regard, more comprehensive measures like the LCF have not been fully utilized, especially within the context of developed regions. This is particularly relevant for EU countries, where diverse economic structures and policy frameworks create varying sustainability dynamics that are not yet fully captured in the literature. Against this backdrop, the present study develops a unified analytical framework to jointly assess the roles of EG, REC, FD, and the DE in shaping environmental sustainability. It further extends the analysis by considering the DE as a conditioning factor that influences these relationships, and employs the Method of Moments Quantile Regression (MMQR) to provide robust and distribution-sensitive evidence.

1.5 | Research objectives and questions

The primary objective of this study is to investigate the impact of EG, REC, FD, and the DE on environmental sustainability, measured by LCF, in EU countries. In addition to examining these direct effects, the study aims to explore the moderating role of the DE in shaping the relationship between each explanatory variable and environmental quality. Specifically, the study addresses the following research questions: How do EG, REC, FD, and DE affect LCF in EU countries? Does the DE enhance or weaken the environmental effects of EG? How does digitalization influence the effectiveness of renewable energy in improving environmental sustainability? And does the DE moderate the relationship between FD and LCF?

2 | Literature Review and Hypotheses Development

This section reviews the relevant theoretical and empirical literature on the relationships between EG, REC, FD, DE, and environmental sustainability. It aims to identify key research gaps and provide a comprehensive foundation for the study. Building upon this review, the section develops testable hypotheses grounded in existing theories and empirical findings. Furthermore, a conceptual framework is proposed to illustrate both the direct effects of the explanatory variables on environmental sustainability, measured by the LCF, and the moderating role of the DE in shaping these relationships.

2.1 | Literature Review

2.1.1 | Economic growth and environmental sustainability

The relationship between EG and environmental sustainability has been extensively examined in the literature, with mixed empirical findings. According to the environmental Kuznets curve hypothesis, EG initially exacerbates environmental degradation but eventually contributes to environmental improvement as income levels rise and cleaner technologies are adopted [1], [7]. However, several studies argue that this relationship is highly context-dependent, particularly in regions with heterogeneous economic structures such as the EU [10]. While economic expansion increases energy consumption and environmental pressure, it can also enhance efficiency and innovation, thereby reducing emissions in the long run [13]. These conflicting findings suggest that the growth–environment nexus cannot be fully understood without considering additional structural and technological factors.

2.1.2 | Renewable energy consumption and environmental sustainability

REC has been widely recognized as a key driver of environmental sustainability. Empirical evidence consistently demonstrates that increasing the share of renewable energy reduces carbon emissions and ecological degradation [17], [20]. Moreover, renewable energy plays a crucial role in facilitating the transition toward a low-carbon economy, particularly in developed regions [18]. However, the environmental benefits of renewable energy may vary depending on technological capacity, policy frameworks, and economic conditions [16]. Some studies also highlight nonlinear effects, suggesting that the marginal impact of renewable energy may decline beyond certain thresholds [8].

2.1.3 | Financial development, digital economy, and environmental sustainability

FD represents another important determinant of environmental sustainability. On one hand, financial systems can support green investments and technological innovation, thereby improving environmental quality [22]. On the other hand, financial expansion may increase environmental degradation by stimulating industrial activity and energy consumption [23]. The empirical evidence on this relationship remains inconclusive, as FD can either mitigate or exacerbate environmental pressure depending on institutional quality and regulatory frameworks [24]. More recently, the DE has emerged as a critical factor influencing environmental outcomes. Digital technologies can improve energy efficiency, optimize production processes, and promote green innovation, thereby contributing to environmental sustainability [26]. However, the expansion of digital infrastructure may also increase energy consumption, leading to ambiguous environmental effects. Furthermore, digitalization may influence the effectiveness of other determinants, such as EG and renewable energy, by enhancing efficiency and facilitating technological diffusion [32]. This highlights the importance of examining the DE as both a direct and moderating factor in environmental sustainability.

2.2 | Key Research Gaps

Despite the growing body of literature examining the determinants of environmental sustainability, several important gaps remain insufficiently addressed. First, while numerous studies have explored the individual effects of EG, REC, and FD on environmental outcomes, these factors are often analyzed in isolation rather than within an integrated framework. Second, although recent research has begun to highlight the role of the DE in environmental sustainability, its dual function as both a direct determinant and a moderating mechanism has received limited empirical attention. Third, the majority of existing studies rely on conventional environmental indicators such as CO2 emissions or ecological footprint, which may not fully capture the balance between ecological demand and environmental capacity. In this regard, the use of LCF remains relatively underexplored, particularly in the context of advanced economies. Finally, empirical evidence focusing on EU countries is still fragmented, despite their strategic importance in global sustainability transitions. Therefore, this study addresses these gaps by developing an integrated framework that simultaneously examines the direct and moderating effects of the DE on environmental sustainability, using LCF as a comprehensive indicator within the EU context. Therefore, this study aims to address this void by rigorously examining the individual and interactive effects of EG, REC, FD, and DE on LCF using the MMQR to ensure robust and reliable estimations.

2.3 | Hypotheses Development

EG affects environmental sustainability through multiple interconnected channels, including increased energy consumption, industrial expansion, and technological advancement. While early stages of growth tend to intensify environmental pressure due to higher resource utilization, advanced stages of development may contribute to ecological improvement through efficiency gains, cleaner production technologies, and stricter environmental regulations [1], [7]. In this context, the net effect of EG on environmental quality remains theoretically ambiguous and empirically dependent on structural and institutional conditions. Based on the foregoing arguments, the first hypothesis is formulated accordingly.

H1: EG has a significant effect on LCF.

REC is widely acknowledged as a fundamental driver of environmental sustainability, primarily due to its ability to reduce dependence on fossil fuels and mitigate greenhouse gas emissions. The transition toward renewable energy sources not only contributes to environmental improvement but also supports long-term ecological balance by lowering environmental pressure [17], [20]. However, its effectiveness may vary across countries depending on technological capabilities and policy frameworks. In light of the above discussion, the second hypothesis is proposed as follows.

H2: REC positively affects LCF.

FD plays a dual role in environmental sustainability by influencing both investment patterns and economic activities. On the one hand, developed financial systems facilitate access to capital for green technologies and renewable energy projects, thereby enhancing environmental quality. On the other hand, financial expansion may stimulate industrialization and energy consumption, potentially increasing environmental degradation [23], [24]. This duality suggests that the overall impact of FD on environmental sustainability is context-specific. Accordingly, the third hypothesis is derived based on the preceding theoretical considerations.

H3: FD significantly affects LCF.

The DE has emerged as a transformative force in shaping environmental sustainability through its impact on production processes, energy efficiency, and technological innovation. Digitalization enhances resource efficiency and promotes the adoption of cleaner technologies, thereby reducing environmental degradation. Nevertheless, the expansion of digital infrastructure may also increase energy consumption, resulting in mixed environmental outcomes [26]. Therefore, the overall impact of the DE on environmental quality remains an empirical question. Building upon the above insights, the fourth hypothesis is formulated as follows.

H4: DE positively affects LCF.

The DE not only directly influences environmental sustainability but also plays a crucial moderating role in shaping the effectiveness of other determinants. By enhancing technological diffusion, improving efficiency, and optimizing resource allocation, digitalization can strengthen or weaken the environmental impact of EG, renewable energy, and FD [32]. This moderating effect highlights the importance of incorporating DE into the analytical framework of environmental sustainability. Consequently, the final hypotheses are specified based on the preceding discussion:

H5: DE moderates the relationship between EG and LCF.
H6: DE moderates the relationship between REC and LCF.
H7: DE moderates the relationship between FD and LCF.
Drawing upon the above theoretical and empirical insights, this study proposes a conceptual framework (see *Fig. 1*) that integrates economic, energy, financial, and technological dimensions in explaining environmental sustainability. The model further considers the DE as a moderating mechanism that conditions the impact of key determinants on the LCF, thereby offering a more nuanced understanding of the sustainability process.

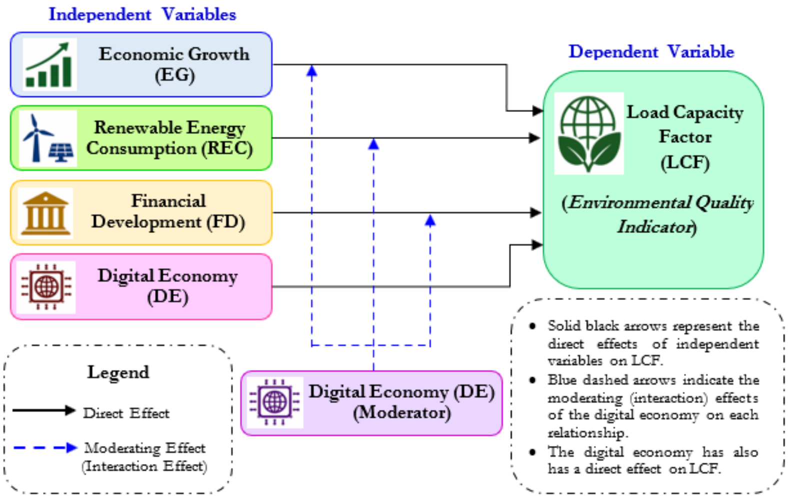

Fig. 1. The conceptual framework for analyzing the direct and moderating effects of de on environmental sustainability.

3 | Data and Methodology

3.1 | Data Collection and Research Variables

This study examines the effects of EG, REC, FD, and the DE on environmental sustainability, proxied by the LCF. The empirical analysis is based on panel data covering the period from 1995 to 2024 for 27 EU economies. All variables used in this study are secondary data obtained from reliable and widely recognized sources, including the World Bank's World Development Indicators, Eurostat, and OECD databases. To ensure consistency and improve the statistical properties of the data, all variables are transformed into their natural logarithmic forms. This transformation helps reduce potential heteroscedasticity, smooth out extreme values, and allows the estimated coefficients to be interpreted in elasticity terms, thereby enhancing the overall robustness and interpretability of the results.

3.2 | Methodology

The empirical strategy of this study follows a systematic sequence of diagnostic and estimation procedures tailored for heterogeneous panel data with potential Cross-Sectional Dependence (CSD). The analysis initially employs descriptive statistics and graphical tools, including density plots, to explore the distributional characteristics of the variables, identify potential outliers, and assess variability across countries. In addition, multicollinearity among the explanatory variables is evaluated using the Variance Inflation Factor (VIF) to ensure the robustness and stability of the estimated coefficients in the multivariate framework. Given the panel structure involving multiple EU countries, testing for CSD is a crucial preliminary step to avoid biased and inconsistent estimations. Following this, the slope homogeneity assumption is examined to determine whether the estimated relationships are uniform across countries. Considering the economic and institutional heterogeneity among EU member states, ignoring slope heterogeneity may lead to misleading conclusions. Therefore, the slope heterogeneity test is conducted to assess the extent of parameter variation across cross-sectional units. Subsequently, the stationarity properties of the variables are investigated using the Cross-Sectionally Augmented Im, Pesaran, and Shin (CIPS) unit root test, which accounts for CSD in non-stationary panels. After determining the order of integration, the existence of long-run equilibrium relationships among the variables is examined through the Westerlund panel cointegration test, which is particularly suitable for panels characterized by cross-sectional interdependence and relatively short time dimensions. Given the presence of heterogeneity and non-normality in the data, the study employs the MMQR to estimate the long-run relationships. This approach allows for capturing heterogeneous effects across different quantiles of the LCF distribution, providing a more comprehensive understanding of how EG, REC, FD, and the DE influence environmental sustainability across countries with varying performance levels.

To examine the determinants of environmental sustainability, this study specifies a functional relationship in which the LCF is modeled as a function of EG, REC, FD, and the DE. The general functional form is expressed as follows:

$$\mathrm{lnLCF}_{i,t} = \alpha_0 + \alpha_1 \ln \mathrm{EG}_{it} + \alpha_2 \ln \mathrm{REC}_{it} + \alpha_3 \ln \mathrm{FD}_{it} + \alpha_4 \ln \mathrm{DE}_{it} + \varepsilon_{it}. \quad (1)$$

To capture both potential nonlinearities and the moderating influence of digitalization, the model is extended by incorporating squared terms of the key explanatory variables alongside interaction terms. The inclusion of squared terms enables the examination of possible nonlinear relationships, such as U-shaped or inverted U-shaped effects, while the interaction terms account for the role of the DE in shaping the impact of EG, REC, and FD on environmental sustainability. In particular, the interaction between EG and the DE is introduced to assess whether digitalization amplifies or mitigates the environmental effects of economic expansion. The extended model is therefore specified as follows:

$$\mathrm{lnLCF}_{i,t} = \alpha_0 + \alpha_1 \ln \mathrm{EG}_{it} + \alpha_2 \ln \mathrm{EG2}_{it} + \alpha_3 \ln \mathrm{REC}_{it} + \alpha_4 \ln \mathrm{FD}_{it} + \alpha_5 \ln \mathrm{DE}_{it} + \alpha_6 (\mathrm{lnEG}_{it} \times \mathrm{lnDE}_{it}) + \varepsilon_{it}, \quad (2)$$

$$\mathrm{lnLCF}_{i,t} = \alpha_0 + \alpha_1 \ln \mathrm{EG}_{it} + \alpha_2 \ln \mathrm{EG2}_{it} + \alpha_3 \ln \mathrm{REC}_{it} + \alpha_4 \ln \mathrm{FD}_{it} + \alpha_5 \ln \mathrm{DE}_{it} + \alpha_6 (\mathrm{lnREC}_{it} \times \mathrm{lnDE}_{it}) + \varepsilon_{it}, \quad (3)$$

$$\mathrm{lnLCF}_{i,t} = \alpha_0 + \alpha_1 \ln \mathrm{EG}_{it} + \alpha_2 \ln \mathrm{EG2}_{it} + \alpha_3 \ln \mathrm{REC}_{it} + \alpha_4 \ln \mathrm{FD}_{it} + \alpha_5 \ln \mathrm{DE}_{it} + \alpha_6 (\mathrm{lnFD}_{it} \times \mathrm{lnDE}_{it}) + \varepsilon_{it}. \quad (4)$$

To further examine potential nonlinearities in the relationships, squared terms of the key explanatory variables are incorporated into the model. This allows for testing the presence of nonlinear effects such as inverted U-shaped or U-shaped relationships. The extended specification is given as:

$$Q_\tau(\mathrm{lnLCF}_{it} \mid X_{it}) = \alpha_i + \varphi_{1\tau}\mathrm{lnEG}_{it} + \varphi_{2\tau}\mathrm{lnEG2}_{it} + \varphi_{3\tau}\mathrm{lnREC}_{it} + \varphi_{4\tau}\mathrm{lnFD}_{it} + \varphi_{5\tau}\mathrm{lnDE}_{it}, \quad (5)$$

$$Q_\tau(\mathrm{lnLCF}_{it} \mid X_{it}) = \alpha_i + \varphi_{1\tau}\mathrm{lnEG}_{it} + \varphi_{2\tau}\mathrm{lnEG2}_{it} + \varphi_{3\tau}\mathrm{lnREC}_{it} + \varphi_{4\tau}\mathrm{lnFD}_{it} + \varphi_{5\tau}(\mathrm{lnEG}_{it} \times \mathrm{lnDE}_{it}), \quad (6)$$

$$Q_\tau(\mathrm{lnLCF}_{it} \mid X_{it}) = \alpha_i + \varphi_{1\tau}\mathrm{lnEG}_{it} + \varphi_{2\tau}\mathrm{lnEG2}_{it} + \varphi_{3\tau}\mathrm{lnREC}_{it} + \varphi_{4\tau}\mathrm{lnFD}_{it} + \varphi_{5\tau}(\mathrm{lnREC}_{it} \times \mathrm{lnDE}_{it}), \quad (7)$$

$$Q_\tau(\mathrm{lnLCF}_{it} \mid X_{it}) = \alpha_i + \varphi_{1\tau}\mathrm{lnEG}_{it} + \varphi_{2\tau}\mathrm{lnEG2}_{it} + \varphi_{3\tau}\mathrm{lnREC}_{it} + \varphi_{4\tau}\mathrm{lnFD}_{it} + \varphi_{5\tau}(\mathrm{lnFD}_{it} \times \mathrm{lnDE}_{it}). \quad (8)$$

As a result, it provides a more reliable framework for examining dynamic interactions in integrated regions such as the EU. An important advantage of this method is its flexibility in accommodating heterogeneous causal structures across countries. It remains valid even in panels where the cross-sectional dimension (N) exceeds the time dimension (T), and it offers a rigorous statistical basis for identifying dynamic linkages beyond simple correlations.

4 | Results and Discussion

First of all, to explore further information, refer to *Table 1* presenting pre-estimation evaluations including descriptive statistics for the variables included in the model. The descriptive statistics reported in *Table 1*, together with the distributional patterns illustrated in *Fig. 2*, provide strong empirical justification for the use of the MMQR. As shown in *Table 1*, several variables exhibit notable skewness and excess kurtosis, indicating departures from normality. In particular, LCF and REC display positive skewness, while FD and DE exhibit negative skewness, suggesting asymmetric distributions across the sample. Moreover, the high kurtosis values for variables such as LCF and DE indicate the presence of heavy tails and potential outliers. These findings are further supported by the Jarque–Bera statistics, which confirm that most variables are not normally distributed at conventional significance levels.

Table 1. Descriptive statistics of the variables.

Variables	lnLCF	lnEG	lnREC	lnFD	lnDE
Mean	1.338	10.625	2.511	4.671	2.267
Maximum	2.758	11.629	5.36	5.718	3.251
Minimum	0.506	9.772	1.12	3.528	0.058
Skewness	1.305	0.182	0.911	-0.323	-0.910
Kurtosis	5.706	3.021	4.398	3.381	6.328
Jarque-Bera (Probability)	259.161 (0.000)	2.447 (0.294)	96.758 (0.000)	10.363 (0.005)	263.829 (0.000)
Observations	440	440	440	440	440

Consistent with these results, *Fig. 2* reveals that the density distributions of the variables are not symmetric and deviate from the normal distribution. The observed dispersion and irregular shapes across variables highlight the presence of heterogeneity in the data. This heterogeneity implies that the relationships between the explanatory variables and environmental sustainability LCF may vary across different points of the conditional distribution, rather than being adequately captured by mean-based estimators. Taken together, the evidence from both *Table 1* and *Fig. 2* suggests that conventional estimation techniques, which focus on average effects, may lead to biased or incomplete inferences. In contrast, the MMQR approach is more appropriate in this context, as it allows the estimation of heterogeneous effects across different quantiles of LCF. This enables a more comprehensive understanding of how EG, REC, FD, and the DE influence environmental sustainability across low, medium-, and high-performance countries.

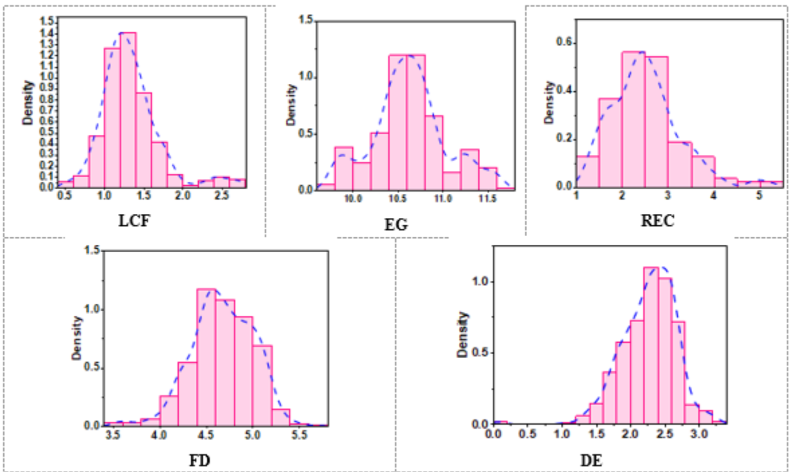

Fig. 2. Density distributions of the study variables.

To assess the potential presence of multicollinearity among the explanatory variables, the VIF, along with its reciprocal measure, tolerance (1/VIF), is examined. Generally, VIF values exceeding conventional thresholds (such as 5 or 10) signal serious multicollinearity concerns, whereas lower values indicate weak correlations among the regressors. As reported in *Table 2*, all VIF values are well below the critical threshold of 2, suggesting that multicollinearity is not a significant issue in the estimated model. Consequently, the explanatory variables can be included simultaneously without compromising the reliability of the regression results.

Table 2. Results of VIF analysis.

	VIF	1/VIF
lnLCF	1.59	0.591
lnEG	1.33	0.744
lnREC	1.32	0.762
lnFD	1.04	0.971
lnDE	1.12	0.889
Mean VIF	1.38	

The findings presented in *Table 3* provide important insights into the relationships between the key explanatory variables, EG, REC, FD, and DE, and environmental sustainability, proxied by the LCF, across EU countries. The analysis begins with the slope homogeneity test developed by Blomquist and Westerlund [37]. The results clearly reject the null hypothesis of slope homogeneity, indicating that the estimated coefficients differ across panel units. This outcome suggests the presence of significant cross-country heterogeneity, implying that the impact of the explanatory variables on environmental sustainability is not uniform across EU member states. Such variation may stem from differences in economic structure, institutional quality, technological development, and energy policies. Consequently, adopting a heterogeneous panel framework is essential to accurately capture these country-specific dynamics. By allowing for parameter heterogeneity, the empirical model can generate more reliable and policy-relevant insights, as it acknowledges that countries may respond differently to changes in EG, renewable energy adoption, FD, and digitalization. This, in turn, enhances the validity of the results and supports the formulation of more targeted and effective environmental policies.

Table 3. Results of Slope heterogeneity analysis.

Test	Value	P-Value
$\hat{\Delta}_{S-HT}$	-1.763*	0.068
$\hat{\Delta}_{adj.\ S-HT}$	-2.241**	0.017
The significance level is indicated as **<5% and *<10%.		

The CIPS unit root test results in *Table 4* show that all variables exhibit stationarity only after first differencing, confirming their I(1) integration.

Table 4. Results of CSD and CIPS analysis.

Variables	BP-LM Test	Prob	CIPS	
			Level	1st Difference
lnLCF	116.201***	0.000	-0.369	-2.807***
lnEG	81.501***	0.000	-1.212***	-3.528***
lnREC	57.363***	0.000	-1.623	-2.709***
lnFD	225.131***	0.000	-1.659***	-4.735***
lnDE	123.781***	0.000	-1.723	-4.344***
The significance level is indicated as ***<1% and **<5%.				

The results of the cointegration analysis, based on the Westerlund [38] framework and presented in *Table 5*, provide strong evidence of a long-run equilibrium relationship among the variables. This finding implies that environmental sustainability, measured by the LCF, maintains a stable long-term association with its key determinants, including EG, REC, FD, and the DE. In other words, these variables move together over time, reflecting a persistent and interconnected dynamic in shaping environmental outcomes across EU countries.

Table 5. Results of Westerlund [38] cointegration analysis.

Statistic	Values	Z-Values	Robust P-Value
G_t	-5.208***	-2.531	0.004
G_a	-1.421	1.851	0.951
P_t	-5.306***	-2.488	0.005
P_a	-1.342	1.221	0.906

The significance level is indicated as ***<1%.

Table 6 reports the MMQR estimates under four model specifications and provides evidence that the effects of the explanatory variables on environmental sustainability, proxied by LCF, are heterogeneous across the conditional distribution. This heterogeneity is consistent with the earlier diagnostic results and confirms that the environmental impacts of growth, renewable energy, FD, and digitalization differ between low-, middle-, and high-LCF countries in the EU. Overall, the results indicate that the determinants of ecological sustainability do not operate uniformly across EU member states, which is plausible given their differences in production structures, energy systems, financial depth, and digital readiness.

Table 6. Results of MMQR analysis.

Variables	Location	Scale	Q10	Q25	Q50	Q75	Q90
lnEG	-0.039***	0.004	-0.040**	-0.038***	-0.031***	-0.028**	-0.022**
lnEG2	-0.042***	0.005***	0.031**	0.029**	0.028***	0.022***	0.019**
lnREC	0.0379**	0.423***	0.428***	0.110***	0.453***	0.667**	0.551**
lnFD	-0.016***	-0.013***	0.019**	0.028**	0.059***	0.99***	0.088**
lnDE	-0.014***	-0.018***	0.108**	0.099**	0.111**	0.106**	0.087***
Variables	Location	Scale	Q10	Q25	Q50	Q75	Q90
lnEG	-0.053**	0.008	-0.037**	-0.036**	-0.029**	-0.027***	-0.024***
lnEG2	0.122	-0.529***	0.036**	0.033**	0.025***	0.021**	0.019**
lnREC	-0.046***	-0.009	0.419***	0.108***	0.463***	0.653**	0.499**
lnFD	-0.009***	0.001	0.018**	0.024**	0.058***	0.98***	0.079**
lnDE	0.118	0.626***	0.101**	0.091**	0.105**	0.112**	0.097***
lnDE*lnEG2	-0.073***	0.004	0.008***	0.005***	0.006***	0.009***	0.007***
Variables	Location	Scale	Q10	Q25	Q50	Q75	Q90
lnEG	-0.088***	-0.011	-0.041**	-0.039**	-0.031**	-0.025**	-0.021**
lnEG2	-0.061***	-0.039***	0.034**	0.030**	0.028**	0.029***	0.017***
lnREC	0.409**	0.464**	0.389***	0.101***	0.455***	0.589**	0.481**
lnFD	0.041	0.002	0.015**	0.022**	0.061***	0.88***	0.075**
lnDE	-0.055**	-0.014**	0.099**	0.102**	0.112**	0.108**	0.096***
lnDE*lnREC	0.021**	0.001*	0.004***	0.002***	0.003***	0.007***	0.009***
Variables	Location	Scale	Q10	Q25	Q50	Q75	Q90
lnEG	-0.089***	-0.010	-0.031**	-0.034**	-0.036**	-0.035**	-0.039**
lnEG2	-0.059***	-0.037***	0.038**	0.032**	0.033**	0.028***	0.022***
lnREC	0.401**	0.404**	0.366***	0.208***	0.355***	0.385**	0.381**
lnFD	0.031	0.003	0.017**	0.021**	0.059***	0.79***	0.072**
lnDE	-0.045**	-0.013**	0.089**	0.107**	0.119**	0.104**	0.099***
lnDE*lnFD	0.031**	0.007*	0.005***	0.004***	0.004***	0.006***	0.007***

The significance level is indicated as ***<1% and **<5%.

Across all four specifications, the coefficient of EG remains negative and statistically significant across most quantiles. This suggests that, in the EU context, higher EG is associated with a decline in LCF, implying that growth still exerts ecological pressure rather than improving environmental sustainability. The magnitude of the negative effect generally becomes smaller at higher quantiles in some specifications, indicating that the adverse effect of growth is stronger in lower-LCF countries and relatively weaker in countries with better environmental performance. This result is broadly consistent with studies that argue that economic expansion increases energy demand, material use, and environmental pressure, especially when growth is still tied to production-intensive sectors, as emphasized by [10], [11] However, it differs from the more optimistic strand of the literature, such as, Su et al. [13] and Ibrahim et al. [14], which suggests that growth may eventually promote environmental improvement through innovation and efficiency gains.

A likely explanation for this result in the EU is that, despite strong sustainability policies, many member states still rely on growth models linked to transport, manufacturing, logistics, and high consumption patterns. Thus, even in advanced economies, economic expansion may continue to raise ecological demand faster than ecological capacity, especially in countries where green structural transformation remains incomplete. The squared term of EG shows mixed signs across the location and quantile estimates, but the quantile coefficients are generally positive and significant. This pattern points to a nonlinear relationship between growth and environmental sustainability. Taken together with the negative coefficient on lnEG, the evidence supports the existence of a U-shaped relationship rather than an inverted U-shaped one. In other words, at lower levels or early phases, growth appears to reduce LCF, and the positive coefficient on the squared term suggests that this effect changes as income rises, although not necessarily enough to reverse the environmental burden straightforwardly. This finding partly resonates with the broader EKC debate discussed in the literature review, but it does not fully validate the conventional inverted-U version. Instead, it suggests that the EU growth–sustainability nexus is more complex and distribution-dependent. One possible reason is that in several EU countries, mature economies already operate at high income levels, where additional growth is often driven by consumption-intensive lifestyles, digital infrastructure expansion, and resource-intensive supply chains. Therefore, the environmental gains from technology and regulation may coexist with rebound effects and continued ecological stress.

REC shows a positive and statistically significant effect on LCF across almost all quantiles and specifications, making it one of the most stable findings in the table. This indicates that greater use of renewable energy improves environmental sustainability in EU countries. The positive impact is especially pronounced in the middle and upper quantiles, suggesting that renewable energy is particularly effective in countries that already possess relatively stronger ecological performance or better institutional capacity to absorb green technologies. This result is fully in line with the findings of [17], [18], [20]. all of whom emphasize the environmental benefits of the renewable energy transition. However, it is somewhat more favorable than the nonlinear or threshold-based concerns noted by [8], who argue that the sustainability benefits of renewable energy may weaken under some structural conditions. The positive EU-specific explanation is straightforward: European countries generally possess stronger renewable-energy governance, better grid integration, more stable green financing, and stronger regulatory support than many developing economies. As a result, renewable energy is not merely replacing fossil fuels symbolically; it is increasingly embedded in electricity generation, transport transition, and industrial decarbonization strategies.

The effect of FD is more nuanced. In the baseline specification, lnFD has a negative location effect, but the quantile coefficients are positive and statistically significant, especially from the median upward. In the interaction models, the positive quantile effect remains largely intact. This suggests that, although the average effect may appear weak or even adverse in some aggregate sense, FD contributes positively to environmental sustainability across much of the LCF distribution, particularly in medium- and high-LCF countries. This result is partly consistent with Alola and Adebayo [22], who show that financial and technological mechanisms can support sustainability, but it differs from the pessimistic view in Marshadi et al. [23] and Shobande and Ogbeifun [24], where financial expansion is often associated with ecological deterioration. The divergence is understandable in the EU setting. FD in Europe is increasingly linked to sustainable finance, ESG disclosure, climate investment, and green bond markets. Hence, the financial sector may facilitate renewable energy deployment, clean innovation, and low-carbon infrastructure rather than simply financing pollution-intensive expansion. At the same time, the positive coefficients becoming stronger at higher quantiles imply that the environmental benefits of finance are not evenly distributed. Countries with deeper institutions, stronger financial regulation, and more developed green capital markets benefit more from FD than those where finance still primarily serves conventional production and consumption.

The direct effect of the DE is somewhat mixed between location/scale and quantile estimates, but the quantile coefficients are consistently positive and significant across all four specifications. This suggests that digitalization improves environmental sustainability across EU countries, even though the average effect may look ambiguous when heterogeneity is ignored. In practical terms, the DE appears to support higher LCF through efficiency gains, smarter production systems, improved information flows, and enhanced coordination in energy and resource use. This finding aligns with Zhong et al. [26], who argue that digitalization can reduce environmental degradation through energy efficiency, green technology innovation, and structural upgrading. It is also consistent with the broader argument in Nathaniel et al. [32] that DE variables can reshape environmental outcomes. However, it differs from the more cautious literature that emphasizes the energy-intensive side of digital infrastructure and data use. The EU context helps explain the positive sign. European countries generally combine digital development with stronger institutions, energy regulation, environmental monitoring, and green innovation frameworks. Therefore, the DE is more likely to complement sustainability goals rather than simply increase energy demand through uncontrolled digital expansion.

The interaction term between the DE and EG is positive and statistically significant across quantiles. This implies that digitalization moderates the adverse effect of EG on environmental sustainability and partly offsets the ecological burden associated with expansion. In other words, although growth alone reduces LCF, the presence of a stronger DE weakens that negative relationship. This is an important result because it suggests that the environmental cost of growth is conditional on the level of digital transformation. In more digitalized EU economies, growth may become less resource-intensive due to productivity improvements, smarter logistics, digital public services, automated resource management, and cleaner production systems. This interpretation is fully consistent with the study's theoretical framework and supports the idea that digitalization can reshape the growth–environment nexus in a more sustainable direction.

The interaction term between the DE and REC is also positive and significant across all quantiles. This indicates that digitalization strengthens the beneficial effect of renewable energy on LCF. Put differently, renewable energy becomes more environmentally effective when it is complemented by higher levels of digital development. This is plausible in the EU because digital technologies improve renewable energy integration through smart grids, real-time demand management, storage optimization, and better forecasting of intermittent energy sources. Therefore, digitalization does not merely act as an independent sustainability driver; it enhances the efficiency and environmental payoff of the renewable energy transition. This result is strongly in line with the argument in the literature that digital systems can facilitate energy transition and technological upgrading.

The interaction term between the DE and FD is positive and significant as well. This means that digitalization amplifies the positive effect of FD on environmental sustainability. In economies with a more advanced digital base, FD appears to be more effective in supporting environmental performance. A likely reason is that digitalization improves financial transparency, reduces transaction costs, expands fintech and green fintech solutions, and enhances the allocation of capital toward cleaner investments. In the EU context, where sustainable finance frameworks are becoming increasingly important, the DE may help channel financial resources more efficiently into environmentally supportive sectors. Thus, the interaction result suggests that digitalization and finance operate as complementary pillars of ecological sustainability rather than as separate forces. A summary of the findings from the estimation is also depicted in *Fig. 3* below.

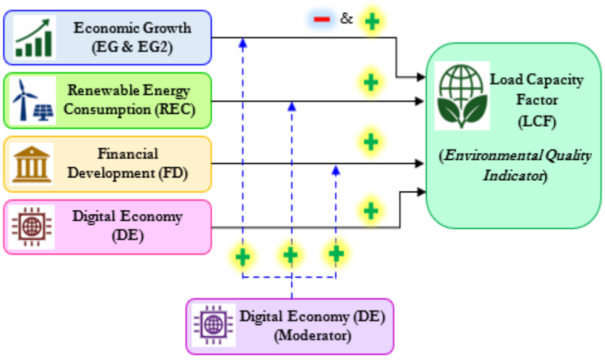

Fig. 3. Graphical presentation of empirical results.

Overall, *Table 6* suggests that EG remains environmentally costly in the EU, whereas renewable energy, FD, and the DE generally improve environmental sustainability. More importantly, the three interaction terms show that digitalization plays a constructive moderating role: it softens the negative ecological effect of growth and enhances the positive effects of renewable energy and finance. These findings reinforce the study's central argument that the DE matters not only directly, but also indirectly by conditioning the environmental effectiveness of other structural determinants.

5 | Conclusion

This study investigates the impact of EG, REC, FD, and the DE on environmental sustainability, measured by the LCF, in EU countries using the MMQR approach. The findings reveal that EG exerts a negative effect on environmental sustainability, indicating that growth in the EU still imposes ecological pressure. In contrast, REC consistently improves environmental quality, highlighting its critical role in sustainability transitions. FD shows a generally positive effect across higher quantiles, suggesting that advanced financial systems can support environmental improvement. The DE also contributes positively to sustainability, particularly across the distribution of LCF. Importantly, the interaction results indicate that digitalization mitigates the adverse effects of EG while strengthening the positive impacts of renewable energy and FD, confirming its dual role as both a direct and moderating factor in shaping environmental outcomes.

5.1 | Policy Recommendation

The findings offer several important policy implications. First, policymakers should accelerate the transition toward renewable energy, as its positive environmental impact is robust across all quantiles. Second, EG strategies should be aligned with sustainability objectives by promoting green technologies and reducing reliance on resource-intensive sectors. Third, FD should be directed toward green investment channels, including sustainable finance and climate-related funding mechanisms. Most importantly, the results highlight the strategic role of the DE. Governments should enhance digital infrastructure, promote smart energy systems, and support digital innovation, as digitalization not only improves environmental sustainability directly but also amplifies the effectiveness of renewable energy and green finance. Therefore, integrating digital transformation with environmental and economic policies is essential for achieving long-term sustainability in EU countries.

Authors' Contributions

M. K.: Writing-original draft, Methodology, Data Curation, Conceptualization, Software, and Visualization, Writing-Review & Editing, and Validation. F. N.: Writing-Review & Editing, and Formal Analysis. S. F. F.: Validation, formal analysis, and investigation. The authors have read and agreed to the published version of the manuscript.

Data Availability

All data supporting the reported findings in this research paper are provided within the manuscript.

Funding

No external funding was received for this research.

Conflict of Interest

There are no competing interests to declare.

Consent for Publication

The authors have given consent for the publication of this manuscript.

Ethics Approval and Consent to Participate

The authors confirm that this research did not involve human participants or animal subjects.

References

[1] Ullah, A., Ahmed, M., Raza, S. A., & Ali, S. (2021). A threshold approach to sustainable development: Nonlinear relationship between renewable energy consumption, natural resource rent, and ecological footprint. *Journal of environmental management*, *295*, 113073. https://doi.org/10.1016/j.jenvman.2021.113073

[2] Berkhout, F. (2002). Technological regimes, path dependency and the environment. *Global environmental change*, *12*(1), 1–4. https://doi.org/10.1016/S0959-3780(01)00025-5

[3] Yıldırım, M. Ş., & Baycan, İ. O. (2023). Analyzing the effects of energy productivity: The case of European Union countries. *Environmental science and pollution research*, *30*(55), 117519-117530. https://doi.org/10.1007/s11356-023-30516-6%0A%0A

[4] Afolabi, J. A. (2025). Towards carbon neutrality in Europe: The role of technology exports, renewable energy consumption, and resource productivity. *Journal of environmental management*, *395*, 127862. https://doi.org/10.1016/j.jenvman.2025.127862

[5] Amer, E. A. A. A., Meyad, E. M. A., Meyad, A. M., & Mohsin, A. K. M. (2024). The impact of natural resources on environmental degradation: a review of ecological footprint and CO2 emissions as indicators. *Frontiers in environmental science*, *12*, 1368125. https://www.frontiersin.org/journals/environmental-science/articles/10.3389/fenvs.2024.1368125/full

[6] Nassani, A. A., Awan, U., Zaman, K., Hyder, S., Aldakhil, A. M., & Abro, M. M. Q. (2019). Management of natural resources and material pricing: Global evidence. *Resources policy*, *64*, 101500. https://doi.org/10.1016/j.resourpol.2019.101500

[7] Aydin, M., Degirmenci, T., & Yavuz, H. (2023). The influence of multifactor productivity, research and development expenditure, renewable energy consumption on ecological footprint in G7 countries: Testing the environmental Kuznets curve hypothesis. *Environmental modeling & assessment*, *28*(4), 693–708. https://doi.org/10.1007/s10666-023-09879-0%0A%0A

[8] Ehigiamusoe, K. U., Ramakrishnan, S., Lean, H. H., & Mustapha, M. (2023). The moderating roles of renewable and non-renewable energy consumption on the ecological impact of economic growth in Southeast Asia. *Energy systems*, 1–19. https://doi.org/10.1007/s12667-023-00616-w%0A%0A

[9] 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

[10] Zhou, X., Patel, G., Mahalik, M. K., & Gozgor, G. (2024). Effects of green energy and productivity on environmental sustainability in BRICS economies: The role of natural resources rents. *Resources policy*, *92*, 105026. https://doi.org/10.1016/j.resourpol.2024.105026

[11] 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: Volume 1* (pp. 1-13). Cham: Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-65203-5_1%0A%0A

[12] Fakher, H. A. (2021). The role of environmental sustainability, foreign direct investment and trade openness in economic growth: With emphasis on the causal linkage. *Big data and computing visions*, *1*(2), 57–70. https://doi.org/10.22105/bdcv.2021.142227

[13] Su, C.-W., Xie, Y., Shahab, S., Faisal, C. M. N., Hafeez, M., & Qamri, G. M. (2021). Towards achieving sustainable development: role of technology innovation, technology adoption and CO2 emission for BRICS. *International journal of environmental research and public health*, *18*(1), 277. https://doi.org/10.3390/ijerph18010277

[14] Ibrahim, R. L., Adebayo, T. S., Awosusi, A. A., Ajide, K. B., Adewuyi, A. O., & Bolarinwa, F. O. (2024). Investigating the asymmetric effects of renewable energy-carbon neutrality nexus: Can technological innovation, trade openness, and transport services deliver the target for Germany? *Energy & environment*, *35*(1), 185–206. https://doi.org/10.1177/0958305X221127020

[15] Fakher, H. A. (2020). Analytical insights on the relationship between economic growth and environmental degradation in framework of EKC hypothesis and various environmental indicators. *Innovation management and operational strategies*, *1*(3), 252–268. https://doi.org/10.22105/imos.2021.272348.1032

[16] Kwilinski, A., Lyulyov, O., & Pimonenko, T. (2024). Renewable power systems: a comprehensive meta-analysis. *Energies*, *17*(16), 3989. https://doi.org/10.3390/en17163989

[17] Grodzicki, T., & Jankiewicz, M. (2022). The impact of renewable energy and urbanization on CO2 emissions in Europe--Spatio-temporal approach. *Environmental development*, *44*, 100755. https://doi.org/10.1016/j.envdev.2022.100755

[18] Twum, A. K., Zhang, J., Ding, X., & Cobbinah, J. (2024). Advancing renewable energy strategies towards sustainable development goal 13: insights from belt and road initiative (BRI) countries. *Environment, development and sustainability*, 1–32. https://doi.org/10.1007/s10668-024-05800-1%0A%0A

[19] Tithi, S. I. (2026). Towards Sustainable Development Goals: An ARDL Analysis of Energy Efficiency, Finance, and Technology in Mitigating CO_2 Emissions in the United States. *Systemic analytics*, *4*(1), 13–26. https://doi.org/10.31181/sa41202667

[20] Abid, M., Gheraia, Z., Abdelli, H., & others. (2022). Does renewable energy consumption affect ecological footprints in Saudi Arabia? A bootstrap causality test. *Renewable energy*, *189*, 813–821. https://doi.org/10.1016/j.renene.2022.03.043

[21] Kongkuah, M. (2024). Impact of Belt and Road countries' renewable and non-renewable energy consumption on ecological footprint: M. Kongkuah. *Environment, development and sustainability*, *26*(4), 8709–8734. https://doi.org/10.1007/s10668-023-03068-5%0A%0A

[22] Alola, A. A., & Adebayo, T. S. (2023). Are green resource productivity and environmental technologies the face of environmental sustainability in the Nordic region? *Sustainable development*, *31*(2), 760–772. https://doi.org/10.1002/sd.2417

[23] Marshadi, A. H. A. L., Aslam, M., & Janjua, A. A. (2025). Ecological footprints, global sustainability, and the roles of natural resources, financial development, and economic growth. *Plos one*, *20*(3), e0317664. https://doi.org/10.1371/journal.pone.0317664

[24] Shobande, O. A., & Ogbeifun, L. (2024). Exploring the criticality of natural resources management and technological innovations for ecological footprint in the OECD countries. *The journal of developing areas*, *58*(1), 157–170. https://doi.org/10.1353/jda.2024.a924520

[25] Tithi, S. I. (2025). Decarbonizing the US economy through artificial intelligence and information technology: An empirical ARDL analysis. *Information sciences and technological innovations*, *2*(2), 108–120. https://doi.org/10.48314/isti.v2i2.45

[26] Zhong, S., Shen, H., Niu, Z., Yu, Y., Pan, L., Fan, Y., & Jahanger, A. (2022). Moving towards environmental sustainability: can digital economy reduce environmental degradation in China? *International journal of environmental research and public health*, *19*(23), 15540. https://doi.org/10.3390/ijerph192315540

[27] Shahnazi, R., & Shabani, Z. D. (2020). Do renewable energy production spillovers matter in the EU? *Renewable energy*, *150*, 786–796. https://doi.org/10.1016/j.renene.2019.12.123

[28] Wang, M., Chen, Y., Xie, Z., Dai, J., Zhang, Y., & Cheng, P. (2026). The Impact of Digital Transformation on Electricity Consumption: The Role of Green Technology Innovation and Urbanization. *Energies*, *19*(4), 882. https://doi.org/10.3390/en19040882

[29] Mushafiq, M., & Prusak, B. (2023). Resource productivity and environmental degradation in EU-27 countries: context of material footprint. *Environmental science and pollution research*, *30*(20), 58536–58552. https://doi.org/10.1007/s11356-023-26631-z%0A%0A

[30] Pié, L., Fabregat-Aibar, L., & Saez, M. (2018). The influence of imports and exports on the evolution of greenhouse gas emissions: the case for the European Union. *Energies*, *11*(7), 1644. https://doi.org/10.3390/en11071644

[31] Tithi, S. I. (2025). Pathways to carbon neutrality in the united states: evaluating private ai investment, financial development, and macroeconomic forces. *International journal of business and economic studies*, *7*(4), 231–242. https://doi.org/10.54821/uiecd.1831647

[32] 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. In *Natural resources forum*. Oxford, UK: Blackwell Publishing Ltd. https://doi.org/10.1111/1477-8947.12590

[33] Hakkak, M., Altintaş, N., & Hakkak, S. (2023). Exploring the relationship between nuclear and renewable energy usage, ecological footprint, and load capacity factor: A study of the Russian Federation testing the EKC and LCC hypothesis. *Renewable energy focus*, *46*, 356-366. https://doi.org/10.1016/j.ref.2023.07.005

[34] Usubiaga-Liaño, A., & Ekins, P. (2021). Monitoring the environmental sustainability of countries through the strong environmental sustainability index. *Ecological indicators*, *132*, 108281. https://doi.org/10.1016/j.ecolind.2021.108281

[35] Wang, T. (2018). Energy ecological footprint changes and its influencing factors at the provincial scale in China. *IOP conference series: Earth and environmental science* (Vol. 186, No. 4, p. 012071). IOP Publishing. https://doi.org/10.1088/1755-1315/186/4/012071

[36] Ridwan, M. (2025). Artificial intelligence and green development: The role of financial market efficiency in the United States. *Development and sustainability in economics and finance*, 100099. https://doi.org/10.1016/j.dsef.2025.100099

[37] Blomquist, J., & Westerlund, J. (2013). Testing slope homogeneity in large panels with serial correlation. *Economics letters*, *121*(3), 374–378. https://doi.org/10.1016/j.econlet.2013.09.012

[38] 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