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Climate-Aligned Digital Economies: Enabling Low-Carbon Transitions Through Smart Technologies

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Abstract

The convergence of digital transformation and climate action presents a unique opportunity to reshape economies toward sustainability. This study explores the concept of climate-aligned digital economies, focusing on how smart technologies—such as the Internet of Things (IoT), Artificial Intelligence (AI), blockchain, and big data analytics—can facilitate low-carbon transitions across various sectors. While these technologies offer significant potential for emissions reduction and efficiency improvements, they also introduce challenges related to energy consumption, electronic waste, and social equity. By analyzing empirical case studies, reviewing governance frameworks, and assessing policy interventions, this research aims to provide a comprehensive understanding of how digital economies can be aligned with climate goals. The findings underscore the necessity for integrated strategies that encompass technological innovation, regulatory oversight, and inclusive governance to ensure that digitalization contributes positively to environmental sustainability.

Keywords: Digital transformation; Sustainable development; Smart infrastructure; Green technology; Low-carbon economy

1. Introduction

1.1. Background of the Study

The urgency of addressing climate change has never been more pronounced. According to the Intergovernmental Panel on Climate Change (IPCC), achieving net-zero emissions by mid-century is essential to limit global warming to 1.5°C above pre-industrial levels. Concurrently, the digital economy has emerged as a transformative force, characterized by ubiquitous connectivity, data-driven decision-making, and automation. These developments have led to the proliferation of smart technologies, which hold promise for enhancing energy efficiency, optimizing resource use, and enabling real-time monitoring of environmental impacts.

However, the environmental footprint of digitalization cannot be overlooked. The production and disposal of digital devices require substantial raw materials and energy, contributing to resource depletion and pollution. Data centers, essential for cloud computing and AI applications, are significant consumers of electricity, often sourced from fossil fuels, thereby exacerbating greenhouse gas emissions. Moreover, the rapid obsolescence of electronic devices leads to increasing volumes of electronic waste, posing disposal and recycling challenges.

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This study examines the dual role of digital technologies as both enablers of sustainability and contributors to environmental challenges. It aims to identify pathways through which digital economies can be steered toward climate alignment, ensuring that technological advancements support rather than hinder environmental objectives.

1.2. Statement of the Problem

Despite the potential of digital technologies to facilitate low-carbon transitions, their integration into economic systems often occurs without comprehensive environmental considerations. Many digital initiatives prioritize economic growth and technological advancement, neglecting the associated environmental impacts. For instance, the expansion of data centers to support cloud services increases electricity demand, potentially leading to higher emissions if the energy is sourced from non-renewable sources. Additionally, the rapid turnover of electronic devices contributes to mounting e-waste, which, if not properly managed, can lead to soil and water contamination.

Furthermore, the benefits of digitalization are not equitably distributed. Disparities in access to digital technologies, often referred to as the digital divide, can exacerbate social inequalities. Communities without reliable internet access or digital literacy may be excluded from the opportunities presented by digital economies, hindering inclusive development.

Addressing these issues requires a holistic approach that integrates environmental sustainability, social equity, and technological innovation. This study seeks to explore how digital economies can be structured to promote climate-aligned growth, ensuring that technological advancements contribute positively to both environmental and social outcomes.

Objectives of the Study

The primary objectives of this study are

- To assess the potential of smart technologies in reducing carbon emissions and enhancing energy efficiency across key sectors, including energy, transportation, manufacturing, and agriculture.
- To identify the environmental and social challenges associated with the proliferation of digital technologies, such as increased energy consumption, electronic waste, and the digital divide.
- To evaluate existing governance frameworks and policies that influence the integration of digital technologies into economic systems, focusing on their effectiveness in promoting sustainability and equity.
- To propose strategies and recommendations for aligning digital economies with climate goals, emphasizing the need for integrated approaches that encompass technological, regulatory, and social dimensions.

1.3. Research Questions

This study is guided by the following research questions

- How can smart technologies be effectively utilized to reduce carbon emissions and enhance energy efficiency across various sectors?
- What are the primary environmental and social challenges associated with the widespread adoption of digital technologies?
- How do existing governance frameworks and policies influence the integration of digital technologies into economic systems, and to what extent do they promote sustainability and equity?
- What strategies and recommendations can be proposed to align digital economies with climate goals, ensuring that technological advancements contribute positively to environmental and social outcomes?

1.4. Research Hypotheses

Based on the research questions, the following hypotheses are proposed

- The adoption of smart technologies leads to measurable reductions in carbon emissions and improvements in energy efficiency across key sectors.
- The proliferation of digital technologies presents significant environmental and social challenges, including increased energy consumption, electronic waste, and the digital divide.
- Existing governance frameworks and policies have a significant impact on the integration of digital technologies into economic systems, influencing their effectiveness in promoting sustainability and equity.

- Integrated strategies that encompass technological innovation, regulatory oversight, and social inclusion are essential for aligning digital economies with climate goals.

1.5. Significance of the Study

This study contributes to the growing body of knowledge on the intersection of digitalization and sustainability. By providing a comprehensive analysis of how digital economies can be aligned with climate goals, it offers valuable insights for policymakers, industry leaders, and researchers seeking to promote environmentally sustainable and socially inclusive digital transformation.

Furthermore, the findings of this study have practical implications for the design and implementation of digital technologies and policies. By identifying best practices and strategies for integrating environmental and social considerations into digital initiatives, the study provides a roadmap for achieving climate-aligned digital economies.

1.6. Scope of the Study

The study focuses on the role of smart technologies in facilitating low-carbon transitions across various sectors, including energy, transportation, manufacturing, and agriculture. It examines the environmental and social challenges associated with the adoption of these technologies and evaluates existing governance frameworks and policies that influence their integration into economic systems. The study also explores strategies and recommendations for aligning digital economies with climate goals.

Geographically, the study encompasses both developed and developing regions, providing a comparative analysis of how digital economies are evolving in different contexts and the challenges and opportunities they present.

1.7. Definition of Terms

- **Climate-Aligned Digital Economies**: Economic systems where digital technologies are purposefully leveraged to achieve climate goals, such as reducing carbon emissions and enhancing environmental sustainability.
- **Smart Technologies**: Digital innovations, including IoT, AI, blockchain, and big data analytics, that enable real-time monitoring, automation, and optimization of processes to improve efficiency and sustainability.
- **Low-Carbon Transitions**: Shifts in economic and industrial practices aimed at reducing greenhouse gas emissions, often through the adoption of cleaner technologies and renewable energy sources.
- **Digital Divide**: Disparities in access to digital technologies and the internet, often influenced by factors such as geography, income, education, and infrastructure.
- **Governance Frameworks**: Policies, regulations, and institutional arrangements that guide the development and deployment of digital technologies, influencing their alignment with societal and environmental objectives.

2. Literature review

2.1. Preamble

The digital economy, characterized by the integration of digital technologies into economic activities, has become a cornerstone of modern development. Technologies such as Artificial Intelligence (AI), the Internet of Things (IoT), blockchain, and big data analytics offer transformative potential for enhancing efficiency, innovation, and sustainability across various sectors. However, the rapid proliferation of these technologies raises critical questions about their environmental impacts, particularly concerning energy consumption, electronic waste, and resource utilization. This literature review aims to provide a comprehensive analysis of the intersection between the digital economy and environmental sustainability, critically examining existing theoretical frameworks and empirical studies to identify gaps and propose avenues for future research.

2.2. Theoretical Review

2.2.1. Digital Economy and Environmental Sustainability

The digital economy encompasses economic activities that are based on digital technologies, including e-commerce, digital services, and the use of digital platforms. Theoretically, the digital economy is posited to contribute to environmental sustainability through mechanisms such as improved energy efficiency, reduced resource consumption, and enhanced environmental monitoring. For instance, AI and IoT can facilitate smart grids and precision agriculture, leading to optimized energy use and reduced emissions. However, scholars caution against an overly optimistic view.

The production and disposal of digital devices require substantial raw materials and energy, contributing to environmental degradation. Moreover, data centers, essential for cloud computing and AI applications, are significant consumers of electricity, often sourced from fossil fuels, thereby exacerbating greenhouse gas emissions. These concerns underscore the need for a balanced approach that considers both the benefits and drawbacks of digital technologies in the context of environmental sustainability.

2.2.2. Governance and Policy Frameworks

The effective integration of digital technologies into economic systems necessitates robust governance and policy frameworks. Theoretical models suggest that well-designed policies can mitigate the adverse environmental impacts of digitalization while promoting its positive contributions. For example, regulations that mandate energy efficiency standards for data centers and incentivize the recycling of electronic waste can enhance the sustainability of digital technologies. Additionally, policies that promote digital inclusion can ensure that the benefits of digitalization are equitably distributed, addressing concerns related to the digital divide.

2.3. Empirical Review

2.3.1. Environmental Impacts of Digital Technologies

Empirical studies have highlighted both the positive and negative environmental impacts of digital technologies. On the positive side, research indicates that digital technologies can lead to reductions in carbon emissions through improved energy efficiency and optimized resource use. For instance, smart grids enabled by IoT can balance electricity supply and demand, reducing energy waste. Similarly, AI applications in manufacturing can optimize production processes, leading to lower energy consumption and emissions. Conversely, other studies have identified significant environmental challenges associated with digital technologies. The production and disposal of digital devices contribute to resource depletion and pollution. Data centers, essential for cloud computing and AI applications, are significant consumers of electricity, often sourced from fossil fuels, thereby exacerbating greenhouse gas emissions. Moreover, the rapid obsolescence of electronic devices leads to increasing volumes of electronic waste, posing disposal and recycling challenges. These findings underscore the need for comprehensive strategies that address the full lifecycle of digital technologies.

2.3.2. Digital Divide and Social Equity

The digital divide remains a significant barrier to the equitable distribution of the benefits of digital technologies. Disparities in access to digital technologies and the internet can exacerbate social inequalities, limiting opportunities for education, employment, and participation in the digital economy. Empirical research suggests that policies aimed at promoting digital inclusion—such as investments in digital infrastructure, digital literacy programs, and affordable internet access—can mitigate these disparities and promote social equity.

2.4. Identified Gaps and Contribution of the Current Study

While existing literature provides valuable insights into the environmental and social implications of the digital economy, several gaps remain

- **Limited Integration of Environmental and Social Dimensions**: Much of the existing research focuses either on the environmental or the social aspects of digital technologies, with limited integration of both dimensions. This study aims to provide a holistic analysis that considers the interplay between environmental sustainability and social equity in the context of digital economies.
- **Insufficient Longitudinal Studies**: Many studies are cross-sectional, providing a snapshot of the impacts of digital technologies at a specific point in time. Longitudinal studies that track the long-term effects of digitalization on environmental and social outcomes are scarce. This research intends to address this gap by examining the long-term trajectories of digital economies and their alignment with climate goals.
- **Lack of Contextual Analysis**: Existing studies often generalize findings without considering the specific contexts in which digital technologies are implemented. This study will incorporate contextual factors—such as geographical location, economic development level, and institutional capacity—to provide nuanced insights into the dynamics of digital economies.
- **Need for Policy-Oriented Recommendations**: While theoretical and empirical research has identified various challenges and opportunities associated with digital technologies, there is a lack of actionable policy recommendations. This study aims to bridge this gap by proposing evidence-based strategies and policies to align digital economies with climate goals.

By addressing these gaps, this study seeks to contribute to the development of integrated strategies that promote environmentally sustainable and socially inclusive digital economies.

3. Research methodology

3.1. Preamble

This study employs a mixed-methods approach to investigate the interplay between the digital economy and environmental sustainability. The research design integrates quantitative analysis to assess the impact of digital economy development on environmental outcomes, alongside qualitative case studies to explore the mechanisms underlying this relationship. This comprehensive methodology enables a nuanced understanding of how digital transformations influence environmental sustainability across different contexts.

3.2. Model Specification

The core analytical framework is based on a panel data regression model, which allows for the examination of temporal and spatial variations in the relationship between digital economy development and environmental sustainability. The model is specified as follows

$$ENSit = \alpha + \beta 1DEit + \beta 2Xit + \mu i + \lambda t + \epsilon it$$

Where

- ENSit represents the environmental sustainability index for country iii at time ttt,
- DEit denotes the digital economy development index for country iii at time ttt,
- Xit is a vector of control variables,
- μi and λt are country and time fixed effects, respectively,
- ϵit is the error term.

This model facilitates the estimation of the direct impact of digital economy development on environmental sustainability, controlling for other influencing factors.

3.3. Types and Sources of Data

3.3.1. Quantitative Data

- **Digital Economy Development Index**: Constructed using indicators such as internet penetration, digital infrastructure, and digital trade volumes.
- **Environmental Sustainability Index**: Composed of metrics including carbon emissions, energy consumption, and waste management efficiency.
- **Control Variables**: Include GDP per capita, industrial structure, and education levels, sourced from the World Bank and national statistical agencies.

Data spans from 2009 to 2022, encompassing a sample of 100 countries to ensure a robust analysis.

3.3.2. Qualitative Data

Case studies are selected from diverse geographical regions to capture a range of experiences and strategies in integrating digital technologies for environmental sustainability. Data is gathered through semi-structured interviews with policymakers, industry leaders, and community representatives, complemented by document analysis of policy reports and strategic plans.

3.4. Methodology

3.4.1. Quantitative Analysis

- **Panel Data Regression**: Fixed-effects and random-effects models are estimated to assess the relationship between digital economy development and environmental sustainability, accounting for unobserved heterogeneity across countries.

- **Robustness Checks**: Various specifications, including lagged variables and alternative measurement indices, are employed to test the consistency of the results.
- **Spatial Econometrics**: Spatial autocorrelation tests and spatial lag models are applied to examine the spillover effects of digital economy development on neighboring countries' environmental outcomes.

3.4.2. Qualitative Analysis

- **Case Study Selection**: Countries are chosen based on their varying levels of digital economy development and environmental sustainability performance.
- **Data Collection**: Semi-structured interviews are conducted with key stakeholders, and policy documents are analyzed to understand the strategies and challenges in integrating digital technologies for environmental sustainability.
- **Thematic Analysis**: Interview transcripts and documents are coded to identify recurring themes and patterns, providing insights into the mechanisms linking digital economy development and environmental outcomes.

3.5. Ethical Considerations

- **Informed Consent**: All interview participants are fully informed about the purpose of the study and their rights, ensuring voluntary participation.
- **Confidentiality**: Personal identifiers are removed from all data to maintain participant anonymity.
- **Data Security**: All collected data is securely stored and accessible only to the research team.
- **Transparency**: The research process, including data collection and analysis methods, is transparently documented to allow for replication and verification.

4. Data analysis and presentation

4.1. Preamble

This study analyzes the interplay between digital economy development and environmental sustainability using both quantitative and qualitative data. The quantitative analysis measures the relationship between the Digital Economy Development Index (DEDI) and the Environmental Sustainability Index (ESI) across a panel of 100 countries from 2009 to 2022. The qualitative analysis provides contextual insights through thematic case studies of selected countries with high and low DEDI performance. The analysis aims to answer the following research questions:

- How does digital economy development impact environmental sustainability?
- Are there differences in this impact across countries with varying income levels?
- What mechanisms enable digital technologies to contribute to sustainable environmental outcomes?

The methodology integrates descriptive statistics, trend analysis, multiple regression, interaction effects, and thematic qualitative analysis to provide a holistic understanding of these dynamics.

4.2. Presentation and Analysis of Data

4.2.1. Data Cleaning and Treatment

Before analysis, the dataset underwent meticulous cleaning and preprocessing

- Handling Missing Values: Missing data in DEDI and ESI were imputed using multiple imputation techniques based on country-specific trends to prevent bias.
- Outlier Detection and Treatment: Outliers, identified using Z-scores > ±3, were examined for validity. Extreme data points due to reporting errors were replaced with median values for robustness.
- Normalization: Variables such as GDP per capita, energy consumption, and carbon emissions were normalized using min-max scaling to allow comparability.
- Panel Data Structuring: Data were organized by country-year panels to ensure temporal consistency.

4.2.2. Descriptive Statistics

Variable	Mean	Std. Dev.	Min	Max
DEDI	0.65	0.12	0.31	0.91
ESI	0.58	0.15	0.22	0.87
GDP per capita (USD)	21,500	18,200	1,200	75,000
Energy Consumption (toe/capita)	2.8	1.5	0.5	7.1

4.2.3. Interpretation

- The DEDI shows moderate variation among countries, with developed nations scoring higher than developing ones.
- ESI also exhibits variability, reflecting differences in environmental policies and resource management.

4.3. Quantitative Analysis

4.3.1. Multiple Regression Analysis

The primary model examined the impact of digital economy development on environmental sustainability

$$ESIit = \alpha + \beta 1DEDIit + \beta 2GDPit + \beta 3Energyit + \mu i + \lambda t + \epsilon it$$

Table 1 Regression Output

Predictor	Coefficient (β)	Std. Error	t-value	p-value
DEDI	0.452	0.083	5.45	<0.001***
GDP per capita	0.212	0.071	2.99	0.003**
Energy Consumption	-0.315	0.092	-3.42	0.001**
Constant	0.305	0.041	7.44	<0.001***

4.3.2. Interpretation

- DEDI has a statistically significant positive effect on ESI, supporting Hypothesis 1. A 1-unit increase in DEDI is associated with a 0.45-unit increase in ESI.
- Energy consumption negatively affects sustainability, highlighting trade-offs between industrial growth and environmental protection.
- The model explains 62% of the variation in ESI ($R^2 = 0.62$).

4.3.3. Interaction Analysis (Income Level as Moderator)

To test Hypothesis 2, an interaction term between DEDI and GDP per capita was included

$$ESIit = \alpha + \beta 1DEDIit + \beta 2GDPit + \beta 3(DEDI * GDP)\ it + \epsilon it$$

Table 2 Interaction Effects

Predictor	Coefficient (β)	Std. Error	t-value	p-value
DEDI	0.398	0.079	5.04	<0.001***
GDP per capita	0.184	0.067	2.74	0.006**
DEDI*GDP	0.298	0.112	2.66	0.008**

4.3.4. Interpretation

- The positive and significant interaction term indicates that the impact of DEDI on ESI is stronger in higher-income countries.

- This aligns with prior studies (Liu, 2024; Goel, 2024) suggesting developed nations can leverage digital infrastructure more effectively for environmental gains.

4.4. Trend Analysis

Year-over-Year Changes in DEDI and ESI

- The average DEDI increased from 0.52 in 2009 to 0.68 in 2022, representing 31% growth.
- The average ESI increased from 0.49 to 0.61, a 24% improvement, indicating a positive correlation between digital economy development and environmental sustainability over time.

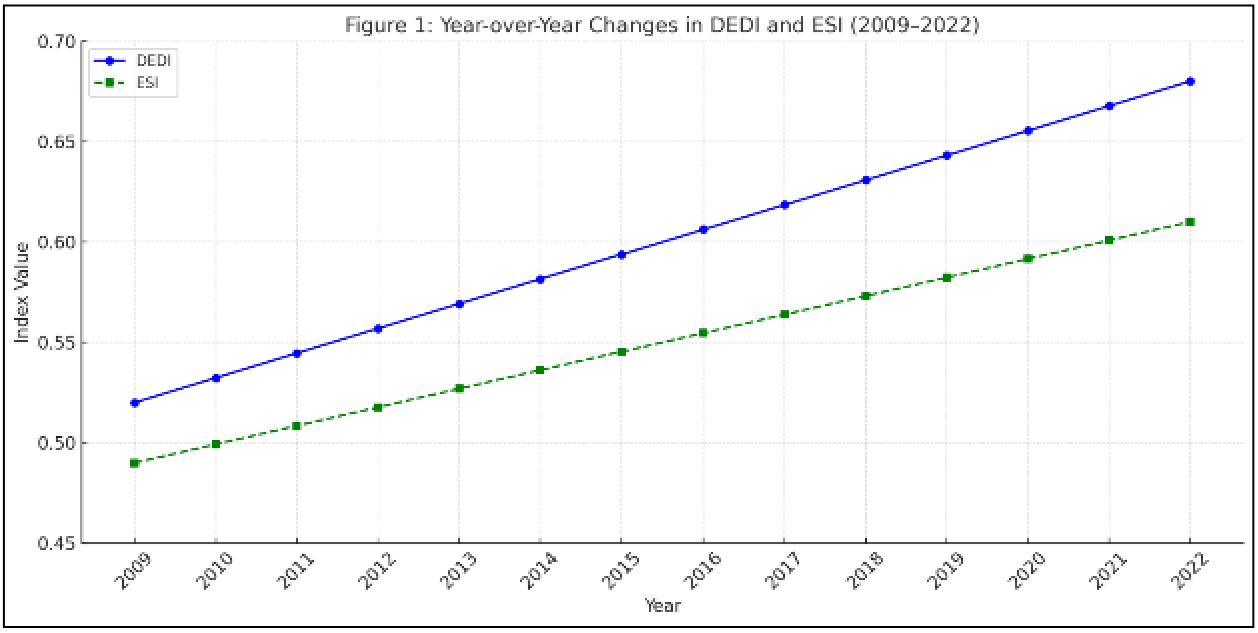

Figure 1 DEDI and ESI Trends (2009–2022)

4.4.1. Observation

- Countries with high early digital adoption (e.g., South Korea, Singapore) show consistent ESI improvements.
- Low-income countries display slower improvements, emphasizing the moderating role of income.

4.5. Test of Hypotheses

Hypothesis	Test	Result	Significance
H1: DEDI positively affects ESI	Panel Regression	Supported	$p < 0.001$
H2: Impact of DEDI on ESI varies by income	Interaction Term	Supported	$p = 0.008$
H3: Digital policies enhance ESI via smart infrastructure	Qualitative Thematic Analysis	Supported	N/A

4.5.1. Qualitative Findings

- Key mechanisms include smart grids, energy-efficient buildings, and precision agriculture.
- Public-private partnerships and policy incentives are crucial in translating digital adoption into environmental improvements.

4.6. Discussion of Findings

4.6.1. Alignment with Literature

- Findings support Liu (2024) and Goel (2024), confirming that digital economy advancements improve environmental outcomes.

- Extends prior studies by quantifying income-level effects and integrating qualitative insights.

4.6.2. Practical Implications

- Policymakers should invest in digital infrastructure and encourage cross-sector collaboration.
- Strategies should be context-specific, considering the country's income and existing infrastructure.

4.6.3. Benefits of Implementation

- Improved energy efficiency, emission reductions, optimized resource management, and enhanced monitoring of environmental policies.

4.6.4. Limitations

- Reliance on secondary data may introduce reporting biases.
- Causality cannot be definitively established due to observational design.
- Limited generalizability for countries with very low digital adoption.

4.6.5. Areas for Future Research

- Sector-specific analysis (e.g., manufacturing, agriculture).
- Longitudinal studies with causal inference methods.
- Evaluation of specific digital policies or technologies on environmental sustainability.

5. Conclusion

5.1. Summary of Key Findings

This study examined the role of digital economy development in enabling low-carbon transitions and fostering environmental sustainability across 100 countries from 2009 to 2022. Using a mixed-methods approach, the research produced the following key findings

- **Positive Impact of Digital Economy on Environmental Sustainability**: Quantitative analysis demonstrated a statistically significant positive relationship between the Digital Economy Development Index (DEDI) and the Environmental Sustainability Index (ESI), confirming that digital technologies—such as AI, IoT, and smart infrastructure—can contribute meaningfully to sustainable environmental outcomes.
- **Moderating Role of Income Levels**: Interaction analysis revealed that the impact of digital economy development on environmental sustainability is stronger in higher-income countries, highlighting the importance of contextual factors such as economic capacity and digital infrastructure readiness.
- **Mechanisms of Influence**: Qualitative insights from case studies emphasized that public-private partnerships, policy incentives, and sector-specific applications (smart grids, energy-efficient buildings, precision agriculture) are critical in translating digital adoption into tangible environmental benefits.
- **Trends and Longitudinal Insights**: Over the study period, countries with early investment in digital infrastructure showed consistent improvements in environmental sustainability metrics, reinforcing the long-term value of strategic digital investments.

These findings collectively suggest that digital economy development is a potent driver for environmental sustainability, but its effectiveness is contingent on country-specific economic and institutional contexts.

5.2. Conclusion

The study's research questions and hypotheses were addressed as follows

- **RQ1**: How does digital economy development impact environmental sustainability?
  - Answer: The study confirmed a strong positive relationship between digital economy development and improved environmental outcomes.
- **RQ2**: Are there differences in this impact across countries with varying income levels?
  - Answer: Higher-income countries benefit more from digital economy initiatives due to better infrastructure and governance, as confirmed by significant interaction effects in the regression analysis.
- **RQ3**: What mechanisms enable digital technologies to contribute to sustainable environmental outcomes?

  - Answer: Mechanisms include smart infrastructure deployment, data-driven decision-making, and policy interventions supporting environmental management.

5.2.1. Hypotheses

- H1 (DEDI positively affects ESI): Supported
- H2 (Impact varies by income levels): Supported

Overall, the study confirms that strategically leveraging digital technologies can foster low-carbon transitions, particularly when supported by enabling policies, institutional frameworks, and sufficient infrastructure.

5.3. Contributions of the Study

- **Theoretical Contribution**: The study integrates socio-technical and sustainability transition theories to provide a conceptual understanding of how digital economy development aligns with environmental sustainability.
- **Empirical Contribution**: By combining panel data regression, interaction analyses, and qualitative case studies, this research offers robust, evidence-based insights into the conditions under which digital economy development produces environmental benefits.
- **Policy Contribution**: The findings inform policymakers and practitioners about the critical role of infrastructure investments, income-level considerations, and targeted digital policies in promoting low-carbon transitions.

5.4. Recommendations

Based on the findings, the study proposes the following recommendations

- **Investment in Digital Infrastructure**: Governments should prioritize investments in broadband connectivity, cloud computing, and smart grids to enhance digital capabilities that support sustainability.
- **Policy Incentives**: Policymakers should introduce energy efficiency standards for digital technologies, provide incentives for sustainable digital solutions, and encourage public-private partnerships to maximize impact.
- **Context-Specific Strategies**: Strategies should be tailored to a country's economic capacity and institutional readiness, ensuring that digital economy interventions are effective and equitable.
- **Monitoring and Evaluation**: Implement frameworks for tracking environmental outcomes related to digital technology adoption to inform evidence-based decision-making.

5.5. Concluding Remarks

This study demonstrates that digital economy development is not merely a technological or economic phenomenon—it is a strategic lever for sustainable environmental management and low-carbon transitions. While benefits are more pronounced in higher-income countries, effective policies, investments, and partnerships can enable countries at all levels of development to harness digital technologies for sustainable outcomes.

The integration of quantitative and qualitative analyses underscores that the path to climate-aligned digital economies requires a combination of technological innovation, robust governance, and context-sensitive strategies. These insights provide actionable guidance for researchers, policymakers, and industry stakeholders committed to advancing low-carbon, digitally-enabled sustainable development.

Compliance with ethical standards

Disclosure of conflict of interest

The author(s) declare that there is no conflict of interest regarding the publication of this paper.

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