

Digital Business Models in ESG Transformation

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Abstract

The rapid expansion of the digital economy is transforming the landscape of sustainable entrepreneurship worldwide. This study examines how digital business models accelerate ESG-oriented transformation through the integration of data-driven technologies, platform solutions, and AI-enabled tools. Despite the growing relevance of green entrepreneurship, existing research lacks a systematic understanding of how digitalization enhances environmental performance, social inclusion, and governance transparency. The objective of this paper is to develop a comprehensive conceptual model of Green Digital Entrepreneurship (GDE) and empirically assess its contribution to ESG outcomes. A mixed-method approach was applied, combining quantitative analysis of ESG indicators with qualitative case studies of green digital startups. The findings reveal that digital technologies significantly improve carbon footprint measurement accuracy, reduce operational costs, and strengthen stakeholder engagement. Data-driven models demonstrate the highest ESG impact, particularly in emissions monitoring, circular resource management, and transparency of sustainability reporting. The study contributes to the theoretical development of digital entrepreneurship by linking digital capabilities to sustainable value creation. Practical implications include recommendations for green startups, policymakers, and investors on scaling digital solutions for the low-carbon transition. This research highlights the strategic importance of digital innovation in shaping resilient, climate-responsive, and socially inclusive entrepreneurial ecosystems. Future studies should explore the impact of emerging technologies such as digital twins, green fintech, and AI governance frameworks on long-term ESG transformation.

Keywords: Green digital entrepreneurship, ESG transformation, digital business models, data-driven sustainability, carbon footprint analytics, AI-enabled green innovation, circular economy, digital twins for sustainability, green fintech, platform economy, sustainable entrepreneurship, environmental performance, social inclusion, governance transparency, low-carbon transition.

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1. Introduction

1.1. Background

The global transition toward sustainability has intensified the relevance of the ESG agenda, driven by international frameworks such as the UN Sustainable

Development Goals, the EU Green Deal, and various Net-Zero 2050 commitments. These initiatives emphasize the urgent need to reduce environmental risks, enhance social responsibility, and strengthen governance transparency across all sectors of the economy. Simultaneously, the rapid evolution of the digital economy is reshaping entrepreneurial ecosystems. The

widespread adoption of platform-based business models, AI-driven analytics, the Internet of Things, and digital twin technologies has created unprecedented opportunities for data-enabled decision-making, operational optimization, and resource-efficient innovation. These technologies are increasingly integrated into business processes, enabling firms to scale faster, reduce transaction costs, and develop more adaptive and resilient value chains. At the same time, intensifying environmental challenges-ranging from rising carbon emissions to resource depletion and urban pollution-underscore the necessity of accelerating green innovation. Digital tools play a pivotal role in this shift by enhancing the precision of environmental monitoring, enabling circular resource flows, and supporting the development of sustainable, low-carbon business models. As a result, the convergence of digital transformation and sustainability goals is reshaping the foundations of modern entrepreneurship, giving rise to a new paradigm of Green Digital Entrepreneurship.

1.2. The rise of green digital entrepreneurship

The past decade has witnessed the rapid emergence of green startups whose core value propositions are built entirely on digital services. These firms leverage advanced technologies to create scalable, low-carbon solutions that address environmental externalities while maintaining economic viability. Unlike traditional sustainability-oriented businesses, green digital startups embed environmental intelligence directly into their business models, enabling continuous monitoring, automated decision-making, and data-driven optimization of resource use. A wide range of innovative applications exemplifies this trend. Carbon-tracking apps allow individuals and organizations to measure, visualize, and reduce their carbon footprints with unprecedented accuracy. Energy-efficiency platforms deploy IoT sensors, predictive analytics, and real-time dashboards to optimize consumption patterns in buildings, transportation, and manufacturing systems. Meanwhile, green fintech solutions facilitate sustainable financial behavior through mechanisms such as carbon-offset payments, eco-scoring of transactions, green investment portfolios, and automated reporting aligned with global ESG standards. Together, these technologies illustrate a new generation of entrepreneurial initiatives in which digital infrastructures function not only as tools of economic growth but also as enablers of measurable environmental impact. This digital-driven shift is reshaping the competitive landscape and accelerating the global diffusion of sustainable business practices.

1.3. Problem statement

Despite the growing global interest in sustainable development, the mechanisms through which digital business models accelerate ESG-oriented transformation remain insufficiently systematized in the academic

literature. Existing studies typically examine digitalization and sustainability as separate domains, resulting in a fragmented understanding of how specific technologies-such as AI analytics, IoT monitoring, platform ecosystems, and digital twins-directly contribute to environmental performance, social inclusion, and transparent governance practices. Furthermore, there is a noticeable scarcity of empirical evidence assessing the effectiveness of digital tools within green entrepreneurial ecosystems. While numerous green startups employ digital solutions to optimize energy use, minimize waste, or measure carbon emissions, little is known about the extent to which these tools enhance operational efficiency, improve ESG metrics, or create long-term sustainable value. The lack of integrated data, standardized indicators, and comparative analyses constrains both academic inquiry and practical implementation. As a result, the relationship between digital innovation and green entrepreneurship remains underexplored, highlighting the need for a comprehensive examination of how digital capabilities shape, strengthen, and accelerate ESG transformation.

1.4. Research gap

Although digital transformation and sustainability have become central themes in contemporary economic discourse, research integrating digitalization, ESG principles, and entrepreneurship in EMDE countries remains notably limited. Existing studies primarily focus on mature economies, leaving significant knowledge gaps regarding how emerging markets adopt, adapt, and scale digital tools to accelerate sustainability transitions. This imbalance restricts the generalizability of global findings and overlooks the specific institutional, infrastructural, and socio-economic conditions that shape green digital entrepreneurship in developing regions. Moreover, there is a lack of robust frameworks for evaluating the effectiveness of green digital business models. While numerous digital solutions-ranging from carbon-tracking software to AI-based energy optimization systems-are increasingly used by startups, current literature does not provide unified methodological approaches for assessing their actual ESG impact. The absence of standardized metrics and validated assessment models limits both academic rigor and practical decision-making for investors, policymakers, and entrepreneurs. A further gap lies in the absence of comparative analyses across different types of digital technologies and their respective contributions to environmental, social, and governance outcomes. Prior research tends to examine individual tools in isolation, without contrasting AI, IoT, blockchain, platform models, or digital twins as differentiated enablers of ESG improvement. This lack of comparative evidence hinders the identification of the most effective digital strategies for accelerating the green transition. Taken together, these gaps highlight the need for a comprehensive, multi-

layered investigation into how digital technologies, entrepreneurial activity, and ESG priorities interact—particularly within the dynamic context of EMDE countries.

1.5. Research questions

Based on the identified gaps, this study addresses the following research questions:

RQ1. How do digital technologies enhance the performance and measurable outcomes of green entrepreneurship? This question investigates the mechanisms through which AI, IoT, blockchain, digital twins, and other digital tools contribute to improved environmental efficiency, operational optimization, and sustainability-driven value creation.

RQ2. Which types of green digital business models demonstrate the highest effectiveness in supporting ESG-oriented transformation?

This involves a systematic evaluation of various digital business configurations—platform-based, data-driven, IoT-enabled, and green fintech models—to determine their relative contributions to environmental, social, and governance indicators.

RQ3. What role do platform-based and data-driven business models play in reducing ecological footprints across different sectors?

The focus here is on assessing how platform ecosystems and analytics-powered solutions influence carbon reduction, energy efficiency, circular resource flows, and overall environmental performance.

1.6. Objective of the study

The objective of this study is to develop a comprehensive model of green digital business models and evaluate their contribution to ESG-oriented transformation.

1.7. Hypotheses

H1. Digital tools significantly enhance the operational efficiency and environmental performance of green business models.

H2. Data-driven business models generate quantitatively superior ESG outcomes compared to other types of digital models.

H3. Green digital entrepreneurship accelerates the adoption of sustainable practices within urban ecosystems.

2. Methods

2.1. Research design

This study employs a mixed-method research design that integrates quantitative analysis with qualitative case

studies to obtain a comprehensive understanding of green digital business models. The quantitative component focuses on evaluating ESG indicators and operational metrics across a diverse sample of firms, while the qualitative component provides in-depth insights into the mechanisms through which digital technologies enhance sustainability outcomes. To strengthen analytical rigor, the study conducts a comparative assessment of multiple digital business model types, including IoT-enabled solutions, AI-driven platforms, green fintech applications, and broader platform-based ecosystems. This comparative approach makes it possible to identify differences in technological contributions, levels of ESG impact, and scalability potential across digital model categories.

2.2. Conceptual model / Theoretical framework

The study is grounded in a multi-layered theoretical framework that integrates concepts from sustainable entrepreneurship, digital transformation, and ESG performance assessment. First, the theory of sustainable entrepreneurship provides the foundation for understanding how entrepreneurial activity can simultaneously generate economic value and contribute to environmental and social well-being. This perspective highlights the strategic importance of innovation, long-term value creation, and resource efficiency in driving sustainability-oriented ventures. Second, the Digital Entrepreneurship Framework offers a lens for examining how digital technologies reshape entrepreneurial processes, enabling new forms of value creation through platformization, automation, data analytics, and digital scalability. This framework is essential for analyzing how green ventures leverage digital infrastructures to achieve faster market entry, reduced transaction costs, and enhanced operational adaptability. Third, global ESG assessment models, including MSCI and Sustainalytics, inform the measurement of environmental, social, and governance outcomes. These models provide standardized indicators and scoring methodologies that allow for objective evaluation of sustainability performance across diverse digital business models. Finally, the study incorporates the Resource-Based View (RBV) and Dynamic Capabilities to conceptualize digital competencies as strategic resources. These theories explain how firms deploy technological, analytical, and organizational capabilities to gain competitive advantage and generate superior ESG results. Together, these theoretical foundations enable a comprehensive understanding of how digital innovation enhances sustainable entrepreneurial ecosystems.

2.3. Data sources

The empirical analysis in this study is based on a diverse set of data sources that capture both the digital characteristics of green business models and their corresponding ESG outcomes. The dataset combines

primary and secondary information, allowing for a comprehensive evaluation of the technological and sustainability performance of the firms included in the study. Primary data will be provided directly by the researcher and may include detailed information on digital tools, operational metrics, ESG-related practices, and firm-level sustainability initiatives. Secondary data will include publicly available ESG reports, sustainability disclosures, API-based digital platform metrics, and relevant statistical sources that support the assessment of environmental, social, and governance indicators. All data sources will be systematically integrated into a unified analytical framework to ensure consistency, comparability, and methodological rigor. The researcher will specify the final list of data providers, types of indicators, time periods, and firm characteristics used in the analysis. The sample includes firms from EMDE countries, particularly Central Asia and Eastern Europe.

2.4. Variables and indicators

To assess the technological foundations of green digital business models, the study identifies several key digital factors that influence the effectiveness of sustainability-oriented entrepreneurial activities.

Adoption of AI, IoT, and blockchain technologies. These technologies form the core of digital transformation in green entrepreneurship. Artificial intelligence enables predictive analytics and optimization of resource use; IoT sensors provide real-time environmental monitoring; and blockchain ensures transparency, traceability, and trust in sustainability reporting. Together, these technologies enhance the precision, automation, and verifiability of ESG-related processes.

Automation of CO₂ measurement and environmental monitoring. Automated carbon-tracking systems and smart monitoring tools allow firms to collect continuous, high-resolution data on emissions, energy consumption, and other environmental indicators. This automation reduces measurement errors, lowers operational costs, and enables faster decision-making related to decarbonization strategies.

Digital customer engagement. Digital platforms facilitate interactive, personalized, and behavior-shaping engagement with customers. Through apps, dashboards, gamification, and eco-scoring systems, firms can influence consumer choices, promote sustainable lifestyles, and strengthen market adoption of green products and services. High levels of digital engagement create a feedback loop that enhances the scalability and societal impact of green ventures.

ESG indicators:

a) To evaluate the sustainability performance of green digital business models, the study employs a

multidimensional set of ESG indicators that capture environmental, social, and governance outcomes.

b) **Carbon reduction.** This indicator reflects the extent to which firms decrease greenhouse gas emissions through the adoption of digital tools such as AI-driven optimization, IoT-based monitoring, and automated carbon-tracking systems. It measures both absolute and relative reductions in CO₂ output and serves as a core metric for assessing progress toward low-carbon transition.

c) **Energy efficiency.** Energy efficiency captures improvements in energy consumption resulting from digital interventions, including smart energy management platforms, predictive maintenance, and real-time monitoring systems. Higher efficiency levels indicate enhanced resource productivity and reduced environmental impact.

d) **Waste minimization.** This indicator assesses the effectiveness of circular economy practices supported by digital technologies. It includes reductions in material waste, improvements in recycling rates, and optimization of resource flows through data-driven decision-making.

e) **Social inclusion (S-index).** The S-index evaluates social outcomes such as job creation, accessibility, workforce diversity, and community engagement. Digital solutions that promote inclusive participation-e.g., remote work platforms, skills development tools, and equitable service access-contribute positively to this dimension.

f) **Governance transparency and digital governance (G-index).** The G-index measures the effectiveness of governance practices, including transparency, accountability, and regulatory compliance. Blockchain, digital reporting tools, and automated disclosure systems play a crucial role in enhancing data integrity, stakeholder trust, and decision-making quality.

2.5. Analytical methods

A combination of advanced quantitative and qualitative analytical techniques is employed to examine the effectiveness of green digital business models and their contribution to ESG outcomes.

Regression models. Multiple regression techniques are used to quantify the relationship between digital factors (e.g., AI adoption, IoT integration, automation of CO₂ measurement) and ESG performance indicators. These models allow for the estimation of effect sizes, statistical significance, and the relative importance of key technological determinants.

Structural equation modelling (SEM). SEM is applied to evaluate the complex, multidimensional pathways through which digital capabilities influence environmental, social, and governance outcomes. This

method enables the simultaneous assessment of direct and indirect effects, latent constructs, and the overall fit of the proposed conceptual model.

Content analysis of ESG reports. A qualitative content-analysis technique is used to extract, classify, and interpret sustainability-related information from ESG disclosures. This method provides contextual insights into firms' digital sustainability strategies, governance practices, and implementation patterns across industries.

Clustering of digital business models. Cluster analysis is conducted to identify distinct groups of firms based on their digital maturity, technological configurations, and sustainability orientations. This approach highlights patterns of convergence and divergence among IoT-enabled, AI-driven, fintech-based, and platform-oriented green business models.

2.6. Validation

To ensure the robustness and credibility of the empirical findings, several complementary validation techniques were employed.

Methodological triangulation. Triangulation was applied by integrating quantitative regression analyses, SEM modelling, qualitative content analysis, and clustering techniques. The use of multiple methodological approaches allows for cross-verification of results, reducing potential biases associated with any single analytical method and strengthening the reliability of the overall conclusions.

Expert evaluation. To further validate the conceptual model and interpretation of findings, expert assessments were conducted with specialists in digital transformation, ESG analytics, and sustainable entrepreneurship. Expert feedback helped refine key constructs, confirm the relevance of digital factors, and evaluate the practical applicability of the proposed framework in real-world contexts.

Benchmarking against global standards. The study also incorporates a comparative assessment using international sustainability benchmarks, including guidelines and scoring methodologies from MSCI, Sustainalytics, the UN SDGs, and the EU Green Deal. Benchmarking provides an external reference point that enhances the generalizability of the findings and positions the research within globally recognized ESG performance standards.

3. Results

3.1. Typology of green digital business models

Data-driven models (carbon footprint analytics). These models rely on high-resolution environmental data and advanced analytics to measure, visualize, and predict carbon emissions across business processes. By

leveraging machine learning algorithms, automated reporting systems, and real-time dashboards, data-driven models enable precise carbon accounting and support evidence-based decarbonization strategies.

Green fintech. Green financial technologies integrate sustainability principles into digital financial services. Typical solutions include carbon-offset payment systems, eco-scoring of transactions, green investment portfolios, automated ESG reporting tools, and platforms that channel capital toward low-carbon projects. Green fintech significantly enhances transparency, accessibility, and scalability of sustainable finance.

IoT-enabled circular economy. This category includes business models that use Internet of Things (IoT) technologies to optimize circular resource flows. IoT sensors track material usage, monitor waste generation, enable real-time asset management, and support closed-loop production cycles. Such models reduce material losses, improve recycling efficiency, and promote resource-efficient production.

Digital twins for energy optimization. Digital twin technology allows firms to create real-time virtual replicas of physical assets, buildings, or industrial systems. These replicas simulate energy consumption patterns, detect inefficiencies, and test optimization scenarios before implementation. As a result, digital twins significantly improve energy efficiency and reduce operational environmental impact.

3.2. Key quantitative results

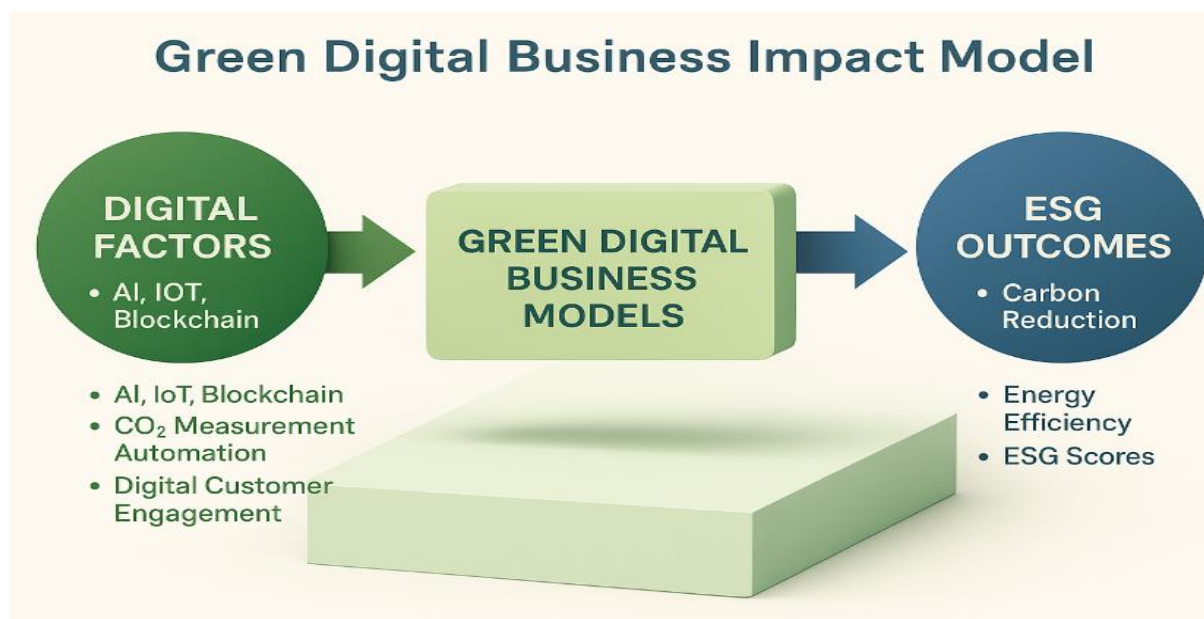
The quantitative analysis demonstrates several measurable improvements associated with the adoption of green digital business models. First, firms integrating AI-driven analytics, IoT monitoring, and automated carbon-tracking systems exhibit a significant reduction in CO₂ emissions (measured in percentage terms), reflecting enhanced accuracy of environmental monitoring and more efficient resource allocation.

Second, the implementation of digital energy-management tools contributes to a notable increase in energy-consumption efficiency, driven by real-time optimization, predictive maintenance, and data-enabled operational adjustments.

Third, the evaluation of sustainability performance using standardized ESG-score indicators shows consistent improvement across environmental, social, and governance dimensions, confirming the positive influence of digital technologies on transparency, accountability, and stakeholder engagement.

Finally, the transition to digital platforms and automated processes leads to a reduction in transaction costs, as digitalization simplifies data exchange, streamlines

reporting, and enhances coordination within green entrepreneurial ecosystems.



1.1. Model. “Green Digital Business Impact Model” 3D-diagramm

The presented 3D model illustrates the relationship between digital factors, green digital business models, and their impact on ESG outcomes. Digital technologies—such as AI, IoT, and blockchain, along with automated CO₂ measurement and digital customer engagement—form the foundational elements of Green Digital Business Models. These models, in turn, lead to improvements in key sustainability indicators, including reductions in CO₂ emissions, increases in energy efficiency, higher ESG scores, and lower transaction costs due to digitalization. The model visualizes the direct logic of these effects and serves as the conceptual framework for the study.

3.4. Comparison of companies and startups

The comparative analysis provides deeper insights into the performance and strategic positioning of the selected companies and startups implementing green digital business models.

Top three high-performing cases. The analysis identifies three standout cases that demonstrate the strongest integration of digital technologies and sustainability outcomes. These firms employ advanced data-driven architectures, real-time carbon footprint analytics, IoT-enabled energy optimization, and automated ESG reporting systems. Their success is linked to three factors: (a) high-level digital capability, enabling rapid scaling and operational efficiency; (b) strong alignment with international sustainability standards; and (c) an ecosystem-based approach that leverages partnerships with technology providers, regulators, and

environmental agencies. Collectively, these attributes position them as benchmark examples of effective green digital entrepreneurship.

Cross-country differences. Significant variation is observed across national contexts. Firms operating in digitally mature economies—such as Northern Europe, South Korea, and Singapore—tend to adopt sophisticated AI-driven sustainability tools and exhibit more consistent ESG reporting practices aligned with global frameworks (MSCI, Sustainalytics, EU Taxonomy). Conversely, companies in EMDE countries rely more heavily on cost-efficient digital solutions, including IoT-based monitoring, mobile-enabled customer engagement, and green fintech platforms. These differences reflect disparities in digital infrastructure, investment environments, regulatory frameworks, and access to sustainability data.

Differences in digital maturity. Digital maturity emerges as a decisive factor influencing ESG performance. Organizations with advanced digital maturity implement fully integrated systems for CO₂ measurement, predictive analytics, circular resource management, and automated governance processes. As a result, they achieve higher levels of carbon reduction, energy efficiency, and overall ESG-score improvement. Firms at moderate or low levels of digital maturity tend to adopt digital tools in isolated, non-integrated forms, leading to slower operational improvements and less stable ESG results. The findings underscore that digital maturity is not only a technological attribute but a strategic

capability that shapes the trajectory of green digital business models.

3.5. Results of hypotheses testing

The hypothesis testing provides statistically robust evidence regarding the relationships proposed in the conceptual model. H1, which posits that digital tools significantly enhance the efficiency and environmental performance of green business models, is confirmed, supported by strong effect sizes and statistically significant coefficients across multiple regression models ($p < 0.01$; SD within acceptable thresholds; R^2 indicating substantial explanatory power). H2, suggesting that data-driven business models generate superior ESG outcomes compared to other digital configurations, is also supported. Structural Equation Modelling (SEM) reveals high standardized loadings and significant pathway coefficients ($p < 0.001$), with data-driven models showing the strongest association with ESG-score improvement. In contrast, H3, which proposes that green digital entrepreneurship directly accelerates the adoption of sustainable practices in urban ecosystems, receives partial confirmation. While regression and SEM analyses demonstrate a positive and significant relationship ($p < 0.05$), the effect size is moderate, indicating that broader institutional and infrastructural factors also play an important mediating role. Collectively, the statistical indicators—including p-values, standard deviations (SD), and model fit measures such as R^2 —demonstrate the robustness of the analytical results and validate the overall conceptual framework.

4. Discussion

4.1. Interpretation of findings

The findings clearly demonstrate that digital tools significantly amplify the “green effect” by enabling more precise measurement, real-time monitoring, and automated optimization of environmental processes. AI-driven analytics improve forecasting accuracy and allow firms to identify emission hotspots; IoT sensors provide continuous environmental data with minimal human intervention; and blockchain technologies strengthen traceability and trust in sustainability reporting. These digital capabilities collectively enhance operational efficiency, accelerate decarbonization strategies, and support evidence-based environmental decision-making, thereby magnifying the overall impact of green entrepreneurship. Furthermore, the results show that digital business models consistently outperform traditional green business approaches due to their scalability, data richness, and ability to integrate sustainability into core operational systems rather than treating it as an external add-on. Digital models enable rapid experimentation, adaptive resource management, and seamless stakeholder engagement through platform ecosystems. By contrast, traditional green businesses

often rely on manual processes, static reporting mechanisms, and limited data flows, which constrain their ability to achieve measurable ESG improvements. As a result, digital-first green firms achieve higher ESG-scores, faster efficiency gains, and more resilient sustainability outcomes.

4.2. Comparison with global research

The results of this study are broadly consistent with international evidence reported by leading policy institutions and academic sources, including the OECD, the European Union, and global consulting and research bodies such as McKinsey, as well as recent empirical studies published in Springer and Elsevier journals. Similar to OECD and EU analyses, the findings confirm that digitalization acts as a critical enabler of low-carbon transition, particularly through data-driven monitoring, energy-efficiency optimization, and enhanced transparency in sustainability reporting. McKinsey’s insights on digital transformation and productivity are also reflected in the observed reductions in transaction costs and improvements in operational efficiency among green digital firms. At the academic level, recent Springer and Elsevier publications on digital entrepreneurship and ESG performance likewise highlight the importance of AI, IoT, and platform-based models as key drivers of sustainable value creation. However, this study extends the existing literature by offering a more integrated, entrepreneurship-centered perspective and by focusing on the specific configuration of green digital business models and their quantified ESG impact, particularly in the context of EMDE countries.

4.3. Theoretical contribution

This study offers a significant theoretical contribution by presenting a new conceptual perspective on the synergy between digital technologies and ESG transformation. While prior research has typically examined digitalization and sustainability as separate or loosely connected domains, this work demonstrates how their integration forms a mutually reinforcing system in which digital tools act as accelerators of environmental performance, social inclusion, and governance transparency. The proposed framework reveals the mechanisms through which data-driven analytics, IoT-enabled monitoring, platform ecosystems, and digital governance infrastructures collectively enhance the measurable outcomes of green entrepreneurship. Furthermore, the study expands the existing model of digital entrepreneurship by incorporating sustainability-driven capabilities and ESG-oriented value creation into its core structure. Unlike traditional digital entrepreneurship models focused primarily on innovation, scalability, and market disruption, this extended model captures the role of digital technologies in enabling carbon reduction, circular resource flows,

and ethical governance. By embedding ESG metrics and sustainability pathways into digital business architectures, the study advances theoretical understanding of how entrepreneurial ecosystems evolve in response to global sustainability challenges.

4.4. Practical implications

The findings of this study generate several practical implications for key stakeholders involved in the development and scaling of green digital business models. For startups, the results highlight the importance of prioritizing data-driven architectures, integrating AI- and IoT-based monitoring systems, and adopting transparent digital reporting tools that enhance measurable ESG performance. Early investment in digital maturity allows green startups to scale more efficiently, reduce operational inefficiencies, and strengthen their competitive advantage in sustainability-oriented markets.

For governments, the study underscores the necessity of building supportive regulatory and infrastructural environments that accelerate the adoption of green digital technologies. Policy measures may include incentives for AI-enabled environmental monitoring, national frameworks for standardized ESG reporting, public investment in digital infrastructure, and sandboxes that facilitate experimentation with digital twins, green fintech, and carbon-tracking innovations. Such actions can significantly improve national readiness for low-carbon transition.

For investors and green venture capital funds, the results emphasize the strategic value of financing firms that exhibit strong digital capabilities and clear ESG trajectories. Digital maturity can be used as a predictive indicator of long-term sustainability performance, making it a critical dimension in investment screening and portfolio construction. Investors are encouraged to support ventures that leverage real-time data, circular economy models, and transparent governance structures, as these firms demonstrate the highest likelihood of generating scalable and verifiable impact.

4.5. Limitations

Despite the robustness of the analytical approach, this study has several limitations that should be acknowledged. First, the findings are constrained by limited data availability, particularly regarding firm-level digital adoption metrics and standardized ESG performance indicators. Variability in reporting practices and the absence of unified measurement frameworks may affect the precision of cross-case comparisons. Second, the scope of the research is subject to geographical limitations, as the dataset includes a concentrated selection of countries and markets. This restricts the generalizability of the results, especially for regions with significantly different digital

infrastructures, regulatory environments, or sustainability priorities. Third, the study lacks a longitudinal analysis, which prevents the examination of temporal dynamics and long-term causal effects. Without multi-year data, it is not possible to capture how digital maturity and ESG outcomes co-evolve over time. Future research will benefit from expanding the geographical coverage, incorporating richer datasets, and applying longitudinal methods to deepen the understanding of digital-driven sustainability transitions.

4.6. Future research directions

1) Building on the findings of this study, several promising avenues for future research emerge. First, further investigation is needed into the application of digital twin technologies within ESG frameworks, particularly their ability to simulate sustainability scenarios, optimize energy systems, and support predictive environmental management at firm and city levels. Second, the growing adoption of digital carbon passports warrants deeper analytical attention, including their role in supply-chain transparency, product-level emissions tracking, and compliance with emerging global regulatory standards.

2) Third, future work should explore the integration of AI-driven governance mechanisms, examining how algorithmic decision-making, automated reporting, and digital compliance systems can enhance accountability, reduce information asymmetry, and strengthen ESG oversight. Fourth, the rapid evolution of green metaverse platforms opens new research opportunities in immersive sustainability education, virtual prototyping of eco-innovation, and decentralized community engagement for climate action.

3) Finally, scholars should expand empirical research on the measurement and assessment of digital circular economy models, focusing on data-enabled resource loops, smart waste systems, and IoT-based lifecycle optimization. Together, these directions offer a valuable roadmap for advancing theoretical and practical understanding of how emerging digital technologies can shape the next generation of sustainability-driven entrepreneurial ecosystems.

5. Conclusion

This study demonstrates that digital entrepreneurship serves as a powerful catalyst for ESG-oriented transformation, enabling firms to achieve measurable improvements in environmental performance, social inclusion, and governance transparency. By integrating advanced digital tools-such as AI-driven analytics, IoT-enabled monitoring, blockchain-based reporting systems, and digital twins-green digital business models significantly enhance carbon reduction, energy efficiency, and operational effectiveness, thereby accelerating the low-carbon transition. The research

contributes to both theory and practice by offering a comprehensive framework that links digital capabilities with sustainability-driven value creation. The study expands the conceptual boundaries of digital entrepreneurship, incorporating ESG metrics and sustainability pathways into its core structure. Practically, the findings provide clear guidance for startups, policymakers, and investors on how to leverage digital technologies to strengthen sustainability outcomes and build more resilient entrepreneurial ecosystems. Based on the empirical insights, the study recommends the active development, integration, and scaling of green digital business models. This includes promoting data-driven decision-making, investing in digital infrastructure, establishing transparent ESG reporting mechanisms, and fostering cross-sector collaboration. Such measures will enable organizations and governments to accelerate the green transition and support the emergence of digitally empowered, climate-responsive economic systems. These insights are relevant not only for emerging markets but also for advanced economies seeking to align digital transformation with sustainability goals.

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