Journal of Entrepreneurship, Management and Innovation (2025)
Volume 21 Issue 2: 116-137

DOI: https://doi.org/10.7341/20252127
JEL Codes: L22, O30, D22, Q56

The Digital-Sustainability Ecosystem: A conceptual framework for digital transformation and sustainable innovation

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Abstract

PURPOSE: *This study introduces the Digital-Sustainability Ecosystem, a conceptual framework to integrate digital transformation and sustainable innovation. It examines how emerging digital technologies, including artificial intelligence, blockchain, and the Internet of Things, drive sustainability transitions by serving as strategic enablers. Addressing a critical gap in the literature, this research focuses on the dynamic mechanisms and synergies that connect digital transformation with sustainable innovation within a complex ecosystem.* ***METHODOLOGY:*** *The study employs a systematic literature review (SLR) of 50 studies and a comparative analysis of 13 existing frameworks to identify and analyze key mechanisms that link digital transformation and sustainable innovation, culminating in the development of the Digital-Sustainability Ecosystem framework.* ***FINDINGS:*** *The study identifies five interconnected mechanisms: efficiency gains, dematerialization, circular economy enablement, innovation acceleration, and digital collaboration. These mechanisms illustrate the relationships between technological advancements and sustainability objectives while addressing synergies and tensions, such as the trade-offs between energy demands and environmental benefits. The Digital-Sustainability Ecosystem emphasizes multi-stakeholder collaboration, iterative feedback loops, and adaptable processes to address gaps in existing models, positioning digital transformation as a transformative force for systemic sustainability improvements.* ***IMPLICATIONS:*** *The Digital-Sustainability Ecosystem advances theoretical discourse by positioning sustainability as a systemic outcome of digital transformation, extending beyond traditional efficiency-focused models. It emphasizes organizational resilience and stakeholder collaboration as pivotal for achieving sustainability objectives. Practitioners can leverage AI, IoT, and blockchain to enhance resource optimization and foster sustainability-driven innovation ecosystems. Policymakers and organizations are encouraged to combine digital strategies with sustainability imperatives, emphasizing adaptive leadership, regulatory alignment, and multi-stakeholder engagement.* ***ORIGINALITY AND VALUE:*** *This study presents a conceptual framework that bridges theoretical and practical gaps in the literature by integrating foundational theories that associate digital transformation with sustainability imperatives while fostering innovation and competitive advantage. The framework sets the stage for future research, emphasizing potential applications in industry-specific contexts, cross-sectoral collaborations, and the evolving role of emerging technologies in sustainability transitions. By incorporating dynamic feedback loops and systemic adaptability, this framework establishes a foundation for advancing both academic inquiry and practical implementation. It offers guidance for exploring unanswered questions about scalability, policy integration, and multi-stakeholder engagement in the digital age.*

Keywords*: digital transformation, sustainable innovation, digital-sustainability ecosystem, sustainability transitions, artificial intelligence, blockchain, Internet of Things, circular economy, efficiency gains, dematerialization, acceleration, digital collaboration, stakeholders*

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Received 11 November 2024; Revised 3 February 2025; Accepted 17 February 2025.
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INTRODUCTION

The digital transformation, characterized by integrating cutting-edge digital technologies into organizational frameworks, has become a transformative force reshaping industries globally. Tools such as artificial intelligence, the Internet of Things (Gabsi, 2024), and blockchain (Omol, 2023; Pham et al., 2025) enhance operational efficiency and fundamentally redefine value-creation processes. Simultaneously, the global urgency for sustainable innovation has intensified, driven by the need to combat environmental degradation, resource scarcity, and social inequalities. These dual forces, digital transformation and sustainable innovation, offer the potential for profound synergy, yet their intersection remains underexplored. Despite advancements, a comprehensive understanding of how digital transformation acts as a catalyst for sustainable innovation is still lacking.

The COVID-19 pandemic has further accelerated the adoption of digital technologies, embedding them deeply into organizational and societal processes (Winarsih et al., 2021). This rapid shift underscores the potential of digital tools to address pressing environmental and social challenges through sustainability-driven innovation (Estrada & Reyes Álvarez, 2023). However, integrating digital transformation with sustainability objectives presents significant challenges. Existing frameworks often fall short of holistically balancing profitability, environmental stewardship, and social responsibility (Pappas et al., 2023). This fragmentation shows the need for comprehensive, integrative frameworks to align sustainability goals with digital transformation processes.

Although prior literature has extensively analyzed digital transformation as a technological and strategic phenomenon, focusing on aspects such as automation (Frank et al., 2019), decision-making (Korherr et al., 2022), and scalability (Thekkoote, 2022). Likewise, sustainable innovation has been analyzed through eco-efficiency (Dyck & Silvestre, 2018; Guo et al., 2020), circular economy (Al Halbusi et al., 2024), and stakeholder inclusivity (Ayuso et al., 2011). The intersection of digital transformation and sustainable innovation requires further exploration. Current research tends to be fragmented, primarily addressing individual mechanisms like resource optimization and waste reduction (Parolin et al., 2024). However, these studies overlook the complex, dynamic interactions between digital technologies and sustainability practices crucial for achieving comprehensive sustainability transitions. To advance understanding in this field, it is essential to consider the systemic interplay between these domains rather than viewing them in isolation.

This study seeks to address these gaps by constructing a conceptual framework, the Digital-Sustainability Ecosystem (DSE), which elucidates the interdependencies and synergies between digital transformation and sustainable innovation. Guided by two research questions (RQs), this study investigates:

RQ1: How can digital transformation be strategically aligned to enhance sustainable innovation within a Digital-Sustainability Ecosystem?

RQ2: What are the key mechanisms through which digital transformation drives the alignment between technological advancements and sustainability practices to achieve systemic and measurable sustainability outcomes?

Addressing these questions, the DSE framework captures the complexities of sustainability transitions through key technological, organizational, environmental, and societal dimensions while emphasizing mechanisms such as efficiency gains, dematerialization, circular economy enablement, innovation acceleration, and digital collaboration. The framework underscores the role of systemic interactions in fostering eco-innovation, optimizing resource use, and enhancing adaptability to changing environmental and market demands. In this context, "ecosystem" refers to the dynamic and interdependent relationships between digital technologies, organizational processes, natural environments, and socio-economic structures. These interactions form an integrated system that promotes resource optimization, innovation, and resilience.

To ground the DSE framework, this study synthesizes foundational theories, including dynamic capabilities (Teece et al., 1997), diffusion of innovation (Rogers, 1995), the resource-based view (Barney, 1991), sociotechnical systems (Baxter & Sommerville, 2011), and institutional theory (Meyer & Rowan, 1977). These theoretical approaches are integrated with sustainability-oriented concepts such as the triple bottom line (Elkington & Rowlands, 1999), circular economy principles (MacArthur, 2013), stakeholder theory (Freeman, 2010), and innovation systems (Lundvall, 1992). Stakeholder theory, while not inherently a sustainability-oriented concept, provides a lens for understanding how organizations can address diverse stakeholder needs and integrate these interests into sustainability strategies. Similarly, innovation systems emphasize the role of networks and institutions in fostering innovation, making them particularly relevant for advancing sustainability transitions by promoting collaboration and knowledge exchange.

This multi-theoretical approach underscores the systemic role of digital transformation in advancing sustainability objectives while addressing environmental impacts (Zulfiqar et al., 2023). According to the United Nations Environment Programme (UNEP, 2024), digital technologies can significantly contribute to achieving all 17 Sustainable Development Goals (SDGs). A total of 103 out of 169 SDG targets are directly influenced by a synergistic application of seven key digital technologies: digital access, high-speed Internet, cloud computing, the Internet of Things (IoT), artificial intelligence (AI), extended reality, and blockchain. These technologies enable advanced monitoring, promoting resource conservation, and influencing market dynamics and consumer behavior (Leal Filho et al., 2024).

A systematic literature review (SLR) of 50 studies and a comparative analysis of 13 frameworks underpin this research. Articles were identified through Scopus, focusing on peer-reviewed papers published between 2018 and 2024. This time frame ensures the inclusion of the most recent advancements in digital transformation and sustainable innovation, reflecting the rapid evolution of technologies and their integration with sustainability practices. The final selection of 50 studies resulted from a rigorous multi-stage filtering process, ensuring traceability in the search methodology and alignment with global sustainability goals. These findings contribute to the ongoing dialogue on fostering resilience and equity in the digital age.

This paper is structured as follows: the Theoretical Background section explores key concepts and definitions of digital transformation and sustainable innovation. The Methodology details the systematic literature review process. The Results and Discussion present the DSE framework, detailing its components, pathways, and implications for practice and policy. The Conclusion outlines the theoretical contributions, practical applications, and potential avenues for future research.

THEORETICAL BACKGROUND

Digital transformation

Digital transformation involves the integration of digital technologies into organizational processes and strategies, fundamentally altering the mechanisms through which organizations create value. It is a technological upgrade and a systemic reconfiguration encompassing strategic, cultural, and operational dimensions (Tebenko et al., 2024). At its core, digital transformation represents a fundamental rethinking of organizations leveraging digital platforms and advanced technologies to innovate. Key enablers include smart technologies, such as artificial intelligence, the Internet of Things (IoT), and big data analytics, enabling firms to harness modern systems' interconnectedness and intelligence (Tang, 2021). Within the concept of Industry 4.0, organizations integrate these technologies to enhance automation and robotization, driving efficiency, reducing costs, and improving decision-making capabilities (Małkowska et al., 2021).

Digital transformation extends beyond operational improvements, encompassing the creation of new revenue streams and scalability through the adoption of digital platforms (Yang et al., 2023). These platforms facilitate the creation of digital business models that transform traditional value chains and customer interactions by utilizing digital ecosystems (Aghazadeh et al., 2024). The concept of "ecosystem" plays a central role in this context, referring to complex, dynamic networks of interconnections between organizations, stakeholders, and their environments (Adner, 2006; Candelario-Moreno & Sánchez-Hernández, 2024). Borrowed from biology, the term underscores the interdependence and coevolution of entities within an integrated system (Tansley, 1935). In digital transformation, ecosystems facilitate resource sharing, collaboration, and innovation, fostering competitive advantage.

The literature provides various theoretical frameworks to understand the drivers and complexities of digital transformation. This study employs a multi-theoretical approach, synthesizing dynamic capabilities theory (Teece et al., 1997), diffusion of innovation (Rogers, 1995), resource-based view (Barney, 1991), sociotechnical systems (Baxter & Sommerville, 2011), and institutional theory (Meyer & Rowan, 1977). Each of these theories offers unique insights into the multidimensional nature of digital transformation, addressing both internal and external dynamics. Dynamic capabilities theory emphasizes organizations' strategic responses to rapidly changing environments, focusing on adaptability and resource alignment to harness external opportunities (Eisenhardt & Martin, 2000). In the context of digital transformation, this theory emphasizes the importance of building internal capabilities to integrate digital tools, realign processes, and reskill employees (Saputra et al., 2024; Warner & Wäger, 2019).

While dynamic capabilities explain the "how" of digital transformation, they do not sufficiently address diffusion and external acceptance of digital innovations. These aspects are better elucidated by the diffusion of innovation theory, which broadens the analysis to explain how innovations are adopted and diffused within and across industries (Rogers, 2003).

This theory examines how innovations spread across social systems, emphasizing the roles of adopters, communication channels, time, and social context (Vargo et al., 2020). Factors such as relative advantage, compatibility with existing systems, complexity, observability, and trialability are pivotal in accelerating or impeding adoption (Tornatzky & Klein, 1982). Regulatory pushes, environmental uncertainties, and informal inter-organizational networks further influence organizational readiness and adaptability and stress how political mandates and market expectations facilitate or hinder the assimilation of innovations (Greenhalgh et al., 2004). When applied to digital transformation, this theory provides a systemic understanding of why some organizations adopt digital technologies earlier than others. However, it treats innovation as a discrete process rather than a continuous, iterative transformation, limiting its ability to explain the long-term evolution of digital transformation (Schneider & Kokshagina, 2021).

Focusing solely on the adoption process also neglects the strategic leveraging of adopted technologies, an area more comprehensively addressed by the resource-based view (RBV). This theory emphasizes the role of unique and often intangible digital assets, such as data analytics, digital platforms, and technological expertise, as critical enablers of sustainable competitive advantage (Teece, 2007). The RBV frames digital resources as pivotal to achieving differentiation and efficiency, focusing on their strategic deployment to differentiate from competitors (c.f., Rumelt, 1984). However, the RBV's inward orientation often underestimates the dynamic and ecosystemic nature of digital resources, which are interdependent and frequently evolve beyond firm-specific boundaries. Furthermore, the RBV often overlooks the interplay between technological and human factors essential for successful digital transformation. Sociotechnical systems theory addresses this gap, highlighting the interdependence of technological and human dimensions in organizational change (Appelbaum, 1997).

Sociotechnical systems theory provides a holistic perspective by emphasizing the alignment of digital tools with organizational culture, skills, and workflows (Sony & Naik, 2020). For instance, the successful implementation of artificial intelligence (AI) or cloud computing often hinges on technical functionality, employee acceptance, ethical considerations, and organizational readiness. This theory underscores the need for buy-in from key stakeholders and adaptable organizational structures to ensure the success of technological initiatives. However, while it effectively addresses internal dynamics, sociotechnical systems theory does not sufficiently account for external pressures and institutional dynamics that influence transformation processes.

In line with institutional theory, organizations frequently undertake digital transformation as a response to three forms of institutional pressure. First, coercive pressures (e.g., digital regulations or mandatory standards) compel compliance to maintain legitimacy and avoid sanctions (DiMaggio & Powell, 1983; Scott, 2013). Second, mimetic pressures (e.g., adopting industry-standard technologies or imitating digitally advanced peers) arise under uncertainty, prompting firms to emulate perceived exemplars (Berrone et al., 2013; Wang et al., 2018). Third, normative pressures (e.g., professional norms or best practices favoring digital fluency) reflect broader societal and occupational expectations, leading organizations to align with prevailing digital standards (Meyer & Rowan, 1977; Zhang et al., 2023)

These theories converge to provide a multifaceted understanding of digital transformation. The strategic alignment and resource deployment described by dynamic capabilities and the RBV are complemented by the systemic and external considerations of diffusion of innovation and institutional theory. Despite their contributions, none of these theories fully capture digital transformation's systemic and iterative nature. Dynamic capabilities and RBV focus heavily on internal organizational capabilities, often overlooking broader ecosystemic dynamics. Diffusion of innovation theory lacks depth in explaining strategic and adaptive processes, while sociotechnical systems theory and institutional theory address contextual factors but inadequately link them to competitive outcomes. It becomes evident that digital transformation is not a linear process but a dynamic and iterative reconfiguration of organizational capabilities and interactions within broader ecosystems.

Sustainable innovation

Sustainable innovation refers to the creation of products, processes, or business models that generate economic value while fostering positive environmental and societal impacts. It represents a fundamental shift from traditional profit-centric innovation to approaches grounded in eco-efficiency and social equity (Varadarajan, 2017). Bocken et al. (2016) describe sustainable innovation as a reconfiguration of business practices that optimize resource use, reduce waste, and deliver systemic environmental and social benefits, thereby positioning firms as proactive contributors to sustainable development. Often referred to as eco-innovation or environmental innovation, sustainable innovation focuses on reducing ecological footprints, enhancing social value, and ensuring economic viability.

A key dimension of sustainable innovation lies in its alignment with circular economy principles, emphasizing resource efficiency, waste minimization, and establishing closed-loop systems (Hapuwatte & Jawahir, 2021). This involves designing innovations that extend product lifecycles, enable recycling, and optimize resource use, thereby decoupling economic growth from environmental degradation. Sustainable innovation also drives competitiveness, enabling firms to meet regulatory demands, respond to shifting consumer preferences for sustainable products, and achieve cost reductions through enhanced efficiency (Voegtlin & Scherer, 2017). Distinctive forms of sustainable innovation, such as green innovation (Afeltra et al., 2023; Ibarra-Cisneros et al., 2024), low-carbon innovation (Shi & Lai, 2013), and sustainability-driven innovation, each reflecting specific dimensions of sustainability goals (Shi & Lai, 2013). Green innovation encompasses innovations that reduce environmental impacts, including a broad range of technologies and processes for environmental protection and resource efficiency (Leal-Millan et al., 2017). Low-carbon innovation targets greenhouse gas emission reductions through energy-efficient technologies, sustainable transportation, and carbon-neutral solutions (Ma, 2024). Sustainability-driven innovation involves the development of new or improved products, services, or processes aimed at decreasing the consumption of natural resources and reducing the emission of harmful substances into the environment. This concept adopts a holistic approach by considering the entire lifecycle, design, production, use, and end-of-life stages to minimize environmental impact (Hansen & Grobe-Dunker, 2013).

At the organizational level, sustainable business models embed sustainability into core strategic priorities, fostering long-term value creation (Achtenhagen et al., 2013). Such models enable resource efficiency, ensure optimal utilization of natural and financial resources, and support firms in mitigating environmental impacts while maintaining economic growth. These dimensions position sustainable innovation as a transformative approach to achieving global sustainability objectives and fostering resilient economic systems (Inigo & Albareda, 2016). As an interdisciplinary concept, sustainable innovation integrates environmental, social, and economic dimensions of sustainability, reflecting the increasing awareness of global challenges such as climate change, resource depletion, and social inequalities (Adams et al., 2016). This growing awareness has driven scholars and practitioners to reconfigure innovation frameworks, balancing competing priorities and fostering equitable and sustainable development.

The triple bottom line (TBL) provides a foundational framework for sustainable innovation, emphasizing that organizational performance must simultaneously account for environmental integrity, social equity, and economic viability (Elkington, 1998; Weidner et al., 2021). Encapsulated as the "3Ps" (Planet, People, and Profits), the TBL challenges traditional profit-driven models by addressing interdependencies among these dimensions. Innovations that reduce carbon emissions or improve energy efficiency exemplify the alignment of economic and environmental goals, while social innovations promoting inclusivity and equitable resource access reinforce the social pillar. However, critiques of the TBL underscore its limitations in operationalizing and quantifying the synergies and trade-offs among the three dimensions (Wu et al., 2024).

Stakeholder theory complements the TBL by emphasizing multi-stakeholder engagement in shaping sustainable innovation pathways (Freeman, 2010). Stakeholder collaboration is crucial for the co-creation and legitimacy of innovation outcomes, addressing systemic issues such as resource inefficiency and waste generation (Kazadi et al., 2016). For instance, incorporating consumer feedback into product development ensures higher market acceptance for sustainability-driven innovations. While stakeholder theory highlights the participatory aspects of sustainable innovation, challenges such as power imbalances, conflicting interests, and network complexity necessitate systemic approaches that account for broader institutional and structural influences.

Innovation systems theory provides a systemic perspective, emphasizing the interconnectedness of actors, institutions, and infrastructures in fostering sustainability transitions (Asheim et al., 2011). This approach is especially significant in the development of renewable energy technologies, where the interplay of institutional frameworks, financial resources, and knowledge networks collectively shapes the paths of innovation. Additionally, Innovation systems theory examines the spatial and sectoral dynamics of influence innovation, emphasizing how regional clusters, industry standards, and policy measures impact sustainability-focused innovation ecosystems. By integrating these systemic elements with normative frameworks like circular economy principles, we can enhance the practical application of sustainable innovation strategies.

The circular economy fundamentally transforms value creation frameworks by emphasizing resource optimization, waste reduction, and the establishment of closed-loop systems (Geissdoerfer et al., 2017). This paradigm shift is exemplified through advancements in recycling technologies, material substitution strategies, and the adoption of product-service systems, all of which work to minimize environmental impacts while generating economic returns. By prioritizing sustainability and a systemic approach to change, the circular economy aligns with the objectives of the TBL and offers

a comprehensive analysis through the lens of innovation systems theory. However, the path to achieving true circularity is fraught with challenges such as technological lock-ins, regulatory mismatches, and consumer pushback. This complexity underscores the necessity for integrated strategies that reconcile these theoretical frameworks and facilitate the transition toward circularity.

Sustainable innovation is a complex concept that requires comprehensive frameworks to balance economic goals with environmental and social objectives. The integration of the Triple Bottom Line (TBL) benchmarks, the participatory principles of stakeholder theory, the systemic analysis of innovation systems theory, and the practical approach of circular economy lay a strong foundation for promoting sustainable innovation. To effectively address the theoretical and practical challenges of aligning these perspectives, further cross-disciplinary collaboration is necessary to create scalable solutions.

METHODOLOGY

This research employs a Systematic Literature Review (SLR) to critically synthesize and analyze existing studies on the relationship between digital transformation and sustainable innovation. The SLR methodology was selected for its structured, transparent, and replicable nature in accordance with established guidelines (Snyder, 2019; Tranfield et al., 2003). The objective is to identify the mechanisms through which digital transformation influences sustainable innovation and develop a conceptual framework grounded in relevant theories. Figure 1 visually summarizes the systematic progression from defining the research objective to constructing the conceptual framework.

Search strategy and screening

The SLR was conducted using the Scopus database to ensure high-quality, peer-reviewed academic sources. An initial search using the keywords "digital transformation" AND "sustainable innovation" within the title, abstract, or keywords yielded 43 articles. To capture a broader scope of digital technologies relevant to sustainable innovation, additional search terms were applied based on their definitions and contexts presented in the Theoretical Background section: ("digital transformation" OR "digital technolog*" OR "digital platform" OR "artificial intelligence" OR "AI" OR "Industry 4.0" OR "smart technolog*" OR "digital business model" OR "automation" OR "robotization") AND ("sustainable innovation" OR "eco-innovation" OR "circular economy" OR "green innovation" OR "sustainability-driven innovation" OR "low-carbon innovation" OR "environmental innovation" OR "sustainable business model" OR "resource efficiency"). This expanded search generated a total of 3,370 articles.

A systematic filtering process was then applied to refine the dataset, ensuring relevance and quality: (1) Publication date: Articles published between 2015 and October 2024 were considered to capture both foundational and recent developments; (2) Document type: Only peer-reviewed journal articles and review papers were selected, ensuring the dataset's academic rigor; (3) Subject Areas: The search was limited to Business, Management and Accounting, Environmental Science, Social Sciences, Engineering, and Decision Sciences; (4) Language: Articles were restricted to English; (6) Publication stage: Only articles in their final publication stage were included to avoid incomplete or preliminary studies. These primary filters reduced the dataset to 1,420 articles.

Given the need for a focused and thematically relevant dataset, an additional refinement phase was applied: (1) Years: The dataset was narrowed to 2018-October 2024 to prioritize recent advancements while preserving theoretical depth and contemporary relevance; (2) Title keyword requirement: The search terms "digital transformation" and "sustainable innovation" were required in the article title to ensure primary relevance to the study's focus and reducing peripheral studies; (3) Subject areas: The search was further restricted to Business, Management, Accounting, and Environmental Science to align with the study's core research theme. Figure 1 provides a structured visualization of this stepwise selection process.

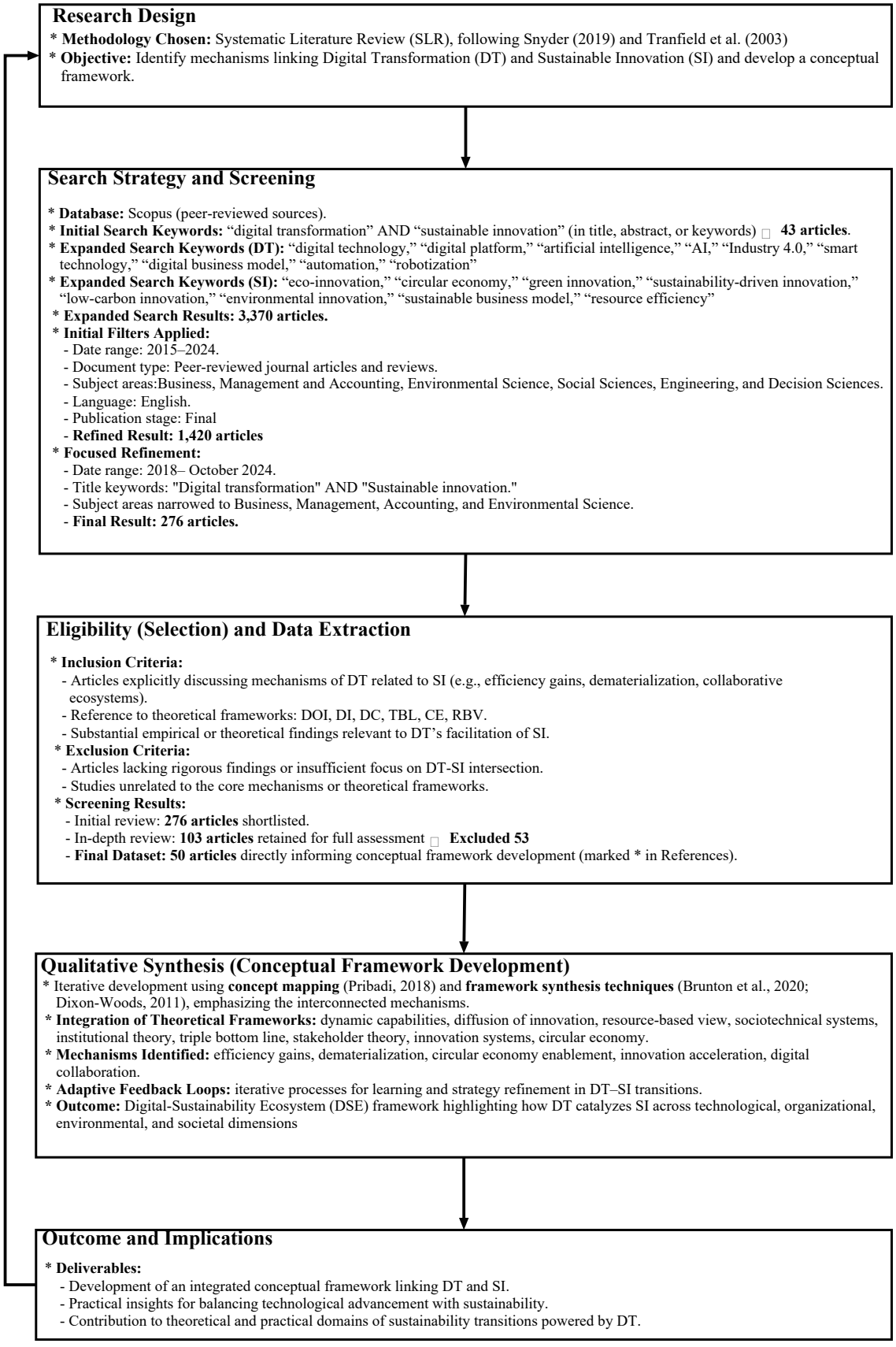

Figure 1. Methodological process for developing the digital-sustainability ecosystem conceptual framework

Eligibility (selection) and data extraction

The refinement process identified 276 articles for further screening, followed by a systematic eligibility review using predefined inclusion and exclusion criteria to ensure conceptual rigor and methodological precision. Studies were included if they: (1) Explicitly discussed mechanisms linking digital transformation to sustainable innovation; (2) Referenced key theoretical frameworks such as dynamic capabilities, diffusion of innovation, resource-based view, sociotechnical systems, institutional theory, triple bottom line, stakeholder theory, innovation systems, and circular economy; or (3) Provided substantial findings on digital transformation's role in facilitating sustainable innovation. In contrast, articles were excluded if they: (1) Lacked sufficient empirical findings on the digital transformation–sustainable innovation nexus; (2) Made only marginal references to these concepts without substantive theoretical contributions; or (3) Were not relevant to mechanisms or conceptual models. Following this rigorous screening, 103 articles underwent full-text assessment, leading to the exclusion of 53 articles. The final dataset consisted of 50 articles, which directly supported conceptual framework development (marked * in References). Within these 50 articles, 13 frameworks were identified for comparative analysis in the final section.

Qualitative synthesis (conceptual framework development)

The Digital-Sustainability Ecosystem conceptual framework was developed through a qualitative synthesis approach, integrating systematic literature review (SLR) findings with established theoretical foundations. This iterative process identified and structured key mechanisms, pathways, and outcomes that characterize digitally-driven sustainable innovation. A comparative analysis of the 50 selected studies led to the identification of five interrelated mechanisms mediating the relationship between digital transformation and sustainable innovation. These mechanisms were further refined through conceptual mapping and systematically cross-referenced with empirical findings and theoretical constructs to ensure both conceptual coherence and empirical validity. To ensure methodological robustness, the framework was developed using concept mapping (Pribadi, 2018) and framework synthesis techniques (Brunton et al., 2020; Dixon-Woods, 2011). These methodological tools enabled a structured integration of theoretical and empirical insights, reinforcing the framework's academic rigor and practical applicability.

RESULTS AND DISCUSSION

The integration of digital transformation and sustainable innovation

Digital transformation and sustainable innovation are pivotal in contemporary organizational strategy and societal development. The intersection of these concepts is central to debates regarding the application of digital technologies to achieve sustainable outcomes. Research in this area has revealed both opportunities and complexities. The literature indicates that digital transformation catalyzes sustainable innovation by facilitating the development of sustainable business models (Li et al., 2023), optimizing resource use (Liang & Sun, 2024), and enhancing stakeholder engagement (Hallioui et al., 2022). Key technologies identified as drivers in this process include the Internet of Things (IoT), artificial intelligence (AI), blockchain, and big data analytics, which have been recognized as primary enablers of sustainable innovation (Belhadi et al., 2022; Wang et al., 2023b). IoT facilitates real-time energy consumption monitoring, helping firms reduce their carbon footprint, while AI-driven predictive analytics enhances decision-making by optimizing resource allocation, extending asset lifecycles, and minimizing waste in manufacturing and energy sectors (Yuan & Pan, 2023a; Li et al., 2024). These technologies enable operational efficiency and create new value propositions in response to the increasing demand for sustainability in global markets. Adaptability is critical in industries facing stringent regulatory requirements, where resilience must be maintained while pursuing sustainability-oriented goals (Lin et al., 2024). AI and IoT-based precision technologies in agriculture minimize resource inputs, such as water and fertilizers, while enhancing environmental outcomes (Ali & Johl, 2023).

These applications illustrate how dynamic capabilities empower firms to integrate emerging technologies into circular economy practices, creating closed-loop systems that reduce resource waste and environmental harm (Ren et al., 2024). For instance, blockchain-enabled supply chain systems enhance collaborative innovation by improving transparency, trust, and accountability among stakeholders (Saberi et al., 2019). Such integration generates long-term strategic value by aligning technological advancements with environmental goals, establishing a basis for sustained competitive differentiation and

leadership in sustainable innovation (Ammar et al., 2024). Scholars have emphasized the role of digital platforms in fostering cross-sector collaboration and knowledge-sharing, enabling businesses, governments, and non-profits to co-develop sustainability solutions through open innovation mechanisms (Arroyabe et al., 2024; Liang & Sun, 2024). This interconnectedness promotes a systemic approach to innovation, with digital transformation as the foundation for scaling and integrating sustainable practices across industries and supply chains.

Despite its transformative potential, digital transformation faces adoption barriers, particularly in developing regions, due to high implementation costs, inadequate infrastructure, and limited digital literacy. These financial and technological constraints disproportionately impact smaller organizations, limiting their ability to integrate sustainability-driven innovations (Trevisan et al., 2023). Regulatory gaps and misaligned incentives further intensify these challenges, discouraging investments in technologies that promote sustainable innovation (Kumar et al., 2021). While digital technologies enable sustainability-oriented transformations, their high energy consumption, particularly in data centers and blockchain applications, raises concerns. To address this paradox, scholars advocate for "green digital transformation," in which digital adoption is explicitly designed to minimize environmental impact (Dong et al., 2024).

Companies pursuing sustainable innovation must incorporate long-term environmental and social considerations into their strategic and operational frameworks, prioritizing systemic transformation over incremental improvements (Neri et al., 2023). Wu et al. (2016) argued that the traditional focus on economic, environmental, and social factors inadequately captures the complexity of sustainability. They advocated incorporating additional dimensions such as operations, resilience, and stakeholder engagement. Tseng (2017) similarly emphasized that effective sustainability strategies necessitate integrating qualitative insights, quantitative data, and technological advancements within the Triple Bottom Line (TBL) framework. The "overlapping bottom line" model proposed by Wu et al. (2018) integrates dimensions like eco-efficiency, socio-economic, and socio-environmental benefits, suggesting that digital technologies can enhance co-benefits across these areas. Emerging tools such as AI, IoT, and blockchain further enhance the relevance of TBL by enabling firms to monitor and optimize sustainability metrics in real-time, thereby improving resource efficiency, regulatory compliance, and equity-driven outcomes (George et al., 2021).

Successfully integrating digital transformation with sustainable innovation necessitates organizational adaptability. Firms that cultivate a culture of continuous improvement, supported by strategic leadership and stakeholder engagement, enhance resilience and long-term sustainability (He et al., 2024; Lin et al., 2024). Additionally, studies emphasize the importance of regulatory frameworks and policy interventions in ensuring digital transformation aligns with sustainability objectives (Akhtar et al., 2024). Governments and international organizations are increasingly promoting standards and incentives to encourage the adoption of technologies that support environmental and social well-being.

Recent advancements in digital technologies are expanding avenues for sustainable innovation in agriculture (Ali et al., 2024) and manufacturing (Lin & Xie, 2024; Schöggl et al., 2023). In agriculture, precision farming technologies employing IoT and drones enhance productivity while reducing resource inputs. In manufacturing, digital twins and 3D printing transform production processes by minimizing material waste and enabling localized production. These sector-specific innovations demonstrate how digital transformation supports sustainable development.

The literature emphasizes a systemic perspective to understand the link between digital transformation and sustainable innovation. Rather than viewing these concepts in isolation, scholars advocate for an integrative approach that considers the interdependencies among technological, economic, and social systems. Digital transformation is both a tool and a process that enhances the impact of sustainable innovation by fostering collaboration. Conversely, sustainable innovation guides digital transformation toward long-term value creation rather than short-term gains. The relationship is synergistic and complex, characterized by mutually reinforcing dynamics and inherent tensions. While digital technologies facilitate sustainability changes, effective implementation necessitates strategic alignment, cultural readiness, and supportive policy environments. Researchers and practitioners face the ongoing challenge of navigating this interplay to maximize digital transformation's potential as a catalyst for sustainable innovation, ensuring that technological progress leads to tangible and equitable benefits for society and the environment.

Key mechanisms driving sustainable innovation through digital transformation

Integrating digital transformation with sustainable innovation has led to the emergence of five interconnected mechanisms. The first mechanism, efficiency gains, enables organizations to optimize resource consumption, enhance operational resilience, and minimize waste, therby advancing sustainability objectives while maintaining productivity (Okorie et al., 2023). Advanced digital technologies facilitate these improvements through real-time data analytics, AI-

driven automation, and predictive maintenance, enabling organizations to proactively address inefficiencies (Qian & Chen, 2024). AI-driven predictive maintenance, for instance, extends machinery lifecycles, reduces unexpected downtime, and optimizes material usage directly contributing to eco-efficiency (Rajput & Singh, 2020). These optimizations align with circular economy (CE) principles, reinforcing digital transformation's role in fostering sustainable resource utilization (Zhao & Fang, 2023). Siemens has pioneered smart grid systems that dynamically adjust energy distribution, optimizing electricity flows and reducing carbon emissions in real-time (Oral et al., 2022; Siemens, 2024). As a result, efficiency gains serve as a core enabler of organizational adaptability, allowing firms to navigate evolving regulatory landscapes and align operations with global sustainability targets (Yuan & Pan, 2023b).

The second mechanism is dematerialization, which reduces material dependency by replacing physical products and services with digital alternatives, significantly lowering environmental impact (Zhang et al., 2024). Cloud computing exemplifies this shift by minimizing the need for on-site data storage, thereby reducing energy-intensive hardware reliance (Paredes-Frigolett & Pyka, 2023). This transition optimizes resource allocation and enhances eco-efficiency, particularly in manufacturing and logistics, where automated systems reduce material waste (Ahmad et al., 2023). The shift to digital services also reduces reliance on physical transportation and storage, reinforcing circular economy (CE) principles and enhancing sustainability outcomes (Toșa et al., 2024). This transformation is particularly evident in the manufacturing and media sectors, where automation, digital platforms, and service-based models replace traditional product-centric approaches (Ranta et al., 2018). 3D printing facilitates localized, on-demand production in manufacturing, reducing material waste and optimizing resource allocation (Lodha et al., 2023). Digital twins replicate physical assets in virtual environments, enabling manufacturers to conduct real-time monitoring, predictive simulations, and process optimizations, minimizing material consumption and improving lifecycle efficiency (Attaran et al., 2023). This is particularly relevant in resource-intensive industries such as automotive and aerospace, where AI-driven digital twins refine designs, optimize production cycles, and extend asset longevity, contributing to eco-efficiency and cost reduction (Ranta et al., 2018).

A third mechanism involves integrating CE principles through digital tools, where IoT and blockchain technologies facilitate real-time materials tracking, resource reuse, remanufacturing, and recycling processes (Agrawal et al., 2022; Yin, 2023). The core CE principles underpin this transition by eliminating waste and pollution, keeping materials in circulation, and regenerating natural systems (Kottmeyer, 2021). For example, the automotive and electronics industries leverage IoT-enabled sensors and blockchain-based material tracing systems to improve supply chain accountability, ensuring the efficient reuse and recycling of resources (Ranta et al., 2018). Innovative CE models, such as textile upcycling initiatives, are redefining product design strategies to enhance recoverability and recyclability (Lombardi Netto et al., 2021). Industry 4.0 advancements, including AI-driven analytics and cloud-based systems, further optimize CE implementation by enhancing process transparency, improving waste management, and reducing resource intensity (Gupta et al., 2021; Ghobakhloo et al., 2021). Blockchain technology plays a pivotal role in these developments, enabling secure, immutable records of material flows, ethical sourcing verification, and reducing inefficiencies in circular supply chains (Schöggl et al., 2023). However, concerns remain regarding the socio-cultural implications of blockchain standardization, as regulatory and economic disparities may disproportionately impact specific regions (Kottmeyer, 2021). Despite high transaction costs, limited secondary material data, and inefficient product design, digital transformation mitigates these barriers by enhancing supply chain transparency and facilitating collaborative decision-making (Kumar et al., 2024; Truant et al., 2024).

Digital transformation also fosters collaborative innovation ecosystems, where digital platforms function as enablers of stakeholder partnerships, resource-sharing networks, and cross-industry synergies (Li et al., 2023; Wang et al., 2023a). For example, blockchain-enabled knowledge-sharing hubs allow firms to co-develop sustainability solutions, optimizing resource utilization and waste reduction strategies (Wang et al., 2023a). These platforms facilitate transparent data flow, allowing stakeholders to engage in real-time decision-making and accountability. These ecosystems enhance multi-stakeholder collaboration through real-time data transparency, supporting scalable sustainability transitions across industries (Calabrese et al., 2021; Zhu et al., 2024). Additionally, AI-powered open innovation platforms aggregate diverse stakeholder insights, including corporations, policymakers, and researchers, accelerating breakthrough innovations in eco-efficient supply chain management and CE implementation (Wang et al., 2023b). Beyond industry applications, digital collaboration platforms also address regional disparities in technology adoption. Research indicates that digital innovation hubs in emerging economies have improved access to sustainability-driven technologies, facilitating localized solutions tailored to unique environmental challenges (Du & Jian, 2024). This highlights the broader role of digital transformation in bridging technological divides and promoting equitable access to sustainable innovation strategies. Furthermore, intersectoral digital collaboration fosters accelerated innovation adoption, reinforcing the critical role of cross-industry partnerships in scaling sustainability-driven initiatives (Arroyabe et al., 2024; K. He & Chen, 2024; Tao et al., 2024).

The five mechanisms, efficiency gains, dematerialization, CE adoption, innovation acceleration, and digital collaboration, form the foundation of our conceptual framework, illustrating how digital transformation catalyzes sustainable innovation. However, effectively translating these mechanisms into strategic initiatives requires considering contextual factors, including regulatory frameworks, market incentives, and organizational readiness.

Conceptual framework: Digital transformation as a catalyst for sustainable innovation

The Digital-Sustainability Ecosystem (DSE) conceptual framework positions digital transformation (DT) as a critical enabler of sustainable innovation (SI) (Figure 2). At the core of this framework lies the Digital-Sustainability Ecosystem (DSE), where DT and sustainability practices dynamically interact. The framework identifies three core components: Inputs, Pathways, and Outputs, moderated by external factors such as regulatory frameworks, market trends, and societal expectations. These components form adaptive feedback loops, reinforcing DT's role in fostering long-term sustainability transitions through continuous technological advancements, organizational learning, and external pressures. This systemic approach integrates technological, organizational, environmental, and societal dimensions, offering a holistic structure for embedding sustainability in digital strategies.

Inputs include technological and organizational capacities underpinning DT-driven sustainability efforts. The technological dimension encompasses AI, IoT, blockchain, big data analytics, and automation, enabling real-time data processing, resource optimization, and predictive analytics. The organizational dimension emphasizes adaptive leadership, agile structures, and cross-functional collaboration, ensuring DT adoption aligns with sustainability imperatives. Adaptive leadership facilitates regulatory navigation and strategic agility, while agile structures enable firms to rapidly integrate digital tools into sustainability-driven business models. These Inputs, therefore, demonstrate how firms must simultaneously develop technological and organizational capabilities to drive systemic, sustainable innovation (Bag, Yadav, et al., 2021; Ghobakhloo et al., 2021).

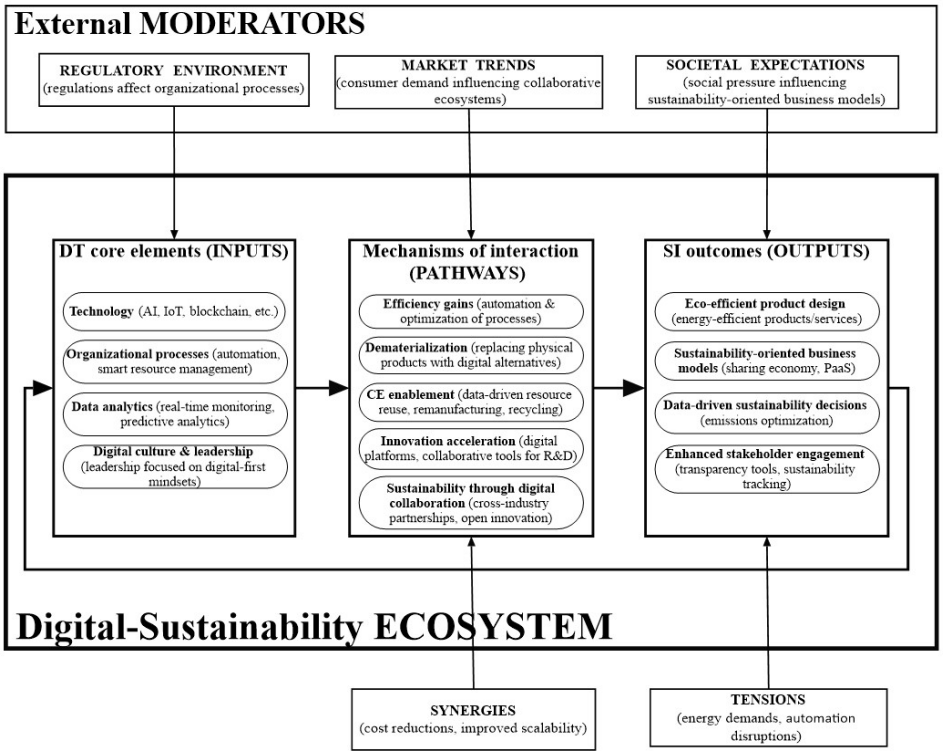

Figure 2. Conceptual Framework of the Digital-Sustainability Ecosystem (DSE)

The framework's Pathways outline how DT converts Inputs into sustainable innovation (SI) Outputs through five interrelated mechanisms: efficiency gains, dematerialization, CE enablement, innovation acceleration, and digital collaboration. These pathways align with the technological, organizational, and environmental dimensions, demonstrating

how diverse mechanisms interact within the DSE. Efficiency gains, facilitated by AI and IoT, optimize resource allocation and waste reduction. Dematerialization replaces physical products and services with digital alternatives, such as cloud computing and digital twins, minimizing material dependency and environmental impact. The CE enablement supported by blockchain and IoT enhances traceability, fostering closed-loop production systems prioritizing recycling and remanufacturing. Innovation acceleration, driven by digital platforms, fosters collaboration across diverse stakeholders, leveraging AI and crowdsourcing to expedite sustainability solutions aligned with the Triple Bottom Line (TBL) (Agrawal et al., 2022; Ghobakhloo et al., 2021; Schöggl et al., 2024; Tao et al., 2024). Multi-stakeholder digital collaboration, supported by blockchain-enabled transparency, facilitates strategic partnerships among various sectors, including industry, government, academia, and civil society. This systemic collaboration aligns disparate organizational priorities with shared sustainability objectives, ensuring scalability and risk-sharing in sustainability transitions.

The Outputs of the DSE encompass the tangible sustainability benefits derived from integrating DT with SI. These outcomes span environmental and societal dimensions, reinforcing DT's transformative role in shaping sustainable business practices. AI-driven eco-efficient product design reduces material waste and optimizes circularity throughout product lifecycles (Xiao et al., 2024b). Sustainability-oriented business models, such as product-as-a-service (PaaS), decrease resource dependency and embed CE principles into systemic practices, addressing both environmental and societal goals (Khan et al., 2021). Big data-driven decision-making facilitates real-time emissions monitoring, resource optimization, and compliance with sustainability policies, ensuring operational sustainability (Ali & Johl, 2023). Enhanced stakeholder engagement emerges from transparency-driven digital platforms, fostering multi-actor collaboration to align corporate strategies with sustainability regulations and societal demands (Li et al., 2023). Together, these outputs emphasize DT's systemic impact in reinforcing sustainability-driven innovation.

The DSE framework incorporates external factors that influence the role of DT in advancing sustainability. These factors, including regulatory frameworks, market trends, and societal expectations, represent the social dimension of the DSE and underscore the impact of external pressures on sustainability. Regulatory initiatives, such as the European Green Deal, exemplify the increasing societal emphasis on sustainability, establishing ambitious environmental goals and incentivizing businesses to adopt eco-friendly practices (European Commission, 2021). Financial incentives and compliance requirements drive organizations to implement technologies like IoT for emissions monitoring and AI for optimizing energy efficiency (Kumar et al., 2021). Market forces also play a decisive role in sustainability transitions. Consumers' growing preference for environmentally responsible products compels businesses to innovate their operations and business models. Additionally, investors, employees, and non-governmental organizations (NGOs) elevate these pressures by demanding greater transparency and accountability and demonstrating sustainability progress. This complex interplay among policy mandates, market expectations, and societal demands emphasizes the societal dimension of the DSE, and illustrates how external forces drive systemic sustainability transformations (Bag, Pretorius et al., 2021; Ren et al., 2024).

Beyond external pressures, the DSE framework addresses the synergies and tensions firms encounter when integrating digital transformation with sustainable innovation. Synergies emerge when advanced technologies enhance operational efficiency, reduce costs, and scale sustainability initiatives. However, tensions arise from trade-offs between digital infrastructure expansion and sustainability objectives. For instance, the high energy demands of AI and blockchain technologies present challenges to carbon neutrality unless paired with renewable energy solutions (Li et al., 2024). Financial constraints further complicate adoption, as firms must justify the substantial upfront investment costs against uncertain long-term sustainability benefits. This challenge is particularly pronounced in resource-constrained industries, where balancing profitability and sustainability commitments remains a strategic dilemma (Kottmeyer, 2021). Integrating digital transformation necessitates significant organizational restructuring, including workforce reskilling and process reconfiguration. While these adjustments are essential for leveraging digital capabilities, they can delay the immediate realization of sustainability benefits (Lin et al., 2024; Wang et al., 2023a).

The DSE framework incorporates an adaptive feedback loop to address these challenges, ensuring continuous sustainability improvements through iterative learning and strategic recalibration. IoT-enabled monitoring systems provide real-time environmental data, allowing firms to reassess and refine sustainability strategies. Concurrently, organizational learning mechanisms enable firms to integrate past insights into future strategies, fostering adaptability and resilience. External pressures, such as shifting regulations and evolving consumer expectations, are systematically incorporated into the loop, ensuring firms remain responsive to sustainability initiatives. This iterative cycle strengthens the interconnectedness of the DSE's technological, organizational, environmental, and societal dimensions, reinforcing its role as a guiding framework for long-term sustainability transitions (Ortiz-Avram et al., 2024).

The development of DT accelerated during the COVID-19 pandemic and catalyzed widespread digital adoption, ranging from remote work solutions to AI-driven healthcare innovations (Tregua et al., 2021). However, this rapid digital expansion also underscored the dual-edged nature of technological advancements. On the one hand, cloud computing and blockchain improve supply chain transparency and promote dematerialization by reducing reliance on physical assets (Mssassi & El Kalam, 2024). On the other hand, we must address ethical concerns, digital inequalities, and cybersecurity risks to ensure technology-driven sustainability transitions (Shayganmehr et al., 2021). While cloud computing enhances resource utilization, its reliance on energy-intensive data centers underlines the need for renewable energy solutions to mitigate environmental impacts (Katal et al., 2023). Achieving this balance remains a key challenge in maximizing digital transformation's contribution to sustainability. The pandemic reinforced the necessity of embedding digital transformation within long-term sustainability strategies, ensuring its role as a catalyst for systemic change. The ability of digital technologies to support resilient and sustainable business models while adapting to external disruptions highlights their importance for future corporate and policy frameworks. To fully harness these systemic benefits, firms must integrate digital strategies with sustainability objectives at both strategic and operational levels, ensuring that technological advancements contribute to resilient, equitable, and environmentally responsible outcomes.

Digital-Sustainability Ecosystem (DSE) against the background of selected frameworks

The conceptual framework presented in this study, the Digital-Sustainability Ecosystem (DSE), provides a holistic view of how DT acts as a catalyst for SI. This section synthesizes findings from 13 frameworks identified in the literature, detailed in Table 1. We evaluate their key focus, core mechanisms, similarities, and differences with the proposed conceptual framework. This discussion evaluates the proposed framework against the identified ones, highlighting its contributions and examining its theoretical and practical implications.

Table 1. Comparative analysis of 13 frameworks and the Digital-Sustainability Ecosystem (DSE) conceptual framework in the context of digital transformation and sustainable innovation

Framework/Model	Key focus	Core mechanisms	Relation to the Digital-Sustainability Ecosystem (DSE)	Distinct contributions of the Digital-Sustainability Ecosystem (DSE)
Bag & Pretorius (2020)	Integration of Industry 4.0 technologies with sustainable manufacturing practices, particularly within the circular economy (CE) framework.	Focuses on the adoption of Industry 4.0 technologies (e.g., IoT, AI, big data analytics) to enhance resource efficiency, promote closed-loop systems, and align with CE principles.	Aligns with the Digital-Sustainability Ecosystem (DSE) pathways of efficiency gains and CE enablement by leveraging digital technologies for resource optimization and recycling.	The DSE introduces additional mechanisms of innovation acceleration through digital platforms and emphasizes multi-stakeholder digital collaboration. Moreover, the DSE integrates leadership-driven strategies and feedback loops for iterative sustainability transitions, offering a more adaptive and systemic approach.
Belhadi et al. (2022)	Integration of CE and Industry 4.0 in supply chains.	Closed-loop supply chains and dynamic capabilities.	Aligns with CE enablement and data-driven decisions.	Extends to emphasize leadership-driven digital culture, integrates collaborative innovation platforms, and incorporates systemic adaptability through feedback loops.
Calabrese et al. (2021)	Digital platform ecosystems for sustainability.	Meta-organizational models, collaboration, open innovation.	Aligns with sustainability through digital collaboration and meta-organizational principles.	Expands on multi-stakeholder engagement by integrating AI and blockchain for transparency and enhancing leadership adaptability.
Gupta et al. (2021)	Integrative framework combining Industry 4.0, cleaner production (CP), and circular economy (CE) for sustainability in manufacturing.	Multi-criteria decision-making (BWM), case study validation of Industry 4.0 practices, CE initiatives, and CP strategies.	Aligns with CE enablement, dematerialization, and efficiency gains.	Expands focus on innovation acceleration, adaptive digital leadership, and iterative feedback mechanisms, ensuring long-term sustainability.

Framework / Model	Key focus	Core mechanisms	Relation to the Digital-Sustainability Ecosystem (DSE)	Distinct contributions of the Digital-Sustainability Ecosystem (DSE)
Hallioui et al. (2022)	Systems-based management for sustainability.	Re-engineered 4th Gen. Management, stakeholder integration, Industry 4.0, and CE.	Aligns with feedback loops and stakeholder engagement.	Adds leadership-driven digital collaboration, broader technological integration (AI, blockchain), and iterative feedback mechanisms.
Li et al. (2023)	Digital Platform Ecosystems for sustainable business model innovation.	Explores the generativity, convergence, share-ability, modularity, and complementarity of digital platform ecosystems driving sustainable business model innovation.	Aligns with sustainability-oriented business models, emphasizing collaboration and customer-centric approaches through digital platforms.	Extends to incorporate dynamic interactions among pathways such as efficiency gains and digital collaboration, integrating AI-driven predictive capabilities and feedback mechanisms for continuous sustainability improvement.
Liu et al. (2022)	Digital Tech for CE.	Digital functions (e.g., monitor, track, optimize) enhance CE strategies (e.g., reuse, recycle).	Aligns with CE enablement through mechanisms like data analysis and automation.	Extends to cross-sectoral collaborations, emphasizes adaptive feedback loops, and integrates external moderators (e.g., societal and regulatory pressures).
Nascimento et al. (2019)	Integration of Industry 4.0 with circular economy (CE).	Circular Smart Production System (CSPS) using additive manufacturing (AM), CE, and reverse logistics.	Supports CE enablement through waste treatment and AM.	Extends to include multi-stakeholder collaboration, leadership-driven strategies, and feedback loops to ensure scalability and adaptability.
Samadhiya et al. (2022)	Total Productive Maintenance (TPM), Industry 4.0, and CE.	Integration of TPM, Industry 4.0, and CE for sustainability in manufacturing firms.	Aligns with process optimization and efficiency gains pathways in the DSE.	Expands on the role of adaptive digital leadership in navigating trade-offs between digital innovation and sustainability, positions CE as a critical enabler within DT processes, and enhances the integration of AI for resource optimization and sustainability-driven decision-making.
Shayganmehr et al. (2021)	Industry 4.0 and CE in ethical business.	Key enablers for CE embedded in business ethics, supported by Industry 4.0 technologies and frameworks like Fuzzy AHP and Delphi.	Supports ethical frameworks and sustainability decisions through cleaner production and CE implementation.	Integrates cross-industry digital collaboration, emphasizes the role of adaptive leadership and aligns AI-driven innovations with ethical sustainability.
Wang et al. (2023)	AI and green innovation	Explores direct, indirect, and spillover effects of AI on green innovation through industrial structure upgrades and human capital optimization..	Aligns with innovation acceleration and data-driven decisions, incorporating AI's role in CE enablement and collaborative platforms.	DSE extends by addressing AI's energy demands, embedding adaptive feedback loops, and focusing on synergies and tensions in integrating AI across systemic sustainability pathways.
Yin et al. (2023)	Digital transformation and green innovation under the Technology-Organization-Environment (TOE) framework	Examines technology, organization, and environment as interdependent factors enabling green innovation.	Supports technological, organizational, and environmental factors in digital transformation.	Adds iterative feedback mechanisms and dynamic pathways across dimensions to manage tensions and synergies; highlights leadership-driven strategies for SI.
Yuan & Pan (2023a)	Digital technology for green innovation.	Resource allocation optimization, enhanced R&D and digital infrastructure investment, and labor dynamics.	Aligns with data-driven decision-making, resource optimization, and integration of R&D with sustainability outputs.	Adds an iterative feedback loop linking digital technology applications to sustainability outputs, emphasizing adaptive learning and resilience in corporate green innovations.

Existing frameworks, such as Bag and Pretorius (2020) and Belhadi et al. (2022), emphasize Industry 4.0 and CE strategies, focusing on efficiency gains, data-driven optimization, and closed-loop supply chains. These frameworks effectively integrate dynamic capabilities to navigate sustainability transitions but overlook innovation acceleration, adaptive digital leadership, multi-stakeholder governance structures, and cross-sectoral digital collaboration mechanisms. The DSE surpasses these limitations by integrating a multi-dimensional perspective that dynamically aligns technological, organizational, environmental, and societal pathways with iterative feedback mechanisms. Unlike prior Industry 4.0-centric models, which focus on incremental efficiency improvements, the DSE framework ensures that digital transformation is deeply embedded within organizational and policy-driven sustainability transitions, promoting long-term resilience. For instance, digital platforms within the DSE facilitate AI-driven real-time collaboration, enabling open innovation ecosystems that extend beyond firm-level boundaries. This approach aligns with the diffusion of innovation and stakeholder theory while advancing beyond frameworks like Calabrese et al. (2021) and Liu et al. (2022), focusing narrowly on collaborative platforms without considering their integration with leadership inputs and iterative feedback loops. The DSE integrates AI-powered predictive capabilities, blockchain-enabled transparency, and adaptive leadership structures, ensuring that digital transformation is not merely a technological enabler but a systemic force driving cross-sectoral sustainability transformations. Similarly, Nascimento et al. (2019) explore smart production systems for CE using additive manufacturing, which aligns with the DSE's CE enablement focus. The DSE extends beyond technological advancements by embedding multi-stakeholder collaboration and leadership-driven adaptability, ensuring that sustainability transitions are scalable across industries rather than confined to specific manufacturing applications.

Moreover, frameworks like Gupta et al. (2021) and Samadhiya et al. (2022) integrate Industry 4.0 with cleaner production and circular economy models, focusing on process optimization and resource efficiency. However, these frameworks lack systemic adaptability mechanisms to accommodate evolving sustainability demands and fail to incorporate iterative learning mechanisms essential for long-term transformation. The DSE advances these contributions by embedding adaptive leadership and feedback-driven mechanisms that dynamically align blockchain, IoT, and AI technologies with sustainability imperatives. This strategic adaptability reinforces the role of leadership in resource reconfiguration and cross-industry coordination, positioning the DSE as a governance-integrated framework that bridges technological, organizational, and policy-driven sustainability efforts. Additionally, while Shayganmehr et al. (2021) address the ethical implications of Industry 4.0 and CE integration, their model lacks institutional adaptability and real-time feedback mechanisms necessary for scalable sustainability transformations. The DSE complements this perspective by incorporating adaptive leadership strategies to navigate ethical trade-offs, ensuring that AI and blockchain-driven sustainability initiatives align with global environmental and social governance (ESG) standards.

Frameworks such as Wang et al. (2023) and Yin (2023) leverage AI and the Technology-Organization-Environment (TOE) framework to explore digital innovation in green transformation. While their models effectively identify technological enablers of sustainable innovation, they treat technology adoption as an isolated driver rather than an interdependent component within broader socio-economic, regulatory, and cultural systems. In contrast, the DSE framework explicitly integrates these dimensions, acknowledging that regulatory incentives, market pressures, and stakeholder alignment are critical moderating forces in digital sustainability transitions. This distinction underscores the DSE's ability to synchronize digital strategies with evolving socio-environmental imperatives, ensuring that technological advancements translate into systemic, long-term sustainability gains.

The DSE's positioning within a continuous improvement cycle further differentiates it from existing frameworks. Unlike models that assume a linear progression of digital transformation, the DSE recognizes adaptive learning, organizational feedback, and iterative recalibration as essential for sustainability transitions. Hallioui et al. (2022) provide a comprehensive view of Industry 4.0 and CE but lack a structured mechanism for adaptive digital sustainability loops, a core principle of the DSE. Li et al. (2023) discuss the modularity and generativity of digital platform ecosystems driving sustainable business model innovation. The DSE framework focuses on digital collaboration and integrates AI-driven predictive capabilities and feedback for continuous improvement. It enhances sustainability performance through real-time monitoring and analytics, ensuring consistent refinement rather than static implementation.

Unlike Liu et al. (2022), which focuses solely on digital technology adoption, without integrating governance mechanisms, or Samadhiya et al. (2022), which emphasizes process efficiency without addressing broader systemic interdependencies, the DSE adopts a multi-dimensional perspective. The framework bridges short-term operational improvements with long-term sustainability imperatives by embedding dynamic feedback loops and external moderators. For instance, blockchain-enabled transparency and cross-sectoral collaboration within the DSE facilitate scalable circular

business models that address complex global sustainability challenges. This systemic adaptability ensures alignment with global sustainability goals, including the United Nations Sustainable Development Goals (SDGs) and regulatory frameworks such as the European Green Deal (European Commission, 2021).

Similarly, Yuan and Pan (2023a) emphasize resource allocation and digital infrastructure investment for green innovation, which aligns with the DSE's focus on optimizing resource efficiency. However, the DSE extends these principles by integrating adaptive feedback mechanisms that allow organizations to continuously refine sustainability strategies in response to evolving market and regulatory conditions. Across these comparisons, the DSE's incorporation of systemic adaptability, leadership-driven transformation, and multi-stakeholder collaboration reinforces its distinct contributions to digital sustainability discourse.

The Digital Sustainability Ecosystem (DSE) conceptual framework exemplifies an integrated approach to bridging digital transformation (DT) and sustainable innovation (SI). By synthesizing advanced digital technologies, multi-stakeholder collaboration, adaptive leadership, and iterative feedback mechanisms, the DSE provides a structured pathway for embedding sustainability into digital transformation processes. While the framework aligns with existing models in areas such as circular economy (CE) enablement, resource efficiency, and digital collaboration, it surpasses prior approaches by incorporating cross-sectoral integration and leveraging advanced technologies such as AI and blockchain to enhance transparency, adaptability, and continuous improvement.

Compared to other frameworks, the DSE emphasizes leadership-driven adaptability, dynamic feedback integration, and systemic resilience. It builds upon foundational concepts from CE and Industry 4.0 frameworks, such as those discussed by Bag and Pretorius (2020) and Gupta et al. (2021), while expanding its focus on innovation acceleration and strategic resilience. Furthermore, the DSE directly addresses tensions and synergies in the interaction between DT and SI, such as the energy demands of AI and blockchain versus their efficiency-enhancing potential and the ethical considerations of digital sustainability implementation. These refinements position the DSE as a governance-driven framework that operationalizes sustainability transitions through structured, iterative adaptation.

CONCLUSION

This study conceptualizes the Digital-Sustainability Ecosystem (DSE) framework, demonstrating how digital transformation (DT) catalyzes sustainable innovation by integrating multiple mechanisms - efficiency gains, dematerialization, circular economy enablement, innovation acceleration, and digital collaboration. When aligned with advanced technologies such as AI, IoT, blockchain, and digital platforms, these mechanisms enhance resource optimization, reduce environmental impact, and facilitate multi-stakeholder collaboration. The DSE framework introduces a systemic perspective, moving beyond isolated technological adoption to position digital transformation as an enabler of sustainability transitions, integrating technological, organizational, environmental, and societal dimensions. By synthesizing insights from existing frameworks, this study extends the theoretical discourse by illustrating how digital capabilities enable systemic sustainability outcomes through dynamic feedback loops and adaptive strategies.

The study integrates dynamic capabilities, diffusion of innovation, and the resource-based view (RBV) to highlight the strategic interplay between digital transformation and sustainable innovation. It extends the RBV by positioning digital resources as intangible assets that create sustained competitive advantages, emphasizing the role of data analytics, blockchain infrastructure, and AI-driven platforms in enhancing organizational resilience and strategic positioning. Furthermore, the study underscores the sociotechnical interplay between digital systems and human factors, demonstrating that organizational adaptability, leadership agility, and stakeholder engagement are fundamental in embedding sustainability within digital strategies. Mechanisms such as digital collaboration and innovation acceleration reinforce the importance of cross-sectoral partnerships, where governments, industries, and civil society actors co-create sustainability solutions through transparent, data-driven decision-making. The study aligns with circular economy principles by identifying digital tools as enablers of resource circularity, particularly through blockchain-enabled traceability, real-time monitoring, and AI-driven waste reduction strategies.

The DSE framework advances current literature by capturing the interdependencies between digital technologies, sustainability objectives, and institutional contexts by integrating existing theoretical approaches with sustainability-oriented concepts such as the triple bottom line, circular economy, stakeholder theory, and innovation systems. It provides a foundation for understanding the synergies and tensions within digital sustainability transitions, including AI's energy demands versus efficiency benefits or blockchain's transparency advantages versus environmental costs. These trade-offs

underscore the need for regulatory interventions that incentivize sustainable digital adoption. While policy considerations were not the central focus of this study, future research could examine how governments can shape sustainability-oriented digital ecosystems through regulatory incentives, tax benefits, and governance mechanisms.

Despite its contributions, this study has certain limitations. The conceptual nature of the DSE framework necessitates empirical validation to test its applicability across different industries, regulatory environments, and technological contexts. Additionally, the reliance on existing literature introduces potential biases inherent in secondary data, which may limit the generalizability of findings. The study also acknowledges that digital sustainability transitions are highly dynamic, requiring continuous adaptation to emerging technologies and regulatory shifts. Addressing the regulatory tensions associated with AI, blockchain, and automation remains an open area for further exploration, particularly concerning data privacy, energy consumption, and market-driven sustainability incentives.

Future research should empirically validate the DSE framework across various sectors, such as manufacturing, agriculture, and energy, to explore its scalability and sector-specific adaptability. Longitudinal studies could examine the dynamic interactions within the DSE over time, providing deeper insights into iterative feedback mechanisms and adaptive learning processes. Furthermore, exploring regional and cultural variations in digital transformation adoption would offer valuable perspectives on institutional and socio-economic barriers to sustainability-oriented digitalization. Investigating the ethical implications of digital technologies, particularly regarding data security, algorithmic bias, and the environmental trade-offs of high-energy technologies.

In conclusion, this study positions the DSE framework as a foundational model for understanding how digital transformation enables systemic sustainability transitions. By synthesizing digital capabilities, leadership adaptability, and multi-stakeholder collaboration, the framework provides a strategic pathway for organizations to align digital innovation with sustainability imperatives. The findings call for continued academic, industry, and policy engagement to maximize the potential of digital transformation in achieving resilient, transparent, and equitable sustainability outcomes.

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Conflicts of interest

The Editors-in-Chief had no involvement in the evaluation or decision-making process of their manuscript.

Citation (APA Style)

Florek-Paszkowska, A., & Ujwary-Gil, A. (2025). The Digital-Sustainability Ecosystem: A conceptual framework for digital transformation and sustainable innovation. *Journal of Entrepreneurship, Management, and Innovation 21*(2), 116-137. https://doi.org/10.7341/20252127