Digital Transformation and Sustainability in Developing Economies: How Industry 4.0 Drives Green Practices: A Systematic Literature Review

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Abstract: In the context of the rapid physical pace of digitalization and the emergence of an environmental agenda, the embrace of Industry 4.0 technologies within sustainability frameworks around the globe is in an accelerated state. This is especially true in developing economies, which are looking into how these advances in technology (artificial intelligence (AI), Internet of Things (IoT), Blockchain, and Big Data) propel green transitions and address environmental challenges. The present research involves a systematic literature review of the existing literature that reviews the intersections between digital transformation and environmental sustainability with meaning in developing contexts. Through the Systematic Literature Review (SLR) approach, we reviewed the peer reviewed articles obtained from Scopus, Web of Science, and ScienceDirect databases, based on the PRISMA framework for article selection The review frames the literature, limited to 2010-2023, and synthesizes to structure around the themes of adoption, barriers to implementation, sectoral considerations, and policy considerations. The review indicates that Industry 4.0 technologies present a significant opportunity for improved energy efficiency, waste reduction, and green innovation, but their uptake is limited by infrastructure, availability of digital skills, and weak policy support in less developed contexts. In contrast, enablers include cross-sectoral collaboration, institutional support, and ESG frameworks. Numerous opportunities for application exist including, but not limited to, manufacturing, energy, agriculture, and logistics. The review provides a contribution to knowledge for academia by bringing together otherwise fragmented knowledge and offering a conceptual platform to guide future research. Policymakers and practitioners will find this piece useful in adding structure and direction to emerging digital sustainability strategies. Overall, the review reinforces the necessity for local and inclusive approaches to realise the transformative opportunities Industry 4.0 can present for sustainable development.

Keywords: Industry 4.0, Sustainability, Digital Transformation, Developing Economies, Green Innovation

1. Introduction

With the emergence of Industry 4.0, the corporate environment has transformed for utilizing advanced digital technologies such as IoT, AI, Big Data, and Cyber-Physical Systems (CPS) with intelligent and sustainable industry processes (Schneider Electric, 2025). With these technologies, efficiency, productivity and sustainability can be improved by predictive maintenance, minimizing unplanned down-time, and optimizing resource consumption (Kamble et al., 2018). Industry 4.0 also has a role in achieving Sustainable Development Goals (SDGs) such as reducing industrial waste and carbon footprint through digital transformation (Jabbour et al., 2020). While the adoption of Industry 4.0 has begun and is underway in developed economies, the challenges surrounding the adoption of Industry

4.0 in the developing world must be resolved. Examples of these challenges include insufficient infrastructure, high costs of investment, or political barriers (Dubey et al., 2019; Yadav et al., 2020). It is essential to confront this issue within the Sustainable Development ideas of developing countries to ensure that they can offer a traversal of industrializing and maintaining its environment (Bag et al., 2021). In addition, connecting Industry 4.0 into circular economy principles can lead the pathway towards accelerated sustainability transitions. The Resolve framework offers insight into how technologies such as IoT and AI can support regenerative practices by extending product lifetimes, and eliminating waste in production processes (MacArthur et al., 2015; de Sousa Jabbour et al., 2018). This achieves engagement with the sustainable development goals [SDG], such as Clean Energy (SDG 7) and Climate Action (SDG 13), while reinforcing the importance of digital transformation for sustainable development (Rodriguez-Anton et al., 2019).

1.1 Significance of Industry 4.0 in Sustainability Transitions

The shift to digital transformation of manufacturing and supply chain activities has conferred considerable sustainability benefits through improved energy efficiency and use of resources. For example, smart grids utilize IoT technologies to manage energy more effectively by improving supply and demand which, in turn, reduces greenhouse gas emissions (Stavropoulos, Tzimotoudis, & Korakis, 2024). Additionally, AI-enabled predictive maintenance can help to ameliorate industrial downtime through the identification of machine inefficiencies, while also suggesting redundancies to promote resource conservation and reduce energy use and waste (LeewayHertz, 2024). Blockchain can also take advantage of technology for sustainability in a different way, by promoting accountability along the supply chain and sustainable sourcing practices, which helps alleviate environmental risk (Saberi et al., 2019). Governments across the globe also incentivize the digital transformation process within their economies so that sustainability is enhance. For instance, the European Green Deal focuses on how Industry 4.0 technologies can help relive carbon-neutral growing economies, while (Sharma et al., 2022), (UNIDO) supported frameworks, help integrate digitalization into its industrial process that nurtures sustainable development. For developing economies, the limitations of financing and infrastructure complicate the potential solution of digital sustainability, as seen with the policy frameworks suggested to invigorate and promote digitalization (Nascimento et al., 2020).

1.2 Relevance to Developing Economies

Emerging economies represent an unusual blend of challenges and opportunities for the implementation of Industry 4.0, as there are limitations on the availability of resources, socio-economic inequalities, and limited access to digital infrastructure (Tiwari & Khan, 2021). Nevertheless, challenges such as unskilled labor and the regulatory landscape significantly decelerate the move towards Industry 4.0 compared to developed economies (Gupta et al., 2021; Taqi et.al., 2025). Nevertheless, emerging economies could be in position to advance agrarian industrial transitions due to rapid urbanization and industrial growth. Digitalization, for instance, can be used to resolve issues around the circular economy and sustainable agriculture, and waste management. For example:

- Precision Agriculture: IoT and AI optimize water and fertilizer usage while increasing crop yields (Kamble et al., 2018).
- Digital Twins: These virtual models simulate manufacturing processes to reduce material waste and enhance efficiency (Ben-Daya, Hassini, & Bahroun, 2019).

Addressing these challenges through targeted policies and investments can unlock the potential of Industry 4.0 technologies in driving sustainable development.

1.3 Research Gaps and Motivation

Despite the current surge of research on Industry 4.0 and sustainability, significant gaps still exist about its effects on developing economies. Existing research has focused primarily on the technologies, not understanding the socio-economic impacts of digital transformation (Ghobakhloo et al., 2021). Furthermore, limited empirical evidence exists of the variation of Industry 4.0 practices across sectors within emerging economies (Nascimento et al., 2022). In addition, it is found that while developed economies to this point have obtained some success in transferring Industry 4.0 into sustainability policies, developing economies are struggling for a road map in this area (Stock & Seliger, 2016). Consequently, this paper arose from the need to fill this knowledge gap from a systematic literature review (SLR) of the effects of Industry 4.0 technologies on sustainability transitions in developing economies.

1.4 Objectives and Research Questions

The aim of this research profile is to integrate and synthesize research undertaken about sustainability transitions related to Industry 4.0 in developing countries, for the benefit of decision-makers, in government and business and researchers alike. The aims are as follows:

1. Identification of key Industry 4.0 technologies that enable sustainability.
2. Understanding of the challenges and opportunities of adopting Industry 4.0 for sustainability in developing economies.
3. Evaluation of policy frameworks that promote digital transformation for green growth.
4. Best practices, in terms of case studies, that model successful digital sustainability.

The study is guided by the following research questions:

- RQ1: What are the most impactful Industry 4.0 technologies in driving sustainability in developing economies?
- RQ2: What are the barriers and enablers of digital transformation for sustainability in these regions?
- RQ3: How can policymakers and industries accelerate Industry 4.0 adoption for green growth?

By addressing these questions, this research seeks to offer strategic recommendations that can enhance the digital sustainability landscape in emerging economies.

2. Methodology

The present study adopts a Systematic Literature Review (SLR) methodology to investigate the role of Industry 4.0 in stimulating sustainability transitions in developing economies shaped by the PRISMA framework (Moher et al., 2009). The SLR method is informed by a systematic process of identifying, screening, and appraising relevant literature to improve methodological rigor (Page et al. 2021). The search was undertaken using key databases, including Scopus, Web of Science, ScienceDirect, IEEE Xplore, and SpringerLink, all of which are established databases with wide coverage of peer-reviewed literature. To develop a systematic and structured search strategy, Boolean operators were utilized to combine key terms, e.g. "Industry 4.0", "sustainability (sustainable)", "developing economies (emerging market)", and "green practices (environmental practices)". The studies were screened using inclusion and exclusion criteria to help guide the selection process based on year of publication, relevancy of the research aim, language (English), and some additional selection criteria. As part of the screening process, the PRISMA flow diagram was utilized to track the study selection and process to maintaining a transparent study selection process (DistillerSR, 2025). Quality appraisal criteria were undertaken to select scholarly impact studies and relevant findings were extracted and coded for thematic analysis.

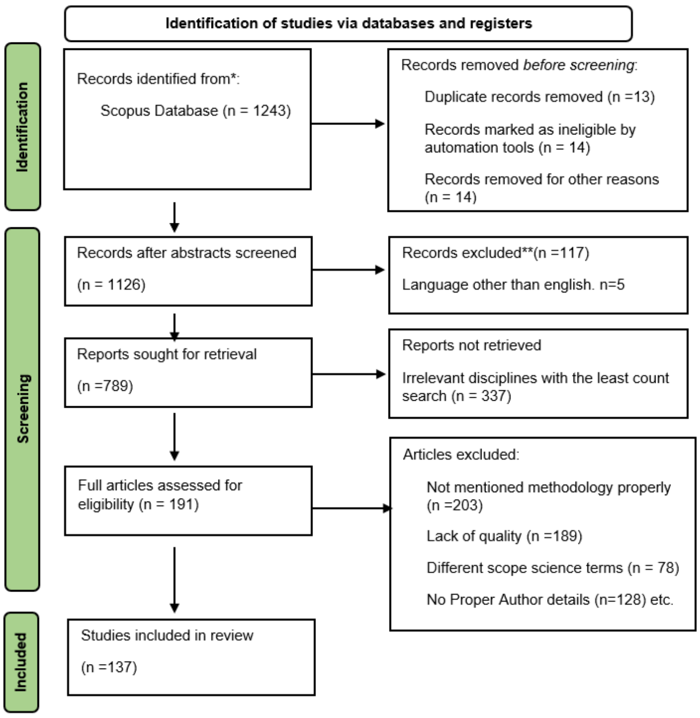

Figure 1. Data Extraction and Filtration (PRISMA Model)

Note. The flow diagram template is based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement on reporting guidance techniques for choosing, evaluating, and synthesizing research (Page et al., 2021).

3. Theoretical Background

3.1 Key Concepts: Industry 4.0, Sustainability, and Digital Transformation

Industry 4.0 encompasses the fourth industrial revolution that harnesses an amalgamation of technologies inclusive of: cyber-physical systems, big data analytics, AI technologies and IoT technologies. These collection of technologies invariably affords an opportunity for automation, smart-manufacturing, and real-time decision-making to improve efficiencies (Stock & Seliger, 2016; Li et al., 2018). Sustainability captures economic, environmental, and social issues to support the demands for long-term efficiency and resilience of resources (Elkington, 1997; Bonilla et al., 2018). The combination of Industry 4.0 and sustainability is coined Green Industry 4.0. Green Industry 4.0 endeavors to harness the full digital technologies to reduce emissions, enhance energy efficiency, and promote the circular economy (Bag et al., 2021; Kiel et al., 2017). Digital transformation connects Industry 4.0 technologies with sustainability through capacity of data to inform decision-making, automate sustainable supply chains, and create innovative business models (Manavalan & Jayakrishna, 2019). The continual advancement of new technologies makes, for example, blockchain, to improve traceability, predictive maintenance, with AI technologies, as well energy monitoring with IoT enabled technologies to lessen energy consumption overall (Shrouf et al., 2014; Munsamy & Telukdarie, 2019).

3.2 Conceptual Link Between Industry 4.0 Technologies and Green Practices

3.2.1 Smart Manufacturing and Energy Efficiency

Intelligent manufacturing uses machine learning, sensors, and cloud computing to increase productivity and reduce waste and energy use. New energy management systems using the Internet of Things (IoT) and artificial intelligence (AI) enable continuous monitoring of energy use, and can result in considerable efficiency increases (Dexma, 2025). AI-enabled predictive maintenance can reduce carbon footprints by up to 20% in industrial environments (Thales Group, 2025). The introduction of multi-criteria decision-making (MCDM) modelling has also begun in order to assess energy saving alternatives in smart factories to improve sustainability in factories (SAP, 2025).

3.2.2 Sustainable Supply Chains and Circular Economy

Technologies that enable Industry 4.0 can support real-time emissions tracking in the supply chain, automate waste management, and support closed-loop systems. Blockchain technologies enable transparency and reduce material waste concerning ethical sourcing (Saberi et al., 2019). Digital technologies, including IoT sensors, enable efficient resource use across the supply chain to support circular economy practices (SAP, 2025).

3.2.3 Digital Twin and Carbon Footprint Reduction

The Digital Twin concept, which refers to a virtual replica of physical assets, is vital for improving energy consumption and resource usage. It simulates production systems to reduce carbon footprints and enhance productivity (MDPI, 2023). Smart grids, combined with the Internet of Things, improve renewables by offering real-time demand and supply relations (Gkikas et.al., 2023). All of this shows that Industry 4.0 technologies, in some instances, can advance manufacturing sustainability transitions.

3.3 Sustainability Challenges in Developing Countries

Despite the promise of Industry 4.0-driven sustainability, developing economies face key challenges, including:

- High Initial Investment Costs
  Small and medium-sized enterprises (SMEs) face substantial financial challenges in using Industry 4.0 technologies largely because of smart technology costs. This encompasses purchasing new technology, costs for integrating cyber-physical systems, and training costs for workers to adapt to the new technology. Research indicates that inadequate access to finance is a huge aggravating factor for SMEs financial constraints, particularly in developing economies (Bag et al., 2020; Müller et al., 2018; Moktadir et al., 2018).
- Lack of Digital Infrastructure
  Ineffective ICT infrastructure has a contradicting effect on the speed and sophistication of data collection and analysis, which is urgent to the successful uptake of Industry 4.0. SMEs have restricted access to high-speed internet, cloud computing channels, and appropriate data storage

platforms, which all create realistic barriers to the adoption of digital transformation (Shin et al., 2019; Satapathy, 2017; Zezulka et al., 2016). The case is much stronger within developing regions, where technology developments are not coherent throughout the region.

- Regulatory and Policy Barriers
  Without clear sustainability policies, the environmental sustainability objectives of SMEs become stalled in the transition period to become more 'green' in their practices. Governments in developing nations poorly provide guidelines and motivations for taking on Industry 4.0 technologies, and SMEs often lack adequate support from their countries around sustainability (Guarnieri & Trojan, 2019; Mishra et al., 2019; Kumar et al., 2014). A sound policy framework is needed to remedy the identified regulatory gaps around digital transformation.
- Workforce Skill Gap
  The shortage of workers with digital skills has a great influence on the uptake of Industry 4.0 technologies for sustainability. SMEs struggle to find employees who can work with new systems developed for IoT or AI technologies. This is compounded by a lack of training and employees' lack of knowledge of supporting new technologies in the SMEs (Cezarino et al., 2019; Satapathy, 2017; Shin et al., 2019).

3.4 Supporting Theories

3.4.1 Resource-Based View (RBV) Theory

According to the Resource-Based View (RBV), firms can ultimately acquire a sustainable competitive advantage when they utilize resources that are valuable, rare, and difficult to imitate (Barney, 1991). With regard to Industry 4.0 and sustainability, firms that can effectively combine the capabilities of digital transformation to support green innovations create a competitive advantage (Alkaraan et al., 2024). As firms learn to develop environmentally sustainable innovations or smart technologies while implementing different ways to optimize efficiency and reduce waste, the process becomes an asset (Hart, 1995; Müller et al., 2018). Therefore, firms that are successfully investing in green digitalization can gain a competitive advantage over other firms and enhance sustainability efforts (Bag et al., 2020).

3.4.2 Institutional Theory

According to the Institutional Theory, external pressures in the form of regulative, normative, and market pressures shape organizations' behavior (DiMaggio & Powell, 1983). In the Industry 4.0 period, governments enforce environmental orders, carbon taxation, and digital sustainability standards to motivate green transitions (Zeng et al., 2020; Ejsmont et al., 2020). Organizations need to follow sustainability norms to retain legitimacy and consumer trust (Scott, 2001). Additionally, industry coalitions and global sustainability commitments (e.g. Paris Agreement) will help accelerate the adoption of eco-friendly technologies (North, 1990; Kang et al., 2016).

3.4.3 Stakeholder Theory

According to Stakeholder Theory, enterprises are meant to take into account the interests of all stakeholders, such as employees, customers, suppliers, and the public, evaluating those considerations in a way that focuses on more than profit and return on investment (Freeman, 1984). For a practice such as Sustainable Industry 4.0 to take place, companies will have to support their activities with stakeholder engagement to promote new green innovations and ethical AI use, and improve carbon footprint (Donaldson & Preston, 1995; Hörisch et al., 2014). By incorporating sustainability measures into their corporate governance and processes, this aligns companies with societal expectations and thereby enhance long-term value creation (Manavalan & Jayakrishna, 2019).

3.4.4 Dynamic Capabilities Theory

The Dynamic Capabilities Theory suggests firms must be able to continuously adapt, innovate and reconfigure their resources to accommodate a changing environment (Teece et al., 1997). In relation to Industry 4.0, this theory suggests the need for technological flexibility, digital upskilling, and the ability to innovate quickly to be able to integrate sustainability process (Teece et al., 1997). The ability to apply IoT enabled energy management, AI across the supply chain for resource efficiency, and data analytics for green supply chain process enables organizations to increase resilience toward new regulation and environmental realities (Chari et al., 2022; Ortiz-Avram et al., 2023). Based on these capabilities firms can reconfigure towards more sustainable practice while maintaining a competitive advantage (Alkaraan et al., 2024).

3.4.5 Technology-Organization-Environment (TOE) Framework

The TOE framework describes Industry 4.0 adoption through consideration of technological, organizational, and environmental factors (Tornatzky & Fleisher, 1990). Technology factors include

IoT, big data, and AI, while organizational readiness consists of managerial support and digital literacy (Oliveira & Martins, 2011). Environmental pressures generated through government, customer, and competitive forces also drive green innovation. The framework emphasizes a need for companies to ensure Industry 4.0 capabilities are aligned with sustainability goals to ensure a competitive advantage (Zeng et al., 2020; Kamble et al., 2021).

4. Analysis and Findings

4.1 Publication Trends by Year, Country, and Journal

The analysis of publication patterns with regard to Industry 4.0 and sustainability has identified a strong growth of interest, especially since 2015, which can be linked to the Paris Accord and the UN Sustainable Development Goals (SDGs) (Patyal et al., 2022; Munsamy & Telukdarie, 2022). A global comparative analysis of published research has shown that leading developed economies such as Germany, the USA and China, are establishing large technology and digital sustainability markets. Nations that are emerging such as India, Brazil and Indonesia, are developing as significant players in digital sustainability and government-led sustainability programs (Bai et al., 2022; Ejsmont et al., 2020). Journal analysis identified high-ranking journals (e.g. Journal of Cleaner Production, Sustainable Production and Consumption, and Technological Forecast & Social Change) are the leading publications in the field and important in disseminating knowledge from research (Gunasekaran et al., 2022; Kamble et al., 2021). The increasing volume of literature suggests that Industry 4.0 is becoming a powerful driver for sustainable change, impacting both policy contexts and business practice (Zhong et al., 2020; Stock & Seliger, 2016).

4.2 Adoption of Industry 4.0 in Developing Economies

The rate at which Industry 4.0 technologies are adopted in developing economies is uneven, shaped by governmental policies, the state of infrastructure, and industrial capability (Chauhan et al., 2021; Kamble et al., 2022). Nations such as China, India, and Brazil have made considerable progress in digital transformation, whereas many low-income countries continue to experience challenges with technology accessibility and readiness of the workforce (Dubey et al., 2019; Bai et al., 2022). To address these forms of digital bias, governments in these regions are increasing the use of policy incentives, subsidy schemes, and digital skilling initiatives to boost adoption of Industry 4.0 in sustainable development frameworks (Munsamy & Telukdarie, 2022; Patyal et al., 2022). Even with the advent of these initiatives, key barriers that hinder progress in developing regions remain such as limited financial capacity, fragmented digital infrastructure and inconsistencies in regulatory regimes (Kamble et al., 2018; Zeng et al., 2020; Taqi et.al, 2025). These barriers necessitate policymaking, collaboration between business, government and academia to embed an enabling eco-system for digital and sustainable transitions (Gunasekaran et al., 2022; Zhong et al., 2020).

4.3 Impact of Digital Transformation on Environmental Sustainability

Digital transformation coupled with sustainability trends has significantly altered the operations of various industries, producing positive results in terms of lowered carbon emissions and waste of useful resources. Emerging technologies such as Artificial Intelligence (AI), the Internet of Things (IoT), and Blockchain have been leveraged for the real-time monitoring of energy consumption, enhanced efficiency of supply chains, and improved application of circular economy principles (Vaishnav, 2024; UNEP, 2024). In the manufacturing sector, for example, the use of smart sensors and predictive analytics enables industries to generate minimal waste and increase their efficiency of energy use (Bag et al., 2021; Raut et al., 2019; Hariyani et.al., 2025). The benefit of the technological advancements aforementioned is outweighed by challenges, such as the increased energy consumption of data systems, cybersecurity, and the problem of e-waste. Each of these challenges requires a response, e.g., a green IT solution, to respond to their negative environmental impacts (Zeng et al., 2020; Chauhan et al., 2021). Based on this evidence, digital sustainability options are beginning to emerge as solutions to lessen the ecological footprint of Industry 4.0. Examples include smart grids, digital twins, and recycling automation (Jayashree et al., 2021; Kamble et al., 2022).

4.4 Key Sectors Benefiting from Digital Green Transitions

Many sectors have gained significant advantages from green transitions triggered by Industry 4.0 within the last few years, specifically in energy, logistics, and agricultural industries. In the renewable energy space, for example, digital platforms have improved the optimization of generation, storage, and distribution to optimize the efficiencies of both solar and wind farms (Munsamy & Telukdarie, 2019;

Amalina et.al., 2025). Significant improvements in reduced waste and operations efficiencies in energy systems have also been enabled by technologies such as Internet of Things (IoT) and artificial intelligence (AI) systems which can enable real time evaluation and predictive maintenance of energy systems (Stock & Seliger, 2016). Advanced smart routing algorithms and IoT-based fleet management have enabled the logistics sector to transition to reducing fuel consumption and emissions. In advanced analytics utilizing data and real-time tracking to maximize supply chain operations has provided major environmental advantages (Jayashree et al., 2021; Chauhan et al., 2021). As for agriculture, precision agriculture utilizing technologies such as AI, blockchain, and drones for more resource efficient farming practices have all contributed to more environmentally sustainable practices, that has proudced less water and fertilizer usage while also increased crop yields (Kamble et al., 2022; Bag et al., 2021).

Although we have seen much improvement, challenges for scaling of Industry 4.0 in developing economy continue to prevail in the market. The most challenging aspects related to costs of technology and lack of expertise, funding opportunities, and infrastructure bottlenecks. Limited finite financial, digital fragmented infrastructure, and technologies are all barriers to Industry 4.0 technologies development in developing economies (Dubey et al., 2019; Zeng et al., 2020). Addressing these barriers requires governments, industry and academia to identify together to understand to develop a more enabling ecosystem of technologies to identify pathways for cleaning transitions.

4.5 Implementation Barriers and Infrastructural Constraints

The successful implementation of Industry 4.0 technologies for sustainability is accompanied by multiple structural, financial and policy barriers. In many developing economies, low infrastructure, slow internet access and mixed regulatory regimes can inhibit seamless digital transformation (Sirimanne, 2025; Ghobakhloo, 2020). Additionally, high upfront costs of smart manufacturing technologies and renewable energy measures tend to hinder small and medium enterprises (SMEs) from adopting sustainable innovation (Chauhan et al., 2021; Zhao et.al., 2025). Moreover, issues such as cybersecurity threats, employee resistance to change, and data privacy are also present as barriers to Industry 4.0 adoption (Bag et al., 2021; Marques et al., 2017).

To manage these barriers, a strong government support, international collaboration and corporate social responsibility are all dictates. Governments should work to provide low cost internet access, upskill individuals via training programs, and develop national strategies for a coordinated Industry 4.0 implementation (Haleem 2024; Kumar et al., 2014). International collaboration will also facilitate the transfer of technology and know-how to bridge the gap between developed and developing economies (Yadav et al., 2020; Luthra & Mangla, 2018).

4.6 Enablers of Successful Digital-Sustainability Integration

Overcoming the obstacles, several reasons exist to suggest the integration of digital transformation and sustainability will occur seamlessly and in ways that will provide ongoing environmental and economic benefits. In this regard, strategic governmental policies are in place to promote green transitions in developed economies, with programs such as carbon pricing, tax credits, and investments in digital infrastructure (Adebayo et.al., 2024; Vaishnav, 2024). Corporate sustainability initiatives are also significant, such as implementing the principles of the circular economy and adopting green procurement practices (Deskbird, 2024; UNDP, 2023).

In addition, AI-driven predictive analytics, smart grid technologies, and blockchain carbon tracking systems mean organizations may now fit sustainability into their long-term goals efficiently (Bejan et.al., 2025; Distor et.al., 2023). The rationalization of sustainability and technology is also facilitated by the presence of a highly skilled workforce with Industry 4.0 competencies to implement technologies (Deskbird, 2024; Vaishnav, 2024). Overall, this underlines the notion that sustainability and technology are most effective when aligned together to assist sustainable development continues moving forward in a greener and resilient manner.

4.7 Role of Policy, Governance, and Cross-Sector Collaboration

Effective policy frameworks and governance structures are essential for scaling Industry 4.0-based sustainability. Governments are pivotal to creating regulatory policies, emissions reductions targets, and digital transformation roadmaps that comply with international sustainability agreements (Ghobakhloo, 2020; Islam et al., 2022). Strategic initiatives such as carbon pricing, tax breaks, and investments into digital infrastructure have driven green transitions in developed economies (Bag et al., 2021; Chauhan et al., 2021).

Additionally, cross-sector collaboration of private firms, research institutions, and non-profits encourages the sharing of knowledge and technological solutions. For example, cooperatives established under frameworks such as the UN Sustainable Development Goals (SDGs) and the European Green Deal allow us to align industry practices with environmental sustainability (Oztemel & Gursev, 2020; Jabbour et al., 2018). An additional mechanism for strengthening Industry 4.0 coding and implementation during sustainability transitions is related to strong governance mechanisms with respect to green finance, corporate social responsibility (CSR), and carbon trading schemes (Zeng et al., 2020; Kamble et al., 2022).

5. Discussion

The thematic findings of this study indicate that in developing economies, the technological readiness, institutional engagement, and policy support converge around Industry 4.0 and sustainability. The pivotal technologies that propel organizations in green initiatives are IoT, blockchain, and AI (Salehi, 2023; Distor et al., 2023). However, the capacity to transfer these technological advances into practice is heterogeneous across sectors and geographic culture (DOAJ, 2024). Some sectors and geographies, like energy, agriculture, and logistics, are showing early signals of digital-sustainability integrations that largely stem from public-private partnerships (Salehi, 2023). Organizational agility and collaborative ecosystems have emerged as prominent enabling factors to overcome constraints associated with capabilities and resources (Rana et al., 2024).

This research corroborates earlier studies indicating that digital technologies will not ensure sustainability unless they are used with frameworks and inclusive governance (Bag et al., 2021; Jabbour et al., 2020). Further studies suggest that commitment to green managerial practices by executives, regulatory push, and diffusion of knowledge is necessary for deploying green digital technologies (Dubey et al., 2019; Müller et al., 2020). Nevertheless, this study departs from the existing literature by focusing on the implications of cultural values, localized innovations, and informal markets on outcomes in emerging economies. These points highlight opportunities to develop sustainability models that are relevant and leverage indigenous capabilities and frugal innovations (Distor et al., 2023; Rana et al., 2024).

From a policy standpoint, these findings highlight the pressing need to develop integrated policy ecosystems to tackle both digital infrastructure and sustainability objectives at the same time. This includes introducing incentives for green innovation through tax deductions, boosting cybersecurity to establish trust in digital systems and infrastructure, and creating capacity-building programs for small-to medium-sized enterprises (SMEs) and public institutions (Fraga-Lamas et.al., 2021; Rana et al., 2024). Additionally, cross-border collaborations with knowledge-intensive economies may facilitate technology transfer, exchange of best-practices, and co-development of green solutions (Salehi, 2023; LeewayHertz, 2024).

There is a stark difference between developed and developing economies. Developed economies benefit from mature digital infrastructures, advanced R&D capacities, and sufficient mechanisms of enforcement for sustainability that ease the transitions to sustainability. Conversely, developing economies do not leverage resource-constrained systems with adaptive approaches that prioritize scale, cost, and equity (Distor et al., 2023; EIB Report, 2021). These disparities necessitate roadmaps that not only are differentiated, but also account for developmental asymmetries with an intention of achieving the common climate goals.

Finally, this study connects Industry 4.0 to larger frameworks, such as the Environmental, Social, and Governance (ESG) reporting and the Circular Economy. Digital transformation provides traceability, transparency, and real-time reporting necessary for ESG tracking (Scheller Center Insights, 2024). Furthermore, Industry 4.0 technologies allow circular practices to be established, including waste reduction and closed-loop supply chains (Page et.al., 2021), making room for a new way to design comprehensive sustainability strategies for developing nations.

6. Research Gaps and Future Directions

While interest continues to grow on the intersection of Industry 4.0 and the sustainability agenda, several research gaps exist. Much of the research base remains focused primarily on several specific sectors, such as manufacturing or energy, with agriculture, education, and urban planning, being relatively less examined, especially in places like Sub-Saharan Africa and Southeast Asia. There is also knowledge gap related to the use of emerging technologies, and particularly, whether the combination of AI, IoT and blockchain will lead to improving sustainability outcomes. A majority of the research to date, relies on cross-sectional studies, rather than longitudinal research to study the digital-sustainability alignment changing over time. Also, there is a need for interdisciplinary approaches to provide holistic solutions that embolden technology centres around management, environmental science, and policy. Future research should continue to emphasize the need for comparative case studies across different development contexts, study what firms are ready to engage in the green digital transformation, and research what grassroots innovations or knowledge systems can augment interoperability to bridge the high-tech focus of Industry 4.0 and sustainable development outcomes.

7. Conclusion

This research aimed to conduct a systematic review of the dynamic interplay of reconciling Industry 4.0 technologies and sustainability practices in developing economies. By reviewing more than ten years of academic writing in this field, this review aimed to uncover how digital transformation facilitated by technology (e.g., IoT, AI, big data) can promote environmentally sustainable practices. The review found increased academic interest in this phenomenon especially in energy, logistics, and manufacturing. The review also revealed the dissimilar research output across geographical contexts and highlighted implementation barriers such as infrastructure, generalized digital literacy, as well as policy fragmentation. However, enablers such as institutional support, alignment with existing policy mechanisms, and public-private collaborations some suggested digital innovation ecosystems are fundamental to the successful integration of digital-sustainable practice. The review contributes to academic and policy discussions by providing a structured summary of themes that highlight both the current state of research as well as practical implications for decision-makers. For the academic community, this review brings attention to gaps in the data – lack of longitudinal data and types of combinations of emerging technologies – to align future research directions. For policymakers and business leaders, the review highlights the importance of establishing adaptive governance models or public-private collaborations that seek to optimize the role of Industry 4.0 in meeting green objectives. Overall, the study conveys that Industry 4.0 has an unprecedented transforming ability for sustainable development in developing economies if used within a relevant context, as scalable, resilient, and inclusive solutions to the pressing environmental challenges of the world.

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