

AYÍKÁ

ISSN: 2664-3030 (Print)
2664-3022 (Online)

**JOURNAL OF ENVIRONMENT AND
POLITICS IN AFRICA**

AYIKA: JOURNAL OF ENVIRONMENT AND POLITICS IN AFRICA

DOI: <https://doi.org/10.69778/2664-3022/2026/8.1/EN>

Editorial Note

This issue of *AYIKA* brings together a rich and timely collection of scholarship that underscores a central truth: in Africa, environmental questions are deeply political, and political realities are increasingly shaped by environmental change. The contributions in this volume reflect the growing complexity of this relationship, engaging themes that span governance, technology, security, sustainability, and identity across diverse African contexts and beyond.

A defining feature of this issue is its strong engagement with the role of digitalisation in advancing sustainability. From the systematic review on how digitalisation enables decarbonisation, to analyses of agri-tech adoption in Nigeria and South Africa, the volume highlights the transformative potential of technology in addressing environmental challenges. These contributions move beyond optimism, carefully examining the mechanisms and constraints that shape technological uptake. They remind us that digital solutions are not neutral; their effectiveness depends on policy frameworks, institutional capacity, and socio-economic conditions.

Equally prominent is the question of governance, particularly in relation to service delivery and institutional performance. The examination of water service failures in Gauteng Province offers a sobering account of how governance lapses can translate into environmental and public health crises. Similarly, the discussions on public service reform and parliamentary oversight reveal the persistent challenges of accountability and administrative effectiveness across the continent. Together, these studies point to a critical insight: sustainable environmental outcomes are contingent on capable, transparent, and responsive institutions.

The issue also engages deeply with questions of political order, security, and regional cooperation. Analyses of Zimbabwe's political history, hybrid regimes in Central Africa, and border conflicts involving Nigeria reveal how political instability and governance structures shape environmental management and development trajectories. The exploration of indivisible security within the SADC region further highlights the interconnectedness of peace, cooperation, and sustainable development. These contributions reinforce the idea that environmental sustainability cannot be pursued in isolation from broader political and security dynamics.

Another important strand in this volume is the emphasis on economic strategies and livelihoods, particularly in rural contexts. Articles on organic agribusiness, marketing strategies aligned with climate action, and the challenges faced by women in agribusiness illuminate the everyday realities of sustainability. They foreground the experiences of local actors, especially women entrepreneurs, whose resilience and innovation are often overlooked. By examining the socio-economic factors shaping revenue growth and participation, these studies contribute to a more inclusive understanding of development.

The volume also makes a significant intellectual contribution by foregrounding indigenous knowledge systems and alternative epistemologies. The exploration of

Ubuntu as a framework for regional governance offers a human-centred perspective that challenges dominant policy paradigms. Similarly, the critique of epistemic violence in transboundary conservation highlights the marginalisation of local knowledge and agency. These interventions are particularly important in rethinking whose knowledge counts in environmental governance and how more equitable frameworks can be developed. Urban spaces and cultural expressions are not left out of this conversation. Contributions on city branding in Harare and the intersection of art, space, and identity in Durban demonstrate how environmental and political dynamics are experienced and expressed in urban contexts. These studies expand the scope of environmental politics by incorporating cultural and spatial dimensions, offering fresh insights into how cities in the Global South are responding to climate change.

Notably, this issue also extends its analytical reach beyond Africa, with a study on urban climate initiatives in Brazil and a comparative examination of socio-economic vulnerability in Sub-Saharan Africa and the Pacific Islands. These contributions enrich the volume by situating African experiences within a broader global context, encouraging cross-regional learning and dialogue.

Finally, the inclusion of research on language and education, such as the study on tense substitution errors among Tshivenda-speaking students, serves as a reminder of the interconnectedness of knowledge production, communication, and development. It highlights the importance of education in shaping the capacity to engage with complex environmental and political issues.

Taken together, the articles in this issue reflect a vibrant and interdisciplinary field of inquiry. They challenge simplistic narratives and instead offer nuanced analyses that recognise the interconnected nature of environment and politics in Africa. As the continent continues to navigate the pressures of climate change, population growth, and political transformation, the insights presented here are both timely and necessary. This volume invites scholars, policymakers, and practitioners to think more critically and act more collaboratively. It is our hope that the conversations sparked within these pages will contribute to more just, sustainable, and context-sensitive approaches to environmental governance in Africa and beyond.

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HOW DIGITALISATION ENABLES DECARBONISATION: A SYSTEMATIC REVIEW OF MECHANISMS, PATHWAYS, AND BOUNDARY CONDITIONS

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Abstract

This systematic literature review examines how digital transformation and Industry 4.0 (including IoT connectivity, cyber-physical systems, advanced analytics, big data, and AI) translate into green/eco-innovation and measurable climate outcomes, especially decarbonisation and reduced carbon emissions, rather than rebound effects or efficiency-driven growth. Building on the observation that digitalisation is not inherently “green” and may raise energy demand and emissions in early adoption phases, the review synthesises fragmented evidence across firm, sector, and country-level studies to clarify the mechanisms and boundary conditions that shape environmental payoffs. Using a structured systematic review process, an initial 1,653 records were screened and progressively refined through time-bounding (2024-2026), subject-area filtering, keyword screening, and eligibility criteria, culminating in 80 open-access, peer-reviewed articles retained for thematic synthesis after full-text review. The findings indicate that digital transformation most often affects emissions indirectly through conversion pathways particularly green technology innovation, circular economy operationalisation, and governance/finance mechanisms rather than through direct emissions reductions.

Keywords: Decarbonization, Industry 4.0, circular economy, digital transformation, IoT, climate action

Background

The accelerating convergence of digital transformation and climate action agendas has intensified scholarly and policy interest in whether Industry 4.0 capabilities can be leveraged to reduce emissions while sustaining productivity and competitiveness (Nelli et al., 2026; Leal Filho et al., 2025). At the same time, a growing body of evidence cautions that digitalisation is not inherently “green”, because digital

expansion can raise energy demand, amplify rebound effects, and deepen carbon lock-in when it is pursued as a narrow efficiency or growth strategy (Hambye-Verbrugghen et al., 2026; Daga et al., 2024). This duality has created a practical and theoretical dilemma, digital transformation is widely promoted as a sustainability enabler, yet real-world decarbonisation outcomes appear uneven across sectors, regions, and institutional contexts (Guo

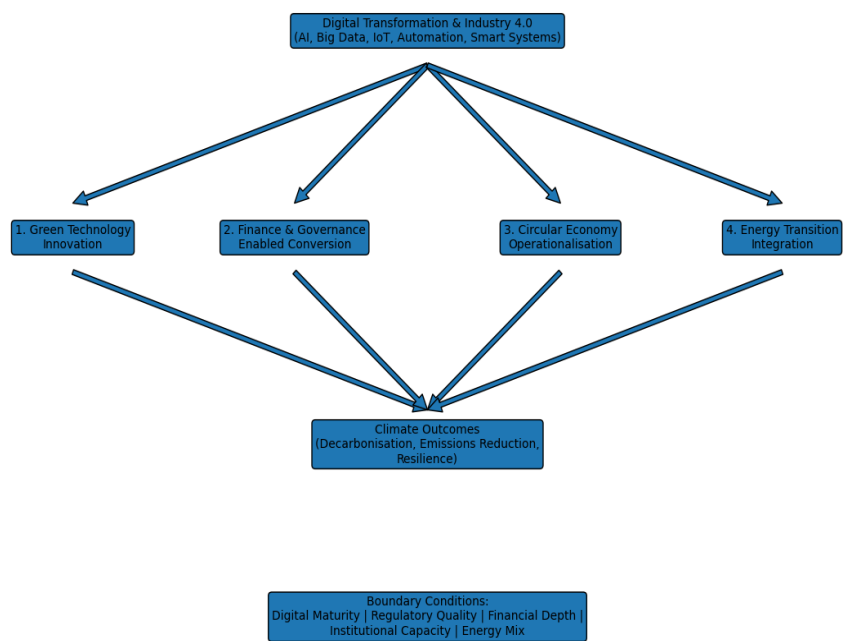
et al., 2024; Karim et al., 2025). As a result, the credibility of “twin transition” narratives increasingly depends on clarifying *how* digitalisation becomes environmentally productive, *when* it fails, and *which mechanisms* convert digital capability into green innovation and measurable emissions reductions (Nelli et al., 2026; Khan et al., 2025).

Green innovation and eco-innovation consistently appear as the key conversion layer linking digital investments to climate mitigation, because digital tools primarily restructure information flows and decision architectures rather than directly reducing carbon intensity (Xia & Chen, 2025; Cuevas-Pichardo et al., 2025). Firm-level evidence indicates that digital transformation can reduce carbon emissions through green technology innovation particularly through process upgrading, cleaner production, and low-carbon product development rather than through automation-only efficiency gains (Guo et al., 2024; Li et al., 2025). Importantly, the relationship can be non-linear, with early-stage digitalisation sometimes associated with higher emissions due to scale expansion, transition frictions, and increased electricity demand, while more mature digital capability is more consistently associated with emissions reductions (Li et al., 2025; Hambye-Verbrugghen et al., 2026). These patterns suggest that the central research challenge is not whether digital technologies exist, but whether organisations and systems can steer them towards innovation pathways that generate absolute mitigation rather than relative efficiency improvements (Leal Filho et al., 2025; Daga et al., 2024).

Evidence from ESG-oriented firm studies indicates that stronger ESG performance is associated with higher green technology innovation, and that digital transformation can strengthen this relationship by improving measurement, coordination, and innovation execution capacity (Xu & He, 2025; Zhao et al., 2025). In parallel, modelling work on environmental governance suggests that digitalisation improves governance outcomes through multiple channels, such as stronger regulation, public participation, and corporate green innovation, implying that digital capability matters most when it is embedded in institutional arrangements that reward low-carbon trajectories (Guo & Shen, 2024; Tergu et al., 2025). Cross-country evidence further shows that policy instruments, including environmental taxation and innovation-supporting frameworks, are linked to improved environmental sustainability when they interact with green technological innovation capacity rather than functioning in isolation (Khan et al., 2025; Cutcu et al., 2024). This points to a broader systems logic, digitalisation becomes climate-relevant when paired with governance mechanisms that translate data and connectivity into enforceable targets, innovation incentives, and credible implementation routines (Zaid et al., 2025; Georgescu et al., 2025). Accordingly, this systematic literature review asks, *under what conditions, and through which organisational, technological, financial, and governance mechanisms, do digital transformation and Industry 4.0 technologies translate into green/eco-innovation that produces measurable climate outcomes, particularly decarbonisation and reduced carbon*

emissions, rather than rebound effects
or efficiency-driven growth

Figure 1: Conceptual framework of mechanisms.



Methodology

Literature Search, Screening, and Selection

This study adopted a systematic literature review approach to identify, screen, and synthesise recent empirical and conceptual research examining the relationships between digital transformation, Industry 4.0 technologies, green and eco-innovation, and climate-related outcomes. A structured and transparent screening process was applied to ensure methodological rigour, relevance, and reproducibility of the review. Scopus database was used, and the initial

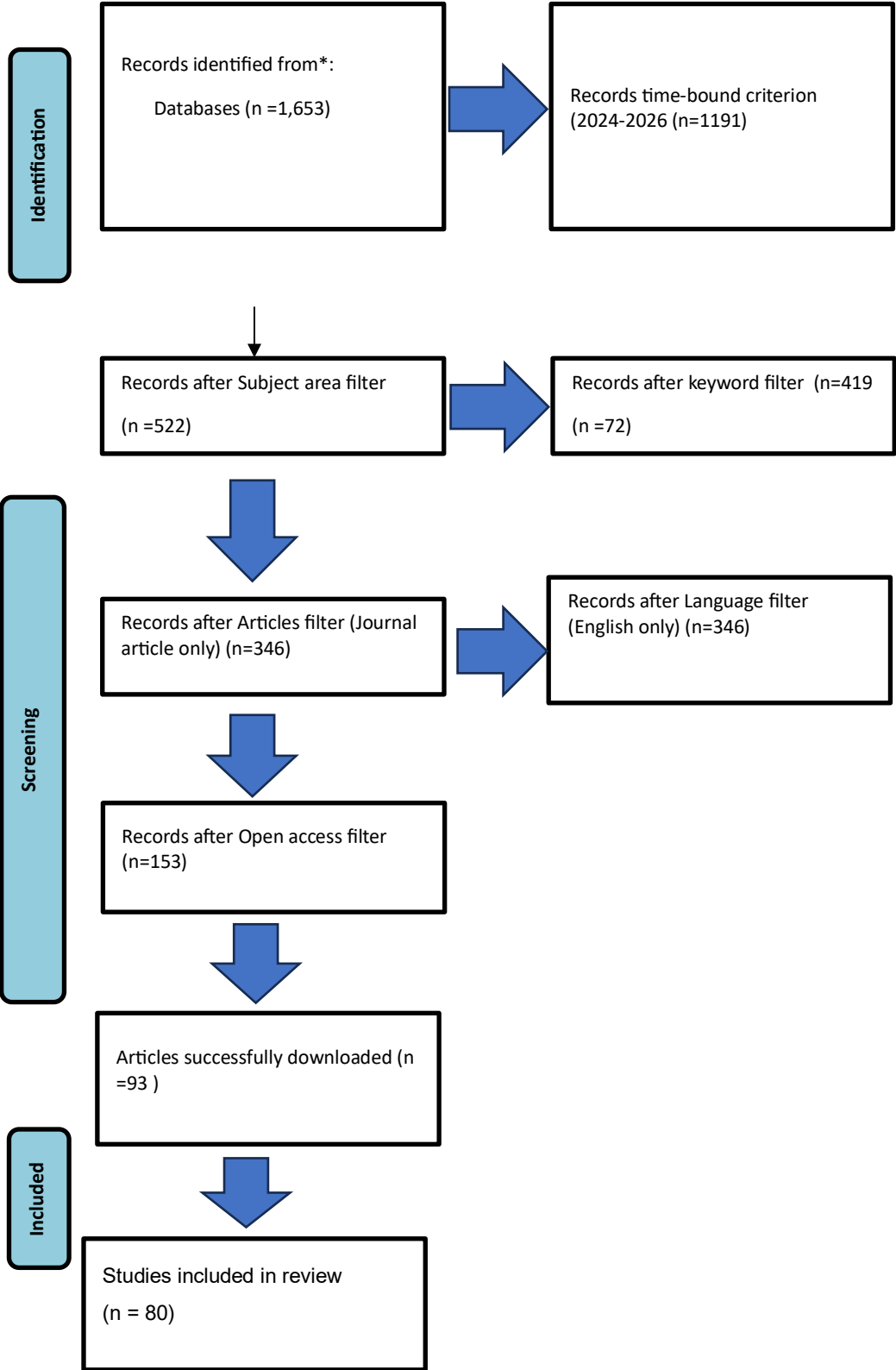
database search generated 1,653 records. Given the fast-evolving nature of digital technologies, sustainability practices, and climate policy debates, the review was intentionally limited to studies published between 2024 and 2026. Applying this time-bound criterion reduced the dataset to 1,191 articles, ensuring that the analysis captured the most recent and policy-relevant evidence. Subsequently, subject-area filtering was conducted to retain studies located within relevant disciplinary domains, including environmental science, sustainability studies, energy, economics, management, engineering, and related interdisciplinary fields. This step

reduced the number of potentially relevant articles to 522, helping to align the dataset with the conceptual focus of the review. A further refinement was undertaken through keyword screening using predefined search terms related to digital transformation, Industry 4.0, artificial intelligence, big data analytics, green innovation, eco-innovation, climate change, carbon emissions, and sustainability outcomes. This process narrowed the sample to 419 articles, ensuring closer alignment with the core constructs under investigation.

The dataset was then restricted to peer-reviewed journal articles, as these provide greater methodological consistency and academic credibility compared to other document types. This criterion reduced the number of eligible studies to 346 articles. All remaining articles were published in English, and therefore no additional exclusions were required on language grounds. To enhance transparency and accessibility of the evidence base, the review was further limited to open-access publications, resulting in 153 articles deemed eligible for potential inclusion. From this pool, 93 articles were downloaded in full for closer examination based on their apparent relevance to the study's objectives. A preliminary full-text review was then conducted to assess conceptual alignment, empirical relevance, and substantive contribution. During this stage, 13 articles were excluded because they were found to be of

limited relevance, largely due to weak alignment with the study's focus, insufficient engagement with digital-green linkages, or a lack of meaningful contribution to the synthesis. Following this final screening step, a total of 80 articles were retained and formed the final corpus for in-depth thematic analysis and synthesis. The thematic synthesis adopted a combined inductive and deductive approach. At the beginning, a preliminary coding framework was developed based on the central research question and the study's conceptual focus on digital transformation, green innovation, governance, circular economy, finance, and energy transition mechanisms. As the 80 selected studies were reviewed in full, additional themes were allowed to emerge from the data through careful, repeated reading and comparison across articles. Coding was conducted manually, with findings continuously reviewed and refined to ensure conceptual clarity and consistency. Themes were retained where clear patterns or recurring insights appeared across multiple studies, while closely related sub-themes were merged to maintain analytical coherence. Overall, this multi-stage screening and selection process ensured that the final set of studies were both current and analytically robust, providing a strong empirical foundation for examining how digital transformation and Industry 4.0 technologies interact with green innovation, climate mitigation, adaptation, and sustainability outcomes across diverse contexts.

Figure 2. PRISMA diagram



Source: Authors, Own Creation

Digital Transformation and Industry 4.0 as Catalysts for Green and Eco-Innovation

The reviewed literature converges on the view that digital transformation and Industry 4.0 (I4.0) technologies operate primarily as *enabling systems* that enhance firms' capacity to pursue green and eco-innovation, rather than functioning as inherently environmental solutions (Xia & Chen, 2025; Torrent-Sellens et al., 2023). In manufacturing and industrial contexts, digitalisation restructures information flows, production visibility, and coordination mechanisms, which collectively expand the opportunity space for environmentally oriented innovation (Guo et al., 2024). Empirical studies consistently demonstrate that digital transformation supports multiple forms of green innovation, including both exploratory eco-innovation (e.g., development of new low-carbon technologies) and exploitative green innovation (e.g., incremental efficiency improvements and emissions reductions) (Xia & Chen, 2025; Zhao et al., 2025). This duality suggests that digital technologies enable firms to simultaneously experiment with novel sustainability solutions while optimising existing production systems, particularly in data-intensive manufacturing environments (Cuevas-Pichardo et al., 2025).

Several studies emphasise that the environmental effects of I4.0 are conditional, not automatic. Evidence from manufacturing enterprises shows that digital transformation can initially increase energy consumption and emissions due to infrastructure expansion and scale effects, before delivering environmental benefits at more advanced stages of digital

maturity (Li et al., 2025). This non-linear relationship highlights the importance of implementation depth and learning effects in determining whether digitalisation ultimately supports or undermines eco-innovation trajectories (Hambye-Verbrugghen et al., 2026). A recurring mechanism identified in the literature is the mediating role of green technology innovation. Firm-level analyses demonstrate that digital transformation reduces carbon emissions primarily by accelerating green technological upgrading, rather than through direct efficiency effects alone (Guo et al., 2024). Similarly, ESG-oriented studies show that digital transformation strengthens the link between sustainability commitments and actual green innovation outputs by improving data integration, monitoring, and R&D coordination (Zhao et al., 2025). From an organisational capability perspective, digital transformation enhances eco-innovation by strengthening research and development intensity, experimentation capacity, and cross-functional knowledge integration (Xia & Chen, 2025). Digital infrastructures such as big data analytics and AI enable faster feedback loops and more accurate evaluation of environmental performance, which improves firms' ability to refine eco-innovative processes and products over time (Alyahya & Agag, 2025).

The reviewed studies further reveal strong complementarities between I4.0 and circular economy (CE) practices. Evidence from manufacturing firms indicates that CE practices mediate the relationship between I4.0 adoption and sustainable performance, suggesting that digital technologies are most

environmentally effective when they support resource recirculation, waste reduction, and eco-design (Cuevas-Pichardo et al., 2025). Similar conclusions are reached in EU-focused research, which highlights digital technologies as critical enablers of circular production systems when aligned with policy support and innovation investment (Georgescu et al., 2025). At the level of data-driven technologies, disaggregated analyses show that data gathering and data analysis technologies (e.g., sensors, cloud systems, big data, AI) are more consistently associated with sustainability and eco-innovation outcomes than generic digitalisation measures (Hernández et al., 2024). These technologies enhance firms' ability to measure environmental impacts, identify inefficiencies, and coordinate low-carbon responses across supply chains, thereby reinforcing eco-innovation capacity (Saputra et al., 2025).

Mechanisms and pathways linking digital transformation and Industry I4.0 to green innovation and emissions outcomes

A dominant insight emerging from the reviewed literature is that the relationship between digital transformation, Industry 4.0, and environmental outcomes is largely indirect, unfolding through identifiable organisational, technological, and policy-mediated pathways rather than through immediate reductions in emissions (Li et al., 2025; Guo et al., 2024). Across firm-level and macro-level studies, digitalisation reshapes how organisations allocate resources, generate innovation, and respond to regulatory and market pressures, which in turn determines whether emissions

are reduced or intensified (Xia & Chen, 2025; Palma & Scotti, 2025). At the firm level, robust empirical evidence from Chinese listed manufacturing enterprises indicates that digital transformation exhibits an inverted U-shaped relationship with carbon emissions, suggesting that early phases of digital adoption may increase emissions due to expansion effects, higher electricity demand, and transition frictions, while more advanced stages of digital maturity are associated with emissions reductions (Li et al., 2025). Similar nonlinear dynamics are reported in energy and technology-intensive sectors, reinforcing the argument that digitalisation initially amplifies production capacity before enabling efficiency gains and cleaner processes (Hambye-Verbrugghen et al., 2026). Crucially, several studies confirm that emissions reductions are more likely when digital investments are translated into green process innovation and cleaner technologies, consistent with the innovation-mediation logic outlined earlier (Guo et al., 2024; Zhao et al., 2025). This reinforces the finding that digital transformation contributes to decarbonisation primarily by strengthening firms' innovation capacity rather than through direct efficiency gains alone (Xia & Chen, 2025).

Evidence suggests that regulatory pressure strengthens the carbon mitigation effects of digital transformation by incentivising firms to align digital strategies with environmental objectives instead of purely efficiency-driven goals (Li et al., 2025). Where regulatory enforcement is weak, digitalisation may prioritise scale and speed, resulting in muted or

even adverse emissions outcomes (Guo & Shen, 2024). Complementing this firm-level evidence, survey-based and structural equation modelling studies in manufacturing contexts demonstrate that Industry 4.0 adoption is associated with substantially improved sustainability performance when embedded in circular economy practices (Cuevas-Pichardo et al., 2025). These studies show that digital connectivity, cyber-physical systems, and real-time monitoring enhance sustainability only when they support reuse, recycling, and resource efficiency initiatives rather than automation-only modernisation (Torrent-Sellens et al., 2023). This reinforces the view that organisational practices and managerial intent shape the environmental payoffs of advanced manufacturing technologies (Torres de Oliveira et al., 2023).

At the macro-policy level, cross-country evidence from OECD economies indicates that environmental taxes, green technological innovation, and financial development are jointly associated with reductions in greenhouse gas emissions, positioning policy design and financial capacity as critical enabling conditions for the diffusion of low-carbon technologies (Khan et al., 2025). Importantly, this body of work shows that green innovation moderates the effectiveness of environmental technologies, implying that technology deployment alone is insufficient unless supported by innovation ecosystems that facilitate adaptation and learning (Khan et al., 2025). Further evidence from EU economies highlights substantial heterogeneity in the drivers of green technology innovation, suggesting that the effectiveness of digitalisation and

environmental policy varies according to countries' initial innovation levels, institutional quality, and financial system maturity (Cutcu et al., 2024). In this context, financial development demonstrates consistently positive effects across innovation quantiles, indicating that access to capital and financial depth play a stabilising role in supporting green innovation for decarbonisation (Cutcu et al., 2024). By contrast, environmental taxes display mixed effects, constraining innovation in low-capability settings while stimulating it in more advanced institutional contexts (Cutcu et al., 2024).

Big Data, AI, IoT, and analytics-driven pathways to green innovation and decarbonisation outcomes

Across the reviewed evidence, analytics-enabled digitalisation (big data platforms, AI/ML, IoT sensing, and related Industry 4.0 infrastructures) is most consistently linked to decarbonisation through *measurement, optimisation, and innovation conversion mechanisms*, rather than through “technology adoption” alone (Hernández et al., 2024; Xu & He, 2025). In practice, these technologies appear to matter most when they improve the quality, granularity, and timeliness of environmental information (e.g., energy, waste, and emissions data) and then translate that information into operational redesign and greener innovation choices (Ageli, 2025; Taghizad-Tavana et al., 2025). A recurring mechanism in firm-level studies is data-driven visibility, where connected systems enable organisations to identify carbon-intensive processes and quantify improvement opportunities with higher precision than conventional audits (Hernández et al.,

2024). This is important because, in several contexts, environmental improvement is portrayed as being constrained not only by capital or intent, but also by limited “decision intelligence”, that is, organisations struggle to know *where* emissions and waste are generated and *which* interventions produce the best marginal gains (Hernández et al., 2024). In this sense, IoT-enabled monitoring and analytics act as a foundational capability that strengthens the firm’s ability to detect inefficiencies and prioritise targeted eco-innovation activities rather than relying on broad, sometimes symbolic sustainability programmes (Xu & He, 2025).

A second, strongly represented pathway is AI-enabled optimisation, particularly where AI/ML is used to improve energy efficiency and streamline resource allocation at scale (Chen et al., 2025). Evidence from energy-enterprise contexts suggests that computing power and AI adoption can support green transformation by improving operational decision-making and strengthening the technological basis for efficiency and cleaner production, with the “green uplift” being most plausible when AI is embedded into production/energy management routines rather than isolated as an IT upgrade (Chen et al., 2025). Related work in energy-system innovation similarly positions AI as a practical tool for improving energy management and integrating cleaner production pathways, which is relevant for emissions reduction when energy demand and process intensity are central drivers of organisational footprints (Taghizad-Tavana et al., 2025). Third, analytics capability becomes environmentally meaningful

when it helps firms accelerate green innovation rather than focusing only on efficiency gains. The evidence suggests that big data analytics and AI support faster experimentation, stronger cross-functional integration, and more evidence-based redesign of processes and products, which strengthens the broader pattern that digital transformation contributes to decarbonisation mainly through innovation conversion rather than automation alone (Hernández et al., 2024; Ageli, 2025; Xu & He, 2025).

A fourth mechanism evident in the reviewed finance-oriented studies is that digitalisation expands “green capital mobilisation” and accountability, thereby supporting decarbonisation indirectly through stronger incentives and improved allocation of financial resources towards environmental innovation (Zaid et al., 2024). In banking-sector evidence, environmental finance is associated with improved sustainability performance partly because it supports financial innovation that channels resources into greener activities, even though contextual constraints can limit the strength of digital-finance moderation effects in some settings (Zaid et al., 2024). Complementary evidence in manufacturing settings suggests that FinTech conceptualised as technology-enabled finance using big data, AI, blockchain, and IoT can improve environmental sustainability partly because it stimulates green innovation, indicating that the finance sustainability link strengthens when financial digitalisation actively supports green product/process innovation rather than remaining focused on transaction efficiency (Bonsu et al., 2025). Fifth, the reviewed

evidence indicates that governance and organisational innovation are pivotal “conversion layers” between digital technologies and sustainability outcomes (Ageli, 2025; Bonsu et al., 2025).

Finance, policy, and governance-enabled pathways for translating digitalisation into green innovation and decarbonisation outcomes

Based on the reviewed literature, financial and governance conditions repeatedly emerge as the *conversion mechanisms* that determine whether digital transformation translates into measurable green innovation and lower-emissions trajectories, rather than remaining a generic productivity intervention (Li et al., 2025; Guo & Shen, 2024). At the firm level, studies show that digital transformation can expand the organisational “bandwidth” required for sustainability-oriented innovation by enabling cross-functional data integration, internal control improvements, and knowledge sharing routines that support greener technology development and better environmental performance management (Li et al., 2025; Xu & He, 2025). More specifically, ESG-oriented governance is associated with stronger green innovation outcomes, and evidence from Chinese A-share firm shows that higher ESG performance supports green technology innovation. The same evidence indicates that digital transformation strengthens this ESG–innovation relationship by improving monitoring, knowledge integration, and the firm’s ability to scale innovation processes (Xu & He, 2025). These findings are consistent with the earlier synthesis that digital capabilities matter most when they are embedded within governance and innovation systems that

support implementation and follow-through. In parallel, national policy reforms that expand digital infrastructure can indirectly deepen green innovation by improving access to financial resources and reducing frictions that normally weaken innovation persistence, which is particularly important for long-horizon green technologies that require sustained investment rather than short bursts of R&D spending (Liu et al., 2024). Evidence from China’s national big data pilot zones indicates that policy-driven digitalisation is associated with stronger persistence of corporate green innovation, and that regional green finance development amplifies this relationship, meaning that finance ecosystems can materially increase the durability and continuity of green innovation trajectories (Liu et al., 2024).

The same policy-focused study further shows that digital reforms support green innovation persistence through identifiable “finance-and-capability channels” including easing financing constraints, facilitating talent aggregation, and supporting industrial upgrading highlighting that digital transformation often requires complementary financial architecture to generate decarbonisation-relevant innovation outcomes at scale (Liu et al., 2024). At the organisational innovation level, firm evidence also indicates that digital transformation supports green *dual* innovation (exploratory and developmental), but that R&D investment is a critical mediator, suggesting that digital tools raise green innovation mainly when they actively increase research capacity rather than simply automating existing production routines (Xia & Chen, 2025).

Importantly, the same findings show that government subsidies can have a differentiated influence strengthening the digitalisation effect on exploratory green innovation but weakening the effect on developmental green innovation implying that external finance can sometimes distort innovation portfolios if it encourages dependence or short-term strategic behaviour (Xia & Chen, 2025).

Institutional, regulatory, and governance conditions that shape whether digital-enabled sustainability efforts translate into measurable decarbonisation

A strong cross-study implication is that digital transformation and Industry 4.0 tend to deliver clearer climate benefits when they are “anchored” in enabling institutions particularly policy mixes, standards, and governance arrangements that reward green innovation and penalise high-emissions pathways (Khan et al., 2025; Cutcu et al., 2024). Evidence from OECD-region modelling suggests that environmental taxes are most effective for environmental sustainability when they operate alongside green technological innovation, implying that fiscal pressure and innovation capability often need to move together for emissions reductions to be sustained rather than temporary (Khan et al., 2025). EU-focused quantile evidence similarly points to “conditional effectiveness” in policy instruments, where financial development appears to support green technology innovation across the distribution, while the effect of environmental taxes varies by context and level signalling that policy design and institutional maturity shape whether taxation stimulates or constrains green innovation (Cutcu et

al., 2024). Governance and standards-based mechanisms are also highlighted as practical decarbonisation levers, with Ghana-focused panel evidence reporting mitigation effects of ISO 14001 and green governance on CO₂ emissions and recommending incentives and sector-specific regulatory harmonisation to mainstream cleaner practices (Tergu et al., 2025).

However, the same evidence also cautions that “innovation pathways” can be harder to realise in practice, since technological innovation and ICT may show weaker or uneven mitigation associations, implying that governance interventions can reduce emissions even when broader innovation capabilities remain constrained (Tergu et al., 2025). At the public-sector level, EU analysis indicates that public digitalisation can improve sustainability outcomes through a technological-innovation channel, which suggests that digital government capacity matters not only for service delivery but also for shaping innovation ecosystems that support sustainability performance (Gariba et al., 2024). From a regulatory experimentation perspective, the circular-economy “sandbox” approach is presented as a governance instrument intended to lower uncertainty, enable controlled testing of circular solutions, and speed up progress towards climate neutrality by aligning innovation with policy oversight rather than leaving it to market diffusion alone (Zaid et al., 2025). Related synthesis also points to circular economy transition frameworks in the EU as being strongly shaped by policy architecture (e.g., action plans, monitoring, and coordination), which matters because

circular metrics and accountability mechanisms influence what organisations prioritise and measure in practice (Georgescu et al., 2025).

Operationally, European evidence on waste management emphasises that innovation and infrastructure (including technology diffusion in waste systems) are central to circular performance, reinforcing the idea that “green outcomes” depend on institutional capacity to implement and scale solutions not only on firm intent (Calafat-Marzal et al., 2025). Manufacturing-sector synthesis further supports the view that decarbonisation requires coordinated action on the factory floor, where climate impact reduction is framed as a multi-lever challenge involving production processes, technology choices, and systemic implementation conditions rather than once-off technology adoption (Leal Filho et al., 2025). Review evidence on “new technologies for circular economy” reinforces that advanced technologies (including digital technologies) create opportunities for circularity, but the realised benefits depend on complementary enablers such as governance, coordination, and implementation readiness across stakeholders (Sanchez-García et al., 2024). At the energy-system level, comparative EU evidence indicates that renewable-support policies can reduce emissions by raising renewable consumption, highlighting policy-driven diffusion as a core mechanism that can complement firm-level digitalisation and innovation efforts (Nelli et al., 2026).

Digital finance, fintech, and financial inclusion as drivers of green innovation and sustainability

Based on the reviewed studies, digital finance and fintech are repeatedly framed as *enabling infrastructures* that reconfigure how capital is mobilised, priced, monitored, and channelled towards environmentally beneficial activities, rather than acting as “green solutions” on their own (Ageli, 2025). Evidence from emerging-market macro panels suggests that fintech expansion can support cleaner production indirectly by widening access to green financial services, lowering transaction frictions, and improving the reach of sustainability-oriented funding, although the strength of these effects varies by country conditions and emissions intensity (Ageli, 2025). Relatedly, panel evidence focusing on developing Asia highlights that digital finance working together with technological innovation and human development can strengthen resource-use efficiency and the diffusion of more sustainable practices, implying that inclusion-oriented finance is part of the institutional fabric that makes green upgrading more feasible (Hehua et al., 2025). A central pathway emphasised in the literature is that fintech and digital finance widen the *availability and accessibility of capital* for green investments, especially where conventional finance is costly, slow, or unevenly distributed (Almasria et al., 2024). In banking-oriented evidence, the “green credit” function of sustainable finance is portrayed as more impactful when supported by fintech capabilities, because digital tools can improve screening, speed up financing processes, and strengthen the monitoring of environmental lending

outcomes (Bonsu et al., 2025). From this perspective, fintech does not merely add “more finance”; it can reshape the *quality* of finance by strengthening traceability, reducing information asymmetries, and improving compliance capacity for sustainability-linked lending (Bonsu et al., 2025).

Several studies converge on the view that digital finance strengthens sustainability outcomes when it supports measurable green innovation rather than generic financial expansion (Asif et al., 2025). Empirical evidence shows that green technology innovation mediates the finance, sustainability relationship, reinforcing the broader pattern identified across sections that environmental impact depends on innovation conversion rather than financial deepening alone (Ageli, 2025). The reviewed evidence further suggests that the fintech sustainability relationship is commonly shaped by *boundary conditions* tied to institutional and structural features (Ageli, 2025). In particular, cross-country quantile-type reasoning in emerging economies implies that weak regulatory capacity, limited technical capability, or institutional constraints can dampen if not reverse the sustainability benefits of fintech in lower-performing contexts (Ageli, 2025). In practical terms, this means fintech-led green finance may work best where regulatory frameworks, implementation quality, and market governance can ensure that digital financial expansion is aligned with credible environmental objectives rather than purely short-term financial or consumption expansion (Asif et al., 2025).

A complementary strand of findings highlights ESG-linked mechanisms as an increasingly important *governance channel* through which sustainable finance influences green innovation (Liu et al., 2025). Evidence using Chinese listed firms indicates that stronger ESG performance is associated with higher green technology innovation, while the link is amplified when firms have higher levels of digital transformation, suggesting that digital capabilities function as “meta-resources” that help organisations convert ESG commitments into innovation outcomes (Liu et al., 2025). The same evidence also shows meaningful heterogeneity, where ESG innovation relationships appear stronger in higher-marketisation settings, implying that financing costs, transparency, and market functioning shape how effectively sustainability commitments translate into innovation (Liu et al., 2025). In addition, the literature suggests that digital and inclusive finance can contribute to sustainability not only through firm-level innovation but also through broader improvements in how resources are governed and used across society (Hehua et al., 2025).

Circular economy, eco-innovation, and sustainable business model transformation

Across the reviewed literature, the circular economy and eco-innovation are consistently positioned as *operational bridges* that translate digital transformation and Industry 4.0 capabilities into tangible sustainability outcomes, rather than as abstract sustainability ideals (Cuevas-Pichardo et al., 2025; Sanchez-García et al., 2024). Empirical and conceptual studies converge on the view that

digital technologies become environmentally meaningful when they are embedded in circular production logics that redesign material flows, extend product lifecycles, and reduce waste and emissions across value chains (Leal Filho et al., 2025). A central finding is that eco-innovation acts as a practical mechanism through which firms operationalise circular strategies. Studies examining manufacturing and industrial firms show that eco-innovation understood as environmentally oriented product, process, and organisational innovation enables firms to reconfigure production systems toward resource efficiency and emissions reduction, particularly when supported by digital monitoring and analytics (Cuevas-Pichardo et al., 2025). This suggests that digital transformation does not directly “create circularity,” but rather enhances firms’ capacity to implement eco-innovative practices that underpin circular business models (Sanchez-García et al., 2024).

Several studies further demonstrate that circular economy practices mediate the relationship between Industry 4.0 and sustainability performance, indicating that automation, cyber-physical systems, and real-time data exchange deliver stronger environmental outcomes when they support reuse, recycling, remanufacturing, and eco-design activities (Cuevas-Pichardo et al., 2025). From this perspective, CE functions as an organisational framework that channels digital capability into sustainability-oriented operational redesign, rather than allowing digitalisation to remain focused on throughput or cost efficiency alone (Torrent-Sellens et al., 2023). Evidence from European waste-

management systems reinforces the importance of infrastructure and innovation alignment in enabling circular outcomes. Studies analysing waste management across EU countries report that innovation capacity, technological diffusion, and coordinated governance structures are critical for translating circular ambitions into effective waste reduction and material recovery outcomes (Calafat-Marzal et al., 2025). These findings highlight that circular business model transformation depends not only on firm-level intent, but also on system-level readiness to support waste valorisation and secondary material markets (Calafat-Marzal et al., 2025).

At the organisational level, research on circular readiness in heavy industries indicates that firms’ ability to adopt circular practices is shaped by technological maturity, managerial commitment, and structural conditions such as capital intensity and supply-chain complexity (Saputra et al., 2025). Heavy industries with higher circular readiness tend to integrate digital tools for monitoring material flows and emissions, which supports more informed eco-innovation decisions and facilitates compliance with tightening environmental standards (Saputra et al., 2025). This suggests that CE adoption is not uniform across sectors but conditioned by industrial structure and digital capability depth. The reviewed literature also extends circular thinking beyond production into market-facing and business-model dimensions, particularly through circular marketing and sustainable value propositions. Studies on sustainable marketing and circular business strategies show that firms increasingly integrate eco-

innovation into branding, customer engagement, and value delivery, thereby aligning environmental performance with competitive positioning (Kraus et al., 2024). This stream of research indicates that circular transformation is not only operational but also strategic, reshaping how firms communicate sustainability value and capture returns from eco-innovative activities (Kraus et al., 2024).

Energy transition pathways

Across the reviewed literature, the energy transition is conceptualised as a multi-dimensional transformation involving changes in energy sources, technological innovation, governance structures, and enabling digital infrastructures, rather than a linear substitution of fossil fuels with renewables (García-Álvarez et al., 2025; Moghadam & Karami, 2024). The evidence consistently shows that renewable energy deployment, energy innovation, and emerging hydrogen pathways contribute to emissions reduction and sustainability outcomes most effectively when they are embedded within broader institutional, technological, and digital ecosystems (Zarrad et al., 2025). A substantial body of empirical work demonstrates that renewable energy consumption is inversely associated with carbon emissions and environmental degradation, although the magnitude and persistence of these effects vary across regions and development stages (Nelli et al., 2026; Karim et al., 2025). Cross-country studies covering the EU, OECD, and Gulf Cooperation Council economies indicate that increasing the share of renewables in national energy mixes contributes to improved environmental sustainability, but these

gains are often conditional on complementary energy policies, market competition, and innovation capacity (García-Álvarez et al., 2025; Karim et al., 2025). This suggests that renewables function as a necessary but insufficient condition for deep decarbonisation when deployed without supportive systemic reforms.

Energy innovation emerges as a critical intermediary in the renewable sustainability relationship. Evidence from MENA and EU economies shows that innovation in energy technologies strengthens renewable energy production and enhances sustainability outcomes, particularly in contexts where renewable penetration has already reached moderate levels (Moghadam & Karami, 2024). These findings imply threshold effects, where early-stage renewable deployment may require policy protection and investment support, while later-stage transitions benefit more strongly from innovation-driven efficiency gains and system integration (Cutcu et al., 2024). Several studies also highlight the role of digitalisation as a moderating force in energy transition pathways. Digital technologies such as smart grids, IoT-enabled energy monitoring, and data-driven optimisation systems are shown to improve the efficiency, reliability, and integration of renewable energy into existing energy systems (Zarrad et al., 2025). In the Eurozone context, digitalisation strengthens the positive impact of renewable energy on sustainable development indicators, suggesting that digital tools help manage intermittency, optimise demand supply matching, and reduce system losses (Zarrad et al., 2025). However, the same evidence cautions that digital expansion can increase

electricity demand, implying that digital–energy synergies depend on the carbon intensity of electricity generation (Hambye-Verbrugghen et al., 2026). Hydrogen pathways represent an emerging but increasingly prominent strand in the energy transition literature. Review-based and systems-oriented studies indicate that green hydrogen, produced using renewable energy, has the potential to decarbonise hard-to-abate sectors such as heavy industry and long-distance transport (Taghizad-Tavana et al., 2025). The integration of artificial intelligence and digital energy management systems is highlighted as a key enabler of hydrogen supply-chain optimisation, improving efficiency in production, storage, and distribution (Taghizad-Tavana et al., 2025).

Discussion

The findings of this review indicate that digital transformation and Industry 4.0 technologies should not be viewed as automatically contributing to environmental sustainability. Rather, their climate relevance appears to depend on how effectively digital investments are translated into environmentally meaningful innovation and operational change. Across the reviewed studies, digitalisation often restructures information flows, improves coordination, and enhances organisational decision-making capacity. However, these improvements do not necessarily result in immediate reductions in emissions. In several contexts, the early stages of digital adoption are associated with increased energy demand, infrastructure expansion, and production scaling, which may temporarily intensify emissions before environmental

benefits begin to materialise. A recurring insight across the literature is that digital technologies primarily influence environmental performance indirectly through green technology innovation and eco-innovation processes. In this sense, digital transformation appears to function more as an enabling infrastructure that supports experimentation, process redesign, and cleaner production pathways rather than acting as a direct mitigation mechanism. The reviewed evidence consistently suggests that measurable emissions reductions are more likely when digital capabilities are embedded within innovation systems that support low-carbon product development, process upgrading, and environmentally oriented organisational practices. The review also highlights that the environmental outcomes of digital transformation are shaped by contextual conditions, including governance quality, regulatory pressure, and financial support systems. Where digitalisation is pursued primarily for productivity or efficiency gains, environmental improvements may remain limited or inconsistent. Conversely, when digital investments are aligned with sustainability-oriented governance frameworks and innovation incentives, organisations appear better able to convert technological capability into green innovation and emissions mitigation outcomes. Financial and governance mechanisms repeatedly emerge as important mediating conditions in this process. Digital finance and fintech are associated with improved sustainability performance in cases where they facilitate access to capital for green innovation activities and support accountability in environmental investment decisions.

However, the reviewed evidence also suggests that the effectiveness of financial digitalisation varies across institutional contexts, indicating that digital financial expansion alone does not guarantee environmentally beneficial outcomes in the absence of supportive governance structures. Similarly, circular economy practices are identified as a practical implementation layer through which digital capabilities become operationally visible in sustainability performance. The findings suggest that Industry 4.0 technologies are more likely to contribute to emissions reduction when they support reuse, recycling, eco-design, and resource efficiency initiatives. In such cases, digital connectivity and data-driven monitoring appear to enable organisations to identify inefficiencies and redesign production systems in ways that reduce material intensity and environmental impact. Energy transition pathways further illustrate the conditional nature of digital-enabled sustainability outcomes. Renewable energy deployment and energy innovation are consistently linked to improved environmental performance, yet their effectiveness appears to depend on complementary policy frameworks and innovation capacity. Digital technologies such as smart grids and real-time monitoring systems enhance the integration and management of renewable energy sources, although they may also increase electricity demand if not supported by low-carbon energy generation systems. Taken together, the reviewed studies suggest that digital transformation contributes to decarbonisation primarily through innovation, governance, financial, and organisational pathways rather than

through direct efficiency effects alone. The environmental implications of digitalisation are therefore shaped by how technological capabilities are embedded within broader institutional and operational systems that support sustainable innovation.

Conclusion

This review examined how digital transformation and Industry 4.0 contribute to green innovation and climate outcomes. The evidence consistently shows that digitalisation is not inherently sustainable. Rather, its environmental impact depends on how digital capabilities are embedded within innovation systems, governance structures, financial ecosystems, circular economy practices, and energy transition strategies. Across the reviewed studies, green technology innovation emerges as the central conversion mechanism through which digital transformation translates into measurable emissions reductions. Financial depth, regulatory quality, institutional strength, and organisational capability repeatedly shape whether digital investments reinforce carbon-intensive growth or support genuine decarbonisation. The findings suggest that digital transformation functions as a structural catalyst for sustainability when aligned with deliberate policy frameworks, innovation capacity, and coordinated governance. Without these complementary conditions, digital expansion may yield efficiency gains without delivering meaningful climate mitigation.

Future Research

Future research should move beyond cross-sectional modelling and examine the long-term dynamics of digital-green transitions, particularly the threshold and rebound effects identified in several studies. More sector-specific and comparative analyses are needed to clarify how digital maturity, regulatory quality, and financial architecture interact across different institutional contexts.

Limitations of study

The review relied primarily on a single major database and was restricted to English-language, open-access publications, which may have excluded relevant studies and introduced publication bias. The analysis focused largely on published empirical and conceptual work, meaning that emerging industry practices and grey literature were not systematically included. These limitations suggest that while the findings provide a robust overview of existing evidence, they should be interpreted with appropriate caution.

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