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Mapping the Role of Blockchain, IoT, and AI in Advancing Sustainable Development Goals: A Systematic Review toward Responsible Investment

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Seyed Alireza Khezri*
Department of Accounting, Qa .c., Isalamic Azad university, Qazvin, Iran
Corresponding Author
E-mail: alireza.khezri9232@iau.ac.ir

Farzin Rezaei[2]
Department of Accounting, Qa .c., Isalamic Azad university, Qazvin, Iran
E-mail: farzin.rezaei@iau.ac.ir

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Abstract

The convergence of Blockchain, the Internet of Things (IoT), and artificial intelligence (AI) is widely regarded as transformative for advancing the Sustainable Development Goals (SDGs) and reshaping responsible investment. Yet, the literature remains profoundly fragmented across technological, sustainability, and financial dimensions. This study addressed this gap through conducting a rigorous qualitative meta-synthesis of 33 peer-reviewed studies published between 2021 and 2026, deliberately prioritizing interpretive depth and thematic integration over Qualitative Meta-Synthesis quantification to extract causal mechanisms and contextual contingencies. Anchored in the Resource-Based View (RBV), Dynamic Capabilities Theory, Institutional Theory, Stakeholder Theory, Information Asymmetry Theory, and Socio-Technical Systems Theory, our analysis delineated eight interconnected thematic categories and identified three core causal pathways: (1) transparency and trust infrastructures, (2) real-time sensing and operational optimization, and (3) predictive and prescriptive intelligence. Critically, the synthesis uncovered four persistent paradoxes including the energy-throughput trade-off, transparency-obfuscation dynamics, governance-accountability voids, and digital divide-exclusion tensions that collectively qualified the prevailing technology-optimism narratives and positioned digital technologies as conditional enablers rather than panaceas. Building upon these insights, we advanced the Digital-Integrated Mechanisms for Transformation (DIMT) Framework, positing that sustainability outcomes are not technologically determined but critically contingent upon data maturity, regulatory coherence, stakeholder literacy, and institutional readiness. Empirical evidence further revealed that synergistic integration of all three technologies remains empirically scarce, comprising merely 2.7% of the corpus, marking a paramount frontier for future inquiry. This review consolidated the fragmented knowledge, explicated the implementation paradoxes, and offered actionable guidance for policymakers, investors, and organizational strategists, underscoring that effective digital transformation for sustainability demands systemic integration, context-sensitive governance, and calibrated implementation strategies.

Keywords

Industry 4.0, Sustainable Development Goals (SDGs), Responsible Investment (ESG Integration), ESG Performance Indicators, Qualitative Meta-Synthesis, DIMT Framework, Digital Governance.

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Introduction

The global shift toward a knowledge-based economy has fundamentally transformed the logic of value creation, positioning knowledge, data, and technological capabilities at the core of economic and organizational performance (Aparicio et al., 2023; Dai et al., 2025; Grant, 2000; Pascucci et al., 2024; Vărzaru & Bocean, 2024). Within this transformation, digitalization has evolved from a supportive function into a structural driver of economic systems, reshaping how value is generated, exchanged, and sustained (Cheng et al., 2026; Işık et al., 2026; Mohamed et al., 2026; Valizada, 2026). Industry 4.0, as a defining manifestation of this transition, reflects the convergence of advanced digital technologies including AI, the IoT, and Blockchain into integrated and intelligent socio-technical systems (Aoun et al., 2021; Fernández-Miguel et al., 2025). These technologies enable unprecedented levels of connectivity, automation, and data-driven decision-making, thereby redefining the architecture of production, governance, and financial systems in the contemporary economy (Bokhari, 2026; Gavrila et al., 2025; Najem et al., 2025; Vărzaru & Bocean, 2024; Zhang et al., 2025).

At the same time, escalating environmental and social challenges have intensified the need to align economic activities with sustainability imperatives (Eelager et al., 2025; Islam, 2025; Trejo-Nieto, 2024). The Sustainable Development Goals (SDGs) have emerged as a globally endorsed framework to guide this alignment, embedding sustainability considerations within policy agendas, organizational strategies, and investment decisions (Fallah Shayan et al., 2022; Wang & Zhao, 2025). In this context, Industry 4.0 technologies are increasingly recognized not merely as tools for efficiency enhancement, but as critical enablers of sustainable development. Their capacity to facilitate real-time monitoring (IoT), predictive and prescriptive analytics (AI), and transparency and trust (Blockchain) positions them as key mechanisms for addressing complex sustainability challenges across environmental, social, and economic dimensions (Díaz-Martínez et al., 2026; Javaid et al., 2024; Piispanen & Hentunen, 2026; Santhi & Muthuswamy, 2023).

We deliberately focus on Blockchain, IoT, and AI as an interconnected triad rather than in isolation, for three interrelated reasons. First, these technologies are functionally complementary: IoT provides the sensory layer for real-time data capture; AI offers the analytical engine for predictive and prescriptive insights; and Blockchain supplies the verification and trust infrastructure for auditable data provenance together forming a complete value chain from data generation to decision validation (Ga et al., 2025; Vilchez Olivares & Astorga De La Cruz, 2026). Second, prior research overwhelmingly examined these technologies in technological or sectoral silos (Almulhim, 2025; Marengo, 2024), leaving their synergistic interactions critically underexplored. This is a gap which is addressed in our systematic synthesis. Third, the convergence of these three digital pillars is increasingly recognized in policy and practitioner discourse (e.g., EU Digital Compass, WEF reports) as the core technological substrate for achieving systemic sustainability transitions, making their simultaneous investigation both theoretically urgent and practically relevant.

This technological transformation has profound implications for financial systems and investment paradigms (Jin & Xie, 2024; Sui & Yao, 2023; Valaskova et al., 2025). In particular, the rise of sustainable and responsible investment reflects a fundamental shift from traditional profit-centric models toward more holistic approaches that integrate environmental, social, and governance (ESG) criteria. Digital technologies play a pivotal role in this transition by reshaping the information flows, reducing information asymmetries, and enabling more accurate assessment of sustainability-related risks and impacts (Bindeeba et al., 2025; Martiny et al., 2024; Meneses Cerón et al., 2026; Perumandla et al., 2025). For instance, Blockchain enhances the credibility of ESG disclosures through immutable records, AI supports the advanced risk modeling and impact prediction, and IoT provides granular, real-time data on sustainability performance. Consequently, the intersection of Industry 4.0, SDGs, and sustainable investment represents a critical frontier in the evolution of the knowledge economy (Alotaibi et al., 2024; Liu et al., 2024; Mbanyale & Muchenje, 2025).

Despite the growing scholarly attention to this intersection, the existing body of literature remains conceptually fragmented and methodologically dispersed (Berntsen et al., 2026; Hlortu et al., 2026; Koutsoupias & Nosios, 2026). A significant portion of prior research has examined AI, IoT, and Blockchain in isolation, overlooking their synergistic interactions within a broader technological ecosystem (Almulhim, 2025; Kaushik et al., 2026; Marengo, 2024). Moreover, many studies adopted context-specific or sectoral perspectives, limiting the ability to derive generalizable insights about the systemic role of digital technologies in advancing sustainability and reshaping investment practices (Hadizadeh et al., 2024; Mohammadian et al., 2022; Zhang & Khaskheli, 2025). Importantly, there is a lack of integrative and methodologically rigorous syntheses that simultaneously capture (i) the intellectual structure of this interdisciplinary field, (ii) its thematic evolution over time, and (iii) the underlying mechanisms through which digital technologies contribute to SDGs and influence sustainable investment. This gap is particularly salient given the rapid expansion of publications and the increasing complexity of research at the nexus of technology, sustainability, and finance (Hakam et al., 2026; Hlortu et al., 2026; Liu et al., 2026; Sakka et al., 2026).

To address these limitations, this study adopted a combined Qualitative Meta-Synthesis and systematic review approach to provide a comprehensive and multi-layered synthesis of the literature. Qualitative Meta-Synthesis analysis enables the mapping of the intellectual and conceptual structure of the field by identifying key research clusters, influential publications, and patterns of scholarly development. Complementarily, the systematic review facilitates an in-depth qualitative examination of thematic linkages, conceptual relationships, and underlying mechanisms. Through this integrated methodological design, the study sought to move beyond the descriptive aggregation toward a more analytical and theory-informed understanding of the domain (Jeppe et al., 2025).

Crucially, we expose four persistent paradoxes that systematically qualify technology-optimistic claims. First, the Energy-Throughput Paradox directly challenges the RBV: while Blockchain offers strategic immutability, its energy-intensive consensus mechanisms (Bhatt & Emdad, 2025; Rahman et al., 2026) consume tangible organizational resources, potentially eroding the very sustainability dividends that constitute the strategic asset. Second, the Transparency-Obfuscation Paradox wherein immutable ledgers enable sophisticated SDG-washing (Kumar & Shah, 2025; Naili et al., 2026) directly complicates the Stakeholder Theory: instead of empowering stakeholders through credible disclosure, enhanced transparency may be appropriated as a symbolic compliance tool, deepening the information asymmetry that stakeholder frameworks seek to mitigate. Third, the Governance-Accountability Gap exposes a core tension within the Institutional Theory: decentralized autonomous systems bypass the established regulatory accountability mechanisms, creating institutional voids and regulatory arbitrage that undermine the legitimacy-seeking behaviour institutional theory assumes (Qudah, 2026; Sanina et al., 2024). Finally, the Digital Divide–Exclusion Trade-off resonates with Socio-Technical Systems Theory, revealing that technological infrastructures are neither neutral nor universally accessible; uneven digital capabilities and algorithmic literacy (Chandran et al., 2025; Islam & Can, 2024) reproduce social inequalities, contradicting the inclusive sustainability narratives that socio-technical frameworks advocate. Thus, these paradoxes suggest that external legitimacy pressures may encourage performative rather than substantive transformation an institutional decoupling effect (Zhang & Zhu, 2025) that prior efficiency-focused work has insufficiently addressed.

Building upon these foundations, this study addressed the following research questions: (1) What is the intellectual and conceptual structure of the literature on Industry 4.0 technologies in relation to SDGs and sustainable investment? (2) What are the dominant thematic clusters and how have they evolved over time? (3) Through which mechanisms do AI, IoT, and Blockchain contribute to sustainable development and influence investment practices? and (4) What critical gaps and future research directions emerge from the existing body of knowledge? By systematically addressing these questions, the study aimed at consolidating the fragmented insights, revealing hidden structures within the literature, and advancing a more integrated understanding of the role of digital technologies in bridging sustainability objectives and investment strategies.

In doing so, this research contributes to the literature in three significant ways. First, it provides a comprehensive mapping of the intellectual landscape at the intersection of Industry 4.0, SDGs, and sustainable investment, thereby enhancing the conceptual clarity in a rapidly evolving field. Second, it identifies key thematic trends, research trajectories, and underexplored areas through conducting a rigorous Qualitative Meta-Synthesis analysis. Third, it develops an integrative analytical perspective that explicates the pathways through which digital technologies enable the translation of sustainability imperatives into investment practices. Consequently, these contributions offer valuable implications for scholars, policymakers, and practitioners seeking to navigate and shape the future of the knowledge-based and sustainability-driven economy.

Literature Review

The expanding scholarly interest in the intersection of digital technologies and sustainability has generated a substantial yet highly fragmented body of literature. A dominant stream of research has examined Blockchain, IoT, and AI in isolation, focusing on their individual technological affordances without adequately addressing their systemic interdependencies (Almulhim, 2025; Kaushik et al., 2026; Marengo, 2024). Within this fragmented landscape, bibliometric and systematic reviews have predominantly mapped thematic clusters such as ESG transparency, green finance, and smart operations without sufficiently interrogating the causal mechanisms that link technological inputs to sustainability outcomes (Alshdaifat et al., 2024; Tandon et al., 2021; Thawani et al., 2025). Moreover, sectoral studies have concentrated disproportionately on manufacturing and supply chains (Kushwaha et al., 2025; Sahar et al., 2026), while critical domains such as healthcare (SDG 3) and agriculture (SDG 2) remained conspicuously underexplored (Chandran et al., 2025; Kumar & Shah, 2025). This thematic concentration, coupled with a persistent geographical bias toward developed economies and China (John et al., 2025; Nada et al., 2026), has constrained the generalizability of the existing frameworks and underscored the necessity for integrative syntheses that transcend both technological and geographical silos.

Within the Blockchain-focused literature, empirical evidence consistently underscored its capacity to enhance ESG disclosure credibility through immutable audit trails and smart contracts, with documented improvements in accountability scores ranging from 35% to 52% (Bhatt & Emdad, 2025; Nguyen Van et al., 2026). However, these gains are critically contingent upon the transition to energy-efficient consensus protocols, as the energy throughput paradox remains a formidable barrier to net sustainability gains (Bhullar et al., 2024; Rahman et al., 2026). Concurrently, IoT-enabled sensing infrastructures have demonstrated measurable operational efficiencies, including 28–42% cost reductions and 50–65% faster processing in industrial operations, yet fragmented data systems and interoperability gaps frequently undermine these benefits (Ding et al., 2024; Piispanen & Hentunen, 2026; Sahar et al., 2026). In the AI domain, predictive and prescriptive analytics have achieved 42–65% improvements in forecast accuracy for ESG risk modeling and scenario simulations (Najem et al., 2025; Sklavos et al., 2024), though algorithmic bias, explainability deficits, and cognitive misalignment with managerial judgments temper these advantages (Abdurrahman, 2025; Zhang et al., 2025). Thus, these technology-specific bodies of knowledge remain largely disconnected with only a handful of studies examining their synergistic integration as a scarcity that constitutes a paramount research frontier (Ga et al., 2025; Vilchez Olivares & Astorga De La Cruz, 2026).

Alongside the technological literature, a mature research stream has examined the reconfiguration of investment paradigms through digital platforms, highlighting how FinTech and green finance instruments mitigate the information asymmetry and facilitate the integration of ESG criteria into capital allocation decisions (Kwong et al., 2023; Rojas-Valdez & Fajardo-Piñan, 2026; Roy & Vasa, 2025). The Blockchain's role in enhancing the credibility of green bonds and regenerative finance infrastructures has been particularly emphasized (Bhullar et al., 2024; Roy & Zaher, 2025), while AI-driven analytics have been shown to improve the predictive accuracy of ESG performance and risk assessments (Jin et al., 2025; Najem et al., 2025). Nevertheless, the translation of technological affordances into tangible investment outcomes is heavily moderated by institutional and regulatory factors, including the harmonization of ESG reporting mandates and the enforcement of accountability mechanisms (de bem Machado et al., 2025; Qudah, 2026; Sanina et al., 2024). Studies further revealed that the investor trust and capital reallocation depend less on the mere presence of digital tools than on the broader ecosystem of data maturity, regulatory coherence, and stakeholder literacy (Garg & Kumar, 2024; Martiny et al., 2024; Thawani et al., 2025). This contingent relationship underscores that digital technologies function as conditional enablers rather than autonomous drivers of responsible investment a nuance that is frequently overlooked in technology-optimistic accounts (Meneses Cerón et al., 2026; Perumandla et al., 2025).

Despite the accumulating evidence, the existing literature suffers from four persistent gaps that collectively motivate the present synthesis. First, there is a critical scarcity of research examining the triadic convergence of Blockchain, IoT, and AI within unified architectures, with empirical investigations of such integration comprising merely 2.7% of the corpus (Alshdaifat et al., 2024; Vilchez Olivares & Astorga De La Cruz, 2026). Second, the literature has insufficiently addressed the implementation paradoxes including the transparency obfuscation dynamics that enable SDG-washing (Kumar & Shah, 2025; Naili et al., 2026), the governance accountability voids inherent in decentralized systems (Qudah, 2026), and the digital divide–exclusion trade-off that disproportionately affects developing economies and marginalized communities (Chandran et al., 2025; Islam & Can, 2024; Trejo-Nieto, 2024). Third, while the theoretical frameworks such as the RVB, dynamic capabilities, institutional theory, and stakeholder theory have been individually applied, integrative multi-theoretical lenses that simultaneously capture technological, organizational, and institutional dimensions remain conspicuously absent (Jeppe et al., 2025; Piispanen & Hentunen, 2026; Zhang & Zhu, 2025). Finally, the predominance of cross-sectional and bibliometric designs has limited the extraction of causal mechanisms and contextual contingencies that shape real-world outcomes (Hlortu et al., 2026; Liu et al., 2026). Addressing these interconnected gaps, the present study undertook a rigorous qualitative meta-synthesis, anchored in an integrated theoretical architecture, to systematically delineate the causal pathways, boundary conditions, and governance imperatives that determine whether digital technologies genuinely advance sustainable development and responsible investment or merely perpetuate symbolic compliance.

Methodology

Research Paradigm and Methodological Rationale

This study adopted an interpretive-constructivist epistemological stance, employing a qualitative meta-synthesis approach to examine the intricate confluence of Blockchain, the IoT, and AI in advancing the SDGs and reshaping responsible investment paradigms. Given the exponentially expanding and inherently interdisciplinary nature of this domain, the extant literature remained profoundly fragmented across technological, sustainability, and financial silos, frequently adopting sector-specific or technology-isolated perspectives (Hlortu et al., 2026; Marengo, 2024). To navigate this complexity, the research was anchored in a pragmatic philosophical position that prioritizes analytical depth over descriptive breadth. Instead of relying on quantitative mapping, this inquiry deployed a rigorous thematic synthesis strategy, which facilitates the extraction of causal mechanisms, contingent pathways, and integrated theoretical frameworks. This methodological choice ensures that the investigation transcends superficial aggregation, yielding a theoretically informed and analytically robust synthesis of the contemporary evidence.

Research Design: A Unitary Thematic Synthesis Framework

The epistemological foundation pragmatically intersects the post-positivist rigor with the interpretivist contextual sensitivity, acknowledging both the necessity of systematic procedural transparency and the inherently theory-laden nature of qualitative interpretation (Snyder, 2019). This duality was operationalized through a unitary, single-phase qualitative design centered on reflexive thematic analysis. To structure the inquiry, the study addressed four formalized research questions (RQs):

RQ1: What is the intellectual and conceptual structure of the literature on Industry 4.0 technologies in relation to SDGs and sustainable investment?

RQ2: What are the dominant thematic clusters and how are they conceptually organized?

RQ3: Through which causal mechanisms do AI, IoT, and Blockchain contribute to sustainable development and reshape investment practices?

RQ4: What critical research gaps and future trajectories emerge from the existing knowledge base?

Accordingly, the core analytical engine of this research was qualitative thematic synthesis, following the reflexive guidelines of Braun and Clarke (2006), applied through an abductive logic that moves iteratively between empirical findings and theoretical prefigurations. All procedural stages including search, screening, quality appraisal, and coding were executed as an integrated, non-fragmented workflow on the final selected corpus.

Systematic Search Protocol and Database Interrogation

A methodical and reproducible literature interrogation was executed across the Scopus and Web of Science (WoS) Core Collection databases. The temporal horizon was deliberately set as a continuous, uninterrupted window from January 2021 to mid-2026. This specific window is justified not merely for novelty but for epistemic maturity. The period 2020–2021 marks the inflection point where convergent digital architectures moved from pilot-scale proof-of-concepts to large-scale, longitudinal empirical investigations (John et al., 2025; Song et al., 2025). Crucially, this interval provides sufficient empirical evidence across multiple sectors and geographies to assess systemic scalability failures, unintended rebound effects, governance voids, and ethical quagmires inherent in real-world implementations, which earlier conceptual or pilot-based studies (pre-2020) could not have captured. Moreover, the rapid proliferation of regulatory instruments such as the EU AI Act, GDPR revisions, and national ESG mandates during this period (Sanina et al., 2024) enables a contextually grounded examination of institutional influences absent in prior literature. This cohesive, uninterrupted timeframe thus ensures that our synthesis is empirically substantive, critically reflective, and contemporarily relevant.

The lexical architecture, meticulously crafted to encompass the multidimensional semantics of technology-enabled sustainability while circumventing purely engineering or abstract finance domains, is detailed in Table 1.

Table 1.
The Lexical Framework and Combinatorial Search Strings

Primary Keywords	Secondary Keywords	Combined Search Strings (Boolean)
Blockchain / DLT	Traceability / Transparency / Trust	(Blockchain OR "distributed ledger") AND (SDG* OR sustainability OR ESG)
Internet of Things (IoT)	Environmental Monitoring / Resource Efficiency	(IoT OR "Internet of Things") AND ("sustainable development" OR "climate action")
Artificial Intelligence / ML	Predictive Analytics / Risk Modeling	(AI OR "artificial intelligence") AND (ESG OR "responsible investment")
Industry 4.0	Circular Economy / Green Finance	("Industry 4.0") AND ("circular economy" OR "green finance")

(**Source: Research findings**)

Eligibility Screening, Quality Appraisal, and Inter-Rater Reliability

Following the initial retrieval and the subsequent removal of duplicate records, a rigorous two-tier PRISMA-aligned screening protocol was applied. Stage 1 (Title/Abstract): Two independent researchers blindly screened the records against the predefined inclusion criteria, resolving discordances through deliberation or third-expert adjudication. Stage 2 (Full-Text): The retained manuscripts underwent exhaustive methodological appraisal against a 10-dimensional quality rubric (adapted from Walsh & Downe, 2006, and the Mixed Methods Appraisal Tool – MMAT). This rubric encompassed clarity of objectives, design appropriateness, analytical robustness, theoretical grounding, sustainability/ESG engagement, technological integration, evidentiary substantiveness, acknowledgment of limitations, novelty, and ethical integrity. Each article was scored on a 50-point scale. Only those attaining a threshold of ≥38 were deemed methodologically sound and retained for synthesis. To mitigate the interpretive bias during the subsequent codification, two researchers thematically coded a randomly selected 30% subsample of the final corpus, yielding a Cohen's Kappa coefficient of $\kappa = 0.821$, which denotes exceptional inter-rater agreement (PRISMA 2020, Item 11; ENTREQ, Item 14). Following the exhaustive application of all eligibility criteria including timeframe adherence, topical relevance, methodological robustness, and full-text accessibility, the final analytical corpus comprised 33 high-quality, peer-reviewed studies, which form the evidential foundation for all subsequent thematic syntheses.

Data Abstraction, Codification, and Thematic Procedures

For the 33 finalized studies, comprehensive metadata and full textual data (including research objectives, methodological designs, empirical findings, discussion sections, and concluding remarks) were extracted into a structured and iterative coding matrix. The codification process was reflexively guided by Braun and Clarke's (2006) thematic analysis framework and explicitly anchored to the theoretical perspectives articulated in the introduction namely, the RBV, dynamic capabilities, institutional theory, stakeholder theory, information asymmetry, and socio-technical systems theory. This matrix was progressively refined to capture: (a) technology-specific mechanisms and synergistic integrations (e.g., Blockchain immutability, IoT sensing capabilities, AI predictive analytics, and convergent architectures); (b) explicit and implicit SDG alignment and impact pathways (particularly SDGs 7, 9, 12, and 13); (c) reconfigurations of investment practices (enhanced ESG accuracy, mitigated information asymmetries, and facilitation of green finance instruments); (d) theoretical anchors and contextual moderators; (e) critical boundary conditions and inherent paradoxes (scalability limitations, energy-consumption trade-offs, data privacy infringements, and the phenomenon of "SDG-washing"); and (f) institutional, regulatory, and cultural contingencies shaping the implementation outcomes. This granular coding enabled the systematic identification of both converging patterns and substantive contradictions pervasive across the contemporary literature.

To ensure analytical transparency and replicability, the core constructs underpinning our keywords were operationally defined with reference to measurable indicators drawn from the synthesized literature:

- ***Responsible Investment*** was operationalized through indicators such as ESG disclosure scores, green bond issuance volumes, and the integration of ESG criteria into asset allocation decisions (Kwong et al., 2023; Roy & Vasa, 2025).
- ***Data Maturity*** was assessed via the interoperability readiness of information systems, data quality dimensions (accuracy, completeness, timeliness), and the existence of integration protocols across technological platforms (Garg & Kumar, 2024; Thawani et al., 2025).
- ***Regulatory Coherence*** was measured through the presence of harmonized ESG reporting mandates, alignment with GDPR/EU AI Act provisions, and standardization of green consensus protocols (Qudah, 2026; Sanina et al., 2024).
- ***Stakeholder Literacy*** was operationalized as the demonstrated capacity of organizational actors to interpret, validate, and act upon digitally generated sustainability intelligence, captured through training intensity and decision-making competence (Abdurrahman, 2025; Sklavos et al., 2024).

This operationalization ensures that the thematic categories (Table 2) and the DIMT Framework components were grounded in empirically verifiable dimensions, enhancing the practical utility and scientific significance of our findings.

Synthesis Strategy: An Integrative and Cross-Cutting Approach

Given that all 33 constituent studies were situated within the continuous 2021–2026 timeframe, the synthesis strategy deliberately refrained from any form of temporal bifurcation, chronological segmentation, or cohort-based comparison. Instead of disaggregating the literature into successive periods, this research adopted a concurrent, synchronous, and integrative analytical posture. The synthesis procedure proceeded by first aggregating open codes into higher-order thematic categories, followed by a constant comparative method across the entire corpus to identify the overarching thematic clusters. Through this iterative interrogation, the principal themes encompassing success mechanisms, implementation barriers, unintended socio-environmental consequences, and requisite governance conditions were delineated and systematically interlinked into a cohesive explanatory framework. This integrated approach not only preserved the internal coherence of the analysis but also revealed the latent conceptual patterns and systemic interdependencies that would remain obscured under a segmented temporal lens.

Ethical Compliance, Transparency, and Reporting Standards

In strict compliance with the PRISMA 2020 and SANRA guidelines, comprehensive procedural transparency has been meticulously maintained. All methodological decisions, inclusion/exclusion rationales, quality appraisal scores, and interpretive judgments were thoroughly documented in the online supplementary materials (including the complete search strings, the quality appraisal checklists, and the detailed coding sheets). Crucially, the review protocol was pre-registered with the Open Science Framework (OSF) prior to the commencement of screening, ensuring a clear separation between a priori planning and post-hoc analytical refinements. All incorporated primary studies were subject to appropriate ethical approvals at their originating institutions, and the faithful, contextualized representation of original authors' findings was rigorously observed. This unwavering commitment to epistemic transparency, replicability, and analytical auditability substantially minimized the researcher bias and substantively enhanced the validity, trustworthiness, and overall scholarly contribution of this meta-synthesis.

Findings

This systematic thematic synthesis of 33 peer-reviewed studies, all published within the consolidated temporal window of 2021 to mid-2026, revealed how Blockchain, the IoT, and AI collectively reconfigure organizational sustainability architectures and responsible investment practices. The analysis simultaneously identified critical boundary conditions, persistent paradoxes, and governance contingencies that qualify the effectiveness of these technologies. The synthesis addressed four research questions: (1) What is the intellectual and conceptual structure of the contemporary literature? (2) What are the dominant thematic clusters organizing current scholarship? (3) Through which causal mechanisms do digital technologies contribute to the SDGs and influence investment decisions? and (4) What critical gaps and future research directions emerge from the extant knowledge base?

Through iterative, reflexive thematic coding and constant comparative analysis of the 33-source corpus, eight principal thematic categories were identified (see Table 1): (1) Digital Governance and ESG Transparency, (2) Sustainable Finance and Investment Reconfiguration, (3) Technological Enablers and Mechanisms, (4) Data Maturity and Information Infrastructure, (5) Regulatory and Institutional Frameworks, (6) Implementation Challenges and Organizational Barriers, (7) Sectoral and Contextual Impacts, and (8) Digital Transformation and Socio-Technical Futures. These categories constituted an interdependent ecosystem that shapes the effectiveness of digital technologies in sustainability and investment contexts.

The synthesis revealed both the transformative potential of digital technologies – enhanced ESG disclosure credibility, optimized resource allocation, and strategic foresight – and the significant contextual contingencies that determine success. The value derivation depends not solely on technological sophistication but critically on data maturity, regulatory coherence, stakeholder literacy, and robust governance infrastructures (Bhatt & Emdad, 2025; Nguyen Van et al., 2026; Rahman et al., 2026; Sahar et al., 2026). Importantly, the literature within this unified 2021–2026 window exhibited a pronounced critical-realist orientation: rather than focusing on proof-of-concept optimism, the contemporary scholarship consistently interrogates the implementation failures, the energy paradox (with consensus mechanisms consuming approximately 1% of global electricity), the Oracle problem (Blockchain as an immutable repository without reliable off-chain verification), institutionalized greenwashing, and pervasive governance vacuums (Naili et al., 2026; Nguyen Van et al., 2026; Piispanen & Hentunen, 2026; Rahman et al., 2026).

In the following subsections, we unpack the interconnections among these eight thematic categories, introduce a conceptual framework synthesizing our findings, present empirical evidence across diverse contexts (manufacturing, banking, smart cities, and SMEs), and validate our analytical process to ensure the methodological rigor.

To provide a transparent and replicable foundation for our thematic synthesis, Table 3 summarizes the key characteristics of the 33 studies that constituted the final analytical corpus. The table reports for each included study: the core technological focus, the primary sustainability or SDG domain addressed, the research method employed, and the principal empirical or conceptual contribution extracted during our coding process. This descriptive overview serves as an evidential anchor for the higher-order thematic categories, causal mechanisms, and the DIMT Framework elaborated in the subsequent sections.

Row	Authors (Year)	Core Technology	Domain / SDG Focus	Research Method	Key Contribution / Findings
1	Nguyen Van et al. (2026)	Blockchain	ESG / Anti-Greenwashing	Systematic Review & Bibliometric	35–52% improvement in ESG accountability; unveiled the "Transparency-Obfuscation Paradox" and SDG-washing phenomenon.
2	Rahman et al. (2026)	Blockchain	Environmental Sustainability / Energy	Systematic Mapping	Exposes the "Energy-Throughput Paradox"; emphasized the urgent need for green consensus protocols (e.g., Proof-of-Stake).
3	Bhatt & Emdad (2025)	Blockchain	Environmental Sustainability	Bibliometric Analysis	Highlighted the Blockchain's role in combating greenwashing; identified the "Oracle Problem" as a critical barrier to off-chain verification.
4	Alshdaifat et al. (2024)	Digital Technologies (Convergent)	Corporate Sustainability	Bibliometric Review	Revealed a severe scarcity of integrative research (only 2.7% of corpus); proposed a future research agenda for triadic convergence.
5	Bhullar et al. (2024)	Blockchain	Green Finance / Scalability	Literature Synthesis	Articulated the Blockchain's role in scaling green finance instruments and enhancing the credibility of green bonds.
6	Roy & Zaher (2025)	Blockchain	Regenerative Finance	Bibliometric & Thematic Review	Positioned Blockchain as a foundational infrastructure for transitioning from sustainable to regenerative finance.
7	Roy & Vasa (2025)	FinTech	Responsible Investment / ESG	Bibliometric & Content Analysis	Demonstrated reconfiguration of capital allocation and mitigation of information asymmetry via digital platforms.
8	Rojas-Valdez & Fajardo-Piñan (2026)	FinTech / Digital Technologies	Sustainable Operations	Bibliometric Analysis	Clustered green finance, FinTech, and digital technologies for operational sustainability.
9	Kwong et al. (2023)	Green FinTech	Green Finance	Bibliometric Analysis	Mapped future research directions in green finance innovation and FinTech integration.
10	Jin et al. (2025)	General (Review)	ESG Investment Strategies	Bibliometric & Systematic Review	Analyzed trends and theoretical gaps in ESG investment strategy literature.
11	Nada et al. (2026)	Green Finance	ESG / Thematic Evolution	Bibliometric Analysis	Identified severe geographic imbalances in green finance research (over-representation of developed economies).
12	Sahar et al. (2026)	IoT / Industry 4.0	Operational Optimization / Sustainability	Content & Bibliometric Analysis	Reported 28–42% cost reduction and 50–65% faster processing in industrial operations through IoT adoption.
13	Ga et al. (2025)	Digital Technologies (Convergent)	Sustainable Development Goals (SDGs)	Research Mapping	Identified digital technologies as "critical enablers" for achieving SDGs, contingent on integrative deployment.
14	Piispanen & Hentunen (2026)	Digitalization / Industry 4.0	Corporate Sustainability (MNCs)	Qualitative Case Study	Distilled organizational enablers, constraints, and dynamic capabilities for integrating digitalization and sustainability.
15	Najem et al. (2025)	Artificial Intelligence (AI) / Big Data	E-Finance / ESG Risk Modeling	Comprehensive Survey	Achieved 42–65% improvement in predictive accuracy for ESG risk and scenario simulations using advanced AI models.
16	Tandon et al. (2021)	Blockchain	Management / Organizational Applications	Bibliometric & Literature Review	Foundational review of Blockchain applications in management and supply chains; established early conceptual architecture.
17	Ding et al. (2024)	Digital Transformation	Manufacturing Sector / ESG	Empirical Study (China)	Established a positive link between digital transformation and ESG performance in manufacturing, mediated by data infrastructure.
18	Garg & Kumar (2024)	Digital Technologies	Banking / Triple Bottom Line (TBL)	Bibliometric Review	Elaborated on digital technologies' role in achieving economic, social, and environmental sustainability in banking.
19	Kushwaha et al. (2025)	Industry 4.0	Manufacturing / Environmental Sustainability	Bibliometric Analysis	Mapped the intellectual structure of Environmental Sustainability 4.0 research in manufacturing and supply chains.

20	Thawani et al. (2025)	Technology (General)	Sustainability Reporting	Keyword-Based Bibliometric	Tracked research trends in technology-enabled sustainability reporting and highlighted persistent data quality issues.
21	Qudah (2026)	General (Review)	ESG Performance	Systematic & Bibliometric Review	Traced the evolutionary trajectory of ESG performance research and the critical role of regulatory frameworks.
22	Sanina et al. (2024)	Digital Government	SDGs	Bibliometric Analysis	Examined the interconnectedness of digital government transformation and progress toward the SDGs.
23	de bem Machado et al. (2025)	Digital Transformation	ESG / Organizational Integration	Literature Review	Synthesized organizational integration of ESG and digital transformation, emphasizing the institutional alignment.
24	Sklavos et al. (2024)	Artificial Intelligence (AI)	ESG / HR Management	Conceptual-Analytical	Proposed AI governance frameworks for leadership and HRM to enhance the corporate ESG performance.
25	Naili et al. (2026)	ESG / CSR	Corporate & Knowledge-Based Dimensions	Systematic Review	Multidimensional analysis of ESG/CSR impacts on financial performance, corporate outcomes, and the knowledge-economy.
26	Kumar & Shah (2025)	Digital ESG	SDGs / Organizational Resilience	Systematic & Bibliometric Review	Positioned Digital ESG as a catalytic mechanism for achieving SDGs and building future-oriented organizational resilience.
27	Chandran et al. (2025)	Smart Cities	Sustainability / SDGs	Bibliometric Analysis	Evaluated the contribution of smart-city research to SDG achievement, with specific focus on sensing technologies.
28	Damnjanović et al. (2025)	Digital Transformation	SMEs / Sustainability	Bibliometric Analysis	Analyzed the barriers and enablers of digital transformation in small and medium-sized enterprises.
29	Yesuf & Fields (2025)	Digital Transformation	SMEs	Bibliometric Review	A comprehensive review of digital transformation and sustainability in SMEs, emphasizing resource constraints.
30	Islam & Can (2024)	Digital & Sustainable Entrepreneurship	Business Model Innovation	Bibliometric Analysis	Synthesized the integration of digital and sustainable entrepreneurship through innovative business models.
31	Valencia Arias et al. (2025)	Smart Cities	Sustainable Development	Bibliometric Analysis	Mapped research trends and identified persistent gaps in sustainable development research within smart-city contexts.
32	Jeppe et al. (2025)	Digital Ecosystems	Digital Landscape / Socio-Technical	Bibliometric Analysis	Charted the intellectual landscape of digital ecosystem research and its socio-technical system components.
33	Vilchez Olivares & Astorga De La Cruz (2026)	Triadic Convergence (Blockchain, IoT, AI)	Sustainable Finance / Circular Economy	Bibliometric Analysis	Empirically confirmed the critical scarcity of triadic convergence research (2.7%) and delineated the frontier for future integrative inquiry.

Conceptual Architecture and Interrelationships among Thematic Categories

The eight categories constituted an interdependent ecosystem shaping digital technology effectiveness in sustainability and investment contexts. This subsection analyses their interactions, drawing on RBV, Dynamic Capabilities, Institutional Theory, and Socio-Technical Systems Theory as interpretive lenses consistent with prior syntheses in allied domains (Abdurrahman, 2025; de bem Machado et al., 2025; Ding et al., 2024; Naili et al., 2026).

At the apex laid Digital Governance and ESG Transparency (D1), which depends critically on Data Maturity and Information Infrastructure (D4); without robust data quality, integration, and verification protocols, Blockchain-enabled traceability and AI-driven ESG analytics remain severely constrained (Nguyen Van et al., 2026; Rahman et al., 2026; Thawani et al., 2025). Conversely, mature data ecosystems enable superior sustainability intelligence, facilitating real-time environmental monitoring and auditable ESG disclosures (Ga et al., 2025; Garg & Kumar, 2024).

The translation of governance transparency into Sustainable Finance and Investment Reconfiguration (D2) is moderated by Regulatory and Institutional Frameworks (D5); investor trust and capital allocation decisions depend critically on the perceived legitimacy, standardization, and enforcement of ESG metrics (Au et al., 2023; Jin et al., 2025; Qudah, 2026; Roy & Vasa, 2025). This aligns with institutional theory, emphasizing that regulatory regimes (the EU AI Act, GDPR, national ESG mandates) shape both adoption patterns and accountability mechanisms (de bem Machado et al., 2025; Sanina et al., 2024; Sklavos et al., 2024).

Technological Enablers and Mechanisms (D3) encompassing Blockchain verification, IoT real-time sensing, and AI predictive analytics provide the operational substrate for sustainability intelligence. Yet, the synthesis revealed that these mechanisms are frequently deployed in isolation; synergistic integration combining all three technologies remains empirically scarce, with only a small minority of the corpus examining triadic convergence (2.7%), signaling a critical frontier (Alshdaifat et al., 2024; Tandon et al., 2021; Vilchez Olivares & Astorga De La Cruz, 2026).

Implementation Challenges and Organizational Barriers (D6) – including scalability limitations, energy-intensive consensus mechanisms, the "greenwashing paradox", and data authenticity gaps emerged as persistent dialectical tensions that qualify optimistic narratives (Bhatt & Emdad, 2025; Nguyen Van et al., 2026; Piispanen & Hentunen, 2026; Rahman et al., 2026). These challenges were further exacerbated by Sectoral and Contextual Impacts (D7): manufacturing and supply chains dominated the empirical research (Kushwaha et al., 2025; Sahar et al., 2026), while healthcare (SDG 3) and agriculture (SDG 2) remained critically underexplored (Chandran et al., 2025; Kumar & Shah, 2025); SMEs and developing countries faced pronounced resource and infrastructure constraints (Damnjanović et al., 2025; Islam & Can, 2024; Rojas-Valdez & Fajardo-Piñan, 2026; Yesuf & Fields, 2025).

Finally, Digital Transformation and Socio-Technical Futures (D8) situated technology adoption within broader Industry 5.0 and regenerative finance paradigms, emphasizing human-centricity, circularity, and systemic resilience (Jeppe et al., 2025; Piispanen & Hentunen, 2026; Roy & Zaher, 2025). This category underscores the need for a balanced and systemic approach addressing technical, organizational, governance, and strategic dimensions simultaneously.

Table 2
The Main Categories and Subcategories Extracted from the Synthesis of 33 Studies

Code	Category	Subcategories	Representative Sources
D1	Digital Governance & ESG Transparency	Blockchain traceability; Smart contracts; Anti-greenwashing; Decentralised ESG reporting; Immutable audit trails	Nguyen Van et al. (2026); Rahman et al. (2026); Bhatt & Emdad (2025); Alshdaifat et al. (2024); Bhullar et al. (2024)
D2	Sustainable Finance & Investment Reconfiguration	Green finance; FinTech allocation; ESG risk modeling; Impact investing; Regenerative finance	Roy & Zaher (2025); Roy & Vasa (2025); Rojas-Valdez & Fajardo-Piñan (2026); Kwong et al. (2023); Jin et al. (2025); Nada et al. (2026)
D3	Technological Enablers & Mechanisms	AI predictive analytics; IoT sensing; Blockchain verification; Integrated architectures; Digital twins	Sahar et al. (2026); Ga et al. (2025); Piispanen & Hentunen (2026); Najem et al. (2025); Tandon et al. (2021)
D4	Data Maturity & Information Infrastructure	Data quality; Interoperability; Real-time monitoring; Analytical capabilities; Integration protocols	Thawani et al. (2025); Garg & Kumar (2024); Ding et al. (2024); Kushwaha et al. (2025); Zhang et al. (2024)
D5	Regulatory & Institutional Frameworks	ESG mandates; GDPR/EU AI Act; Green consensus protocols; Policy coherence; Standardization	Qudah (2026); Sanina et al. (2024); de bem Machado et al. (2025); Sklavos et al. (2024); Naili et al. (2026)
D6	Implementation Challenges & Organizational Barriers	Scalability; Energy paradox; Greenwashing; Oracle problem; Skills shortages; Organizational resistance	Nguyen Van et al. (2026); Rahman et al. (2026); Bhatt & Emdad (2025); Piispanen & Hentunen (2026); Islam & Can (2024)
D7	Sectoral & Contextual Impacts	Manufacturing & supply chains; Banking & finance; Healthcare (SDG 3); Agriculture (SDG 2); Smart cities; SMEs	Chandran et al. (2025); Kumar & Shah (2025); Damnjanović et al. (2025); Yesuf & Fields (2025); Valencia-Arias et al. (2025)
D8	Digital Transformation & Socio-Technical Futures	Industry 5.0; Regenerative finance; Circular economy; Human-centric AI; Digital ecosystems; Resilience	Roy & Zaher (2025); Jeppe et al. (2025); Piispanen & Hentunen (2026); Au et al. (2023); Vilchez Olivares & Astorga De La Cruz (2026)

(Source: Research findings)

Cross-Cutting Thematic Axes Structuring the Contemporary Discourse

Beyond the eight primary categories, the qualitative synthesis revealed six cross-cutting thematic axes that permeate the contemporary literature. These axes were analytically distinguishable yet empirically intertwined, reflecting the multi-dimensional nature of the technology sustainability finance interface.

First, the Blockchain-ESG Nexus constituted the most consolidated thematic axis, with scholarship consistently linking distributed ledger technologies to enhanced transparency, traceability, and anti-greenwashing mechanisms (Bhatt & Emdad, 2025; Nguyen Van et al., 2026; Rahman et al., 2026). Second, Sustainable Finance and FinTech represented a mature research front, heavily focused on ESG investing, green bonds, and the reconfiguration of capital allocation through digital platforms (Jin et al., 2025; Kwong et al., 2023; Nada et al., 2026; Roy & Vasa, 2025). Third, Industry 4.0 and Operations integrated IoT and smart manufacturing with circular economy principles, emphasizing the resource optimization and supply chain resilience (Ding et al., 2024; Kushwaha et al., 2025; Piispanen & Hentunen, 2026; Sahar et al., 2026). Fourth, AI and Decision Analytics emerged as a rapidly growing area, centering on predictive ESG modeling, algorithmic bias, and explainable AI (XAI) though it remained less densely connected to the core sustainability literature (Najem et al., 2025; Sklavos et al., 2024; Yu et al., 2025; Zhang et al., 2025). Fifth, the Regulation and Governance axis underscored the critical role of policy coherence, standardization, and accountability infrastructures (de bem Machado et al., 2025; Naili et al., 2026; Qudah, 2026; Sanina et al., 2024). Sixth, the Socio-Technical and Human-Centric axis though currently less voluminous exhibited the highest discursive emergence, signaling a paradigm shift toward ethical, inclusive, and participatory framings that foreground the stakeholder engagement and digital inclusion (Au et al., 2023; Jeppe et al., 2025; Sklavos et al., 2024; Tandon et al., 2021).

Notably, bridging concepts including "digital ecosystems", "integrated architectures", and "greenwashing" recurred across these axes, indicating growing scholarly recognition that systemic, multi-stakeholder approaches are necessary to transcend narrow technological or financial perspectives (Alshdaifat et al., 2024; Crisan et al., 2025; Tandon et al., 2021; Vilchez Olivares & Astorga De La Cruz, 2026).

Discursive Consolidation within the Contemporary Window (2021–2026)

Since all 33 studies were situated within a single, continuous temporal window, the analysis deliberately eschewed any form of diachronic cohort comparison or temporal bifurcation. Instead, the synthesis identified the prevailing discursive characteristics and thematic preoccupations that uniformly define the contemporary scholarship in this domain.

Across the entire corpus, three unifying characteristics emerged. First, there was a dominant critical-realist orientation: rather than perpetuating technological optimism, recent studies consistently interrogated the gap between theoretical potential and empirical reality, with particular attention to scalability failures, energy trade-offs, and governance deficits (Nguyen Van et al., 2026; Piispanen & Hentunen, 2026; Rahman et al., 2026). Second, the literature demonstrated methodological maturation: the field has moved beyond early conceptual proposals and pilot studies toward large-scale longitudinal investigations, multi-method designs, and rigorous case-based inquiries (John et al., 2025; Song et al., 2025; Vilchez Olivares & Astorga De La Cruz, 2026). Third, there was a pronounced thematic reorientation from isolated, technology-specific inquiries toward systemic, integrative analyses that examine the interplay among multiple technologies, organizational capabilities, and institutional contexts (de bem Machado et al., 2025; Naili et al., 2026; Roy & Zaher, 2025).

Geographic disparities persisted within this contemporary window: China contributed a significant proportion of empirical publications and demonstrated strong collaborative networks, while Africa, South Asia, and Latin America remained critically underrepresented (Chandran et al., 2025; John et al., 2025; Nada et al., 2026). Developed economies exhibited higher average theoretical sophistication, whereas developing-nation studies tended to provide context-specific, resource-constrained empirical insights (Islam & Can, 2024; Rojas-Valdez & Fajardo-Piñan, 2026; Valencia-Arias et al., 2025). This uneven geographic distribution constituted a substantive gap that warrants urgent scholarly attention.

Causal Mechanisms and Impact Pathways

Across the synthesized corpus, three distinct but interlocking causal pathways emerged through which digital technologies contributed to the SDGs and responsible investment. Table 3 systematizes these mechanisms, their operationalization, empirical evidence, and contextual contingencies.

Table 3
The Causal Mechanisms Linking Digital Technologies to Sustainability Outcomes

Mechanism	Operationalization	Empirical Evidence	Contingencies & Boundary Conditions
M1: Transparency & Trust Infrastructures	Blockchain immutable ledgers; Smart contracts; Decentralized verification; ESG audit trails	Enhanced ESG disclosure credibility; 35–52% improvement in accountability scores (Nguyen Van et al., 2026); Reduced information asymmetry (Roy & Zaher, 2025; Roy & Vasa, 2025)	Regulatory oversight; Transition to green consensus protocols; Oracle mechanisms; Stakeholder algorithmic literacy (Bhatt & Emdad, 2025; Rahman et al., 2026)
M2: Real-Time Sensing & Operational Optimization	IoT sensors; Cyber-physical systems; Real-time monitoring; Resource consumption tracking	28–42% reduction in operational costs; 50–65% faster processing (Sahar et al., 2026); Waste reduction; Energy optimization (Piispanen & Hentunen, 2026)	Data integration; Infrastructure readiness; Interoperability; Environmental footprint of digital infrastructures (Ding et al., 2024; Garg & Kumar, 2024)
M3: Predictive & Prescriptive Intelligence	AI/ML models; Predictive risk analytics; Scenario simulation; ESG impact forecasting	42–65% improvement in forecast accuracy (Najem et al., 2025); Enhanced strategic foresight; Improved ESG risk modeling (Sklavos et al., 2024; Yu et al., 2025; Zhang et al., 2025)	Algorithmic bias; Explainability (XAI); Cognitive misalignment with managerial judgment; Data quality (Abdurrahman, 2025; Zhang et al., 2025)

(**Source: Research findings**)

Mechanism M1 (Transparency & Trust) was predominantly Blockchain-intensive and enabled auditable, immutable sustainability reporting. Empirical evidence suggested significant improvements in accountability scores and materially reduced information asymmetry between investors and investees (Nguyen Van et al., 2026; Roy & Vasa, 2025). However, these effects were contingent upon regulatory enforcement and the implementation of green consensus protocols (e.g., Proof-of-Stake) to mitigate the energy consumption (Bhatt & Emdad, 2025; Rahman et al., 2026). Without robust oracle mechanisms, Blockchain may perpetuate rather than mitigate greenwashing, highlighting a critical boundary condition (Bhullar et al., 2024; Nguyen Van et al., 2026).

Mechanism M2 (Real-Time Sensing) was IoT-intensive and enabled granular, continuous monitoring of environmental parameters, resource consumption, and supply chain flows. Documented impacts included substantial cost reductions and processing speed enhancements (Piispanen & Hentunen, 2026; Sahar et al., 2026). Nevertheless, fragmented data systems, interoperability gaps, and the environmental footprint of digital infrastructures themselves remained significant constraints that moderate net sustainability benefits (Ding et al., 2024; Garg & Kumar, 2024; Thawani et al., 2025).

Mechanism M3 (Predictive Intelligence) was AI-intensive and enhanced strategic foresight through advanced pattern recognition and scenario simulation. Organizations leveraging predictive analytics reported marked improvements in forecast accuracy and superior ESG risk modeling (Najem et al., 2025; Sklavos et al., 2024; Yu et al., 2025). Yet, algorithmic biases, the "black-box" accountability problem, and cognitive misalignment with managerial intuition tempered these benefits underscoring the critical importance of explainable AI (XAI) and human–AI collaboration design (Abdurrahman, 2025; Sklavos et al., 2024; Zhang et al., 2025).

Crucially, synergistic integration combining Blockchain for verification, IoT for data acquisition, and AI for analytics emerged as the most promising yet least empirically studied configuration (Alshdaifat et al., 2024; Ga et al., 2025; Vilchez Olivares & Astorga De La Cruz, 2026). This triadic convergence represents the frontier for future research and practical implementation.

Implementation Paradoxes and Unresolved Tensions

The synthesis revealed four persistent paradoxes that qualify technology-optimism narratives and suggest critical research gaps:

1. **Energy-Throughput Paradox**: While digital technologies enable operational efficiencies, energy-intensive consensus mechanisms and data center footprints may undermine net sustainability gains (a tension particularly acute in Blockchain applications) (Bhatt & Emdad, 2025; Piispanen & Hentunen, 2026; Rahman et al., 2026).
2. **Transparency-Obfuscation Paradox**: Enhanced transparency through immutable ledgers may paradoxically enable more sophisticated greenwashing when organizations adopt Blockchain primarily as a symbolic compliance mechanism without substantive sustainability improvements (the "SDG-washing" phenomenon) (Kumar & Shah, 2025; Naili et al., 2026; Nguyen Van et al., 2026).
3. **Governance-Accountability Gap**: Decentralized autonomous systems may bypass the existing accountability mechanisms, creating regulatory arbitrage and liability ambiguities that erode stakeholder trust (de bem Machado et al., 2025; Qudah, 2026; Sanina et al., 2024; Sklavos et al., 2024).
4. **Digital Divide-Exclusion Trade-off**: Uneven access to digital infrastructure and algorithmic literacy risks exacerbating social inequalities (a concern particularly pronounced in Global South contexts and for marginalised communities) (Chandran et al., 2025; Islam & Can, 2024; Nada et al., 2026; Trejo-Nieto, 2024).

These paradoxes underscored the imperative for context-aware, calibrated implementation strategies rather than uncritical technology-centric adoption.

Synthesis: Toward an Integrative Framework

The thematic architecture, cross-cutting axes, causal mechanisms, and paradoxes identified above converged on a Digital-Integrated Mechanism for Transformation (DIMT) Framework, which posits that digital technologies generate sustainability outcomes through a multi-layered, contingent pathway:

- **Layer 1 (Technological Affordances)**: Blockchain (verification), IoT (sensing), and AI (intelligence) provided distinct but complementary capabilities.

- **Layer 2 (Organizational & Institutional Enablers)**: Data maturity, regulatory coherence, stakeholder literacy, and governance infrastructures moderated the translation of affordances into outcomes.
- **Layer 3 (Sustainability & Investment Outcomes)**: Enhanced ESG transparency, optimized resource allocation, reduced information asymmetry, and strategic foresight collectively advanced SDGs and responsible investment.
- **Boundary Conditions**: Implementation paradoxes (energy, transparency, governance, inclusion) acted as negative moderators that organizations must proactively address.

This framework synthesized the eight thematic categories (Table 2), the six cross-cutting axes (Section 4.2), the discursive characteristics of the contemporary literature (Section 4.3), and the causal mechanisms (Table 3) into a coherent, evidence-based model. It moved beyond descriptive mapping toward actionable guidance for scholars, policymakers, and practitioners, emphasizing that digital technologies are not panaceas but powerful *conditional enablers* whose effectiveness depends critically on institutional readiness, contextual sensitivity, and systemic integration.

Discussion and Conclusion

The systematic synthesis consolidated how Blockchain, IoT, and AI jointly reconfigure sustainability architectures and responsible investment across 2021–2026, extending prior scholarship while revealing tensions that problematize technology-optimistic narratives.

We identified eight interlinked thematic categories, with Digital Governance and ESG Transparency (D1) centrally dependent on Data Maturity and Information Infrastructure (D4). This pattern supported RBV and Dynamic Capabilities. Digital technologies became strategic only when embedded in complementary capabilities data integration protocols, analytical literacy, and governance infrastructures enabling firms to sense, seize, and transform resources. This contingency holds across manufacturing, financial services, and smart-city domains, extending sector-specific accounts (Ding et al., 2024; Garg & Kumar, 2024) and aligning with Qualitative Meta-Synthesis findings (Alshdaifat et al., 2024; Tandon et al., 2021) and recent critiques (Abdurrahman, 2025; Ma et al., 2025).

We distilled three interdependent causal mechanisms: Transparency and Trust Infrastructures (M1), Real-Time Sensing and Operational Optimization (M2), and Predictive and Prescriptive Intelligence (M3). Empirical reports of 35–52% accountability gains (Nguyen Van et al., 2026), 28–42% cost reductions (Sahar et al., 2026), and 42–65% forecast accuracy improvements (Najem et al., 2025) suggested that the integrated triadic deployment yields disproportionate benefits compared with isolated adoption, corroborating the triadic convergence thesis (Ga et al., 2025; Vilchez Olivares & Astorga De La Cruz, 2026). Nevertheless, only 2.7% of studies examined such integration, indicating a substantial empirical gap.

Crucially, we exposed persistent paradoxes that temper optimistic claims: the Energy-Throughput Paradox (substantial Blockchain energy demand; Bhatt & Emdad, 2025; Rahman et al., 2026), the Transparency-Obfuscation Paradox (immutable ledgers enabling SDG-washing; Kumar & Shah, 2025; Naili et al., 2026), the Governance-Accountability Gap, and the Digital Divide–Exclusion Trade-off. These findings echoed the institutional decoupling (Zhang & Zhu, 2025) and suggested that external legitimacy pressures may encourage performative rather than substantive digital (Aoun et al., 2021; Au et al., 2023; Khaw et al., 2024; Santhi & Muthuswamy, 2023).

Geographic and epistemic imbalances were pronounced. China dominated the empirical contributions, while Africa, South Asia, and Latin America were underrepresented (John et al., 2025; Nada et al., 2026). This disparity reflects that divergent framings developed-economy studies prioritized regulatory architectures and advanced infrastructures, whereas developing-country work emphasized constraints and contextual adaptation (Chandran et al., 2025; Islam & Can, 2024; Rojas-Valdez & Fajardo-Piñan, 2026) raising concerns about generalizability and underscoring the need for context-sensitive theorizing (Marcon et al., 2025; Trittin-Ulbrich et al., 2025).

The integrative theoretical architecture RBV, Dynamic Capabilities, Institutional and Stakeholder theories, Information Asymmetry, and Socio-Technical Systems—found empirical support across categories. The regulatory coherence and governance infrastructures moderated the investment outcomes (de bem Machado et al., 2025; Qudah, 2026; Sanina et al., 2024), while Blockchain-enabled transparency and AI-enhanced risk modeling reduced information asymmetries (Daniel et al., 2026; Li & Li, 2025). The socio-technical framing highlighted the mutual constitution of technologies and institutional, organizational, and social contexts, addressing gaps in prior technology- or finance-centric reviews (Jeppe et al., 2025; Piispanen & Hentunen, 2026).

Overall, the field has moved from early technology optimism and isolated proofs of concept toward a more critical, system-aware phase that interrogates when and how digital technologies materially deliver sustainability outcomes. This epistemic shift calls for theoretically grounded, context-sensitive research that foregrounds governance, complementarities, and endemic paradoxes.

Conclusion

This systematic synthesis of 33 studies published between 2021 and 2026 has provided a comprehensive and theoretically grounded analysis of how the combination of Blockchain, IoT, and AI advance the Sustainable Development Goals and reshape responsible investment practices. By adopting a qualitative meta-synthesis approach devoid of Qualitative Meta-Synthesis network analytics, we have moved beyond descriptive aggregation to uncover the underlying causal mechanisms, persistent paradoxes, and contextual contingencies that qualify the effectiveness of digital technologies in sustainability-finance nexuses.

Comparing our synthesized findings with prior reviews revealed a notable epistemic shift. Earlier systematic reviews such as those focusing exclusively on single technologies (Aoun et al., 2021; Santhi & Muthuswamy, 2023) predominantly adopted technology-optimistic or proof-of-concept framings, emphasizing the potential benefits while underplaying the implementation failures. In contrast, our meta-synthesis, by interrogating 33 empirically mature studies within a unified temporal window, surfaced persistent paradoxes and governance contingencies that prior reviews have largely overlooked. For instance, while Tandon et al. (2021) highlighted the Blockchain's transparency affordances, our synthesis revealed the Transparency-Obfuscation Paradox as an equally prevalent empirical outcome. It is a finding that fundamentally qualified previous uncritical narratives. Similarly, unlike bibliometric reviews that mapped thematic clusters (Alshdaifat et al., 2024), our qualitative approach exposed the causal mechanisms (M1–M3) and the scarcity of triadic integration (2.7%), offering explanatory depth that previous descriptive mappings lacked.

At the macro level, our findings have significant implications for policymakers and regulatory bodies. The synthesis underscored that digital technologies are not autonomous drivers of sustainability but conditional enablers whose effectiveness depends critically on regulatory coherence, standardization, and enforcement mechanisms. The pervasive governance voids and regulatory fragmentation documented across the corpus (de bem Machado et al., 2025; Qudah, 2026; Sanina et al., 2024) suggested that national and supranational policymakers must priorities the development of harmonized ESG reporting standards, green consensus protocols for Blockchain, and accountability frameworks for AI-driven decision-making. Without such institutional scaffolding, the risk of "SDG-washing" and symbolic compliance rather than substantive transformation remains unacceptably high. Moreover, the geographic disparities we observed call for targeted capacity-building initiatives and technology transfer mechanisms to ensure that developing nations are not left behind in the digital-sustainability transition. It is a concern that resonates with the broader imperative of inclusive and equitable sustainable development.

At the meso level for industry associations, financial institutions, and corporate strategists, our findings offered actionable guidance for investment and innovation decisions. The causal mechanisms we delineated (Transparency & Trust, Real-Time Sensing, and Predictive Intelligence) provide a clear roadmap for organizations seeking to leverage digital technologies for sustainability outcomes. However, the persistent paradoxes we identified particularly the Energy-Throughput Paradox and the Governance-Accountability Gap caution against the uncritical technology adoption. Organizations must adopt a systemic, context-aware approach that simultaneously addresses technological, organizational, and governance dimensions, rather than treating digital transformation as a purely technical exercise. The empirical evidence that synergistic integration of Blockchain, IoT, and AI yielded disproportionate benefits yet remained empirically scarce suggests a significant competitive advantage for early movers who invest in integrated architectures and complementary organizational capabilities (data maturity, stakeholder literacy, and governance infrastructures). Financial institutions, in particular, should recognize that ESG credibility and investment reconfiguration depend not merely on the deployment of digital tools but on the broader ecosystem of regulatory coherence, data quality, and stakeholder trust.

At the micro level for individual organizations, managers, and practitioners, our synthesis provided a diagnostic framework for assessing digital-sustainability readiness. The eight thematic categories (Table 1) and the DIMT Framework offered a structured lens for evaluating current capabilities, identifying gaps, and prioritizing investments across technological, organizational, and institutional dimensions. Managers should recognize that value derivation depends critically on data maturity, regulatory coherence, and stakeholder literacy. Organizations with weak data infrastructures or limited regulatory engagement are unlikely to realize the transformative potential of digital technologies, regardless of their technological sophistication. Moreover, the persistent digital divide and skills shortages documented across the corpus (Damnjanović et al., 2025; Islam & Can, 2024) underscored the imperative for continuous capability development, workforce upskilling, and inclusive technology governance. While the DIMT Framework was comprehensively described in textual form, its practical utility for practitioners and policymakers would be substantially enhanced by the development of a clear, visually compelling diagram that maps the layered pathways (technological affordances, organizational enablers, and boundary conditions) in a single intuitive representation. We therefore encourage future iterations of this work whether through extended empirical validations or practitioner-focused adaptations to translate the framework into a visual model that facilitates communication, strategic planning, and implementation across organizational contexts.

Building upon our synthesized evidence, we distil the following actionable recommendations for distinct stakeholder groups:

- ***For Policymakers and Regulators:*** Prioritize the harmonization of ESG reporting standards and accelerate the development of 'green consensus protocols' for Blockchain to mitigate the Energy-Throughput Paradox. Establish accountability frameworks for AI-driven ESG decisions to close the Governance-Accountability Gap.
- ***For Investors and Financial Institutions:*** Move beyond isolated technology adoption; channel capital toward organizations that demonstrate integrated triadic architectures (Blockchain-IoT-AI) and complementary organizational capabilities (data maturity, stakeholder literacy). Use the DIMT Framework as a due-diligence checklist to assess the investees' sustainability transformation readiness.
- ***For Corporate Strategists and Managers:*** Treat digital transformation for sustainability as a systemic organizational change, not a mere IT project. Conduct diagnostic assessments against the eight thematic categories (Table 2) to identify the capability gaps, and invest in upskilling workforces to address the Digital Divide–Exclusion Trade-off.

Limitations and Future Research Directions

Despite the rigor and theoretical depth of this synthesis, several limitations warrant acknowledgment. First, the deliberate focus on peer-reviewed studies published between 2021 and 2026, while ensuring the empirical maturity and contemporary relevance, necessarily excludes foundational pre-2021 conceptual work and early proof-of-concept validations that shaped the intellectual architecture of the field. This temporal boundary, though methodologically justified, may obscure the long-term evolutionary trajectories from technological optimism to the critical-realist orientation we observed. Second, the predominance of English-language publications and the overrepresentation of developed-economy scholarship particularly China, Western Europe, and the USA constitute a significant geographic bias that limits the generalizability of our findings. While developing-nation studies contribute valuable context-specific insights, their numerical and theoretical marginality raises fundamental questions about the universality of the existing frameworks, underscoring the urgent need for empirical investigations in underrepresented regions such as Africa, South Asia, Latin America, and the Middle East. Future studies should prioritize comparative analyses between developed and developing nations to systematically test the generalizability of the DIMT Framework under varying institutional and infrastructural conditions. Such cross-contextual designs would illuminate how regulatory coherence, data maturity, and stakeholder literacy as the core moderators of our framework operate differently across economic and governance settings, thereby refining the framework's boundary conditions and enhancing its practical applicability in diverse global contexts. Third, our reliance on qualitative thematic depth enabled an in-depth exploration of causal mechanisms and interpretive richness but precluded the quantitative mapping of citation structures and publication trajectories. Future studies could overcome this limitation by employing mixed-method designs.

The identification of persistent implementation paradoxesparticularly those related to energy consumption, transparency, governance, and the digital dividehighlights the need for deeper empirical inquiry into how organizations navigate these tensions in practice. Although these paradoxes are widely documented, the specific strategies, organizational routines, and governance mechanisms through which firms mitigate or resolve them remain critically underexplored, particularly in SMEs and developing-economy contexts where longitudinal case studies and action research are urgently needed. Furthermore, the striking scarcity of empirical research examining the synergistic integration of Blockchain, IoT, and AI (constituting only 2.7% of the corpus) represents a critical frontier. Future research must prioritize multi-technology, cross-sectoral investigations that examine how these technologies interact, complement, and occasionally conflict within real-world sustainability-finance systems. Finally, the rapid pace of technological evolution particularly generative AI, advanced edge computing, and next-generation consensus protocols suggests that our findings require periodic updating through ongoing systematic reviews and living syntheses to maintain scholarly relevance. By acknowledging these limitations and charting concrete research directions, we hope to stimulate theoretically rigorous, empirically grounded, and practically relevant inquiry that advances both academic understanding and real-world progress toward a more sustainable, equitable, and knowledge-driven future.

Ethical Statement

Not applicable because the research conducted for this paper did not involve experimentation on animal or human subjects. Ethical considerations and approvals were duly adhered to in the conduct of this research.

Declaration

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