

Industry 4.0 and Sustainability: A Systematic Review on Advanced Technologies and Collaborative Models

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Abstract

INTRODUCTION: Industry 4.0 (I4.0) technologies demonstrate strong potential to enhance sustainable industrial practices; however, their holistic and integrated application across sustainability dimensions remains insufficiently explored in the literature.

OBJECTIVES: This paper aims to analyse how Industry 4.0 technologies contribute to sustainability across environmental, economic, and social dimensions, identifying dominant technologies, sectoral adoption patterns, existing gaps, and alignment with the United Nations Sustainable Development Goals (SDGs).

METHODS: A systematic literature review of 32 peer-reviewed articles published between 2015 and 2025 was conducted using the PRISMA framework. The study combines bibliometric analysis with qualitative content analysis to assess technological contributions, sectoral applications, and sustainability outcomes.

RESULTS: The results show that IoT and Artificial Intelligence are the most frequently adopted I4.0 technologies, predominantly contributing to environmental (78% of studies) and economic sustainability. Social sustainability remains underrepresented, appearing in only 25% of the analysed studies. Manufacturing and energy sectors lead adoption, while agri-food and construction sectors lag despite their high potential. Major challenges include data privacy risks associated with IoT and scalability limitations of Blockchain technologies, with mitigation strategies focusing mainly on SME-oriented adoption models.

CONCLUSION: The findings highlight the need for a more balanced deployment of Industry 4.0 technologies that equally addresses environmental, economic, and social dimensions of sustainability. Future research should prioritize the development of measurable social impact indicators and integrated technological-policy frameworks to support inclusive and sustainable industrial transformation aligned with the UN SDGs.

Keywords: I4.0, Digital Transformation, Sustainable Manufacturing, Smart Technologies

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1. Introduction

Contemporary industry faces unprecedented challenges, marked by the need to reconcile technological innovation with sustainable practices. In a global context where environmental, economic, and social pressures are intensifying, the adoption of solutions that promote efficiency and responsibility has become imperative.

Industry 4.0, a concept encompassing the digitization and automation of industrial processes through advanced technologies, emerges as a catalyst for this transformation. However, its implementation is not without complexities, requiring a balanced approach that integrates technological progress with a commitment to sustainability [1].

Industry 4.0, also referred to as the Fourth Industrial Revolution, redefines production paradigms through the integration of cyber-physical systems, the Internet of Things (IoT), artificial intelligence, big data, and other

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emerging technologies. These innovations not only optimize operational efficiency but also pave the way for more flexible and customized production models. Nevertheless, their impact transcends the economic sphere, directly influencing environmental and social pillars. The convergence between these technologies and sustainability has garnered increasing interest in both academic and industrial sectors, given their potential to mitigate negative impacts and promote more responsible practices [2]. This article conducts a Systematic Literature Review (SLR) with the aim of exploring the state of the art of Industry 4.0 technologies applied to sustainability. The adopted methodology follows the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines, ensuring rigor and transparency in the selection and analysis of studies. The analysis period covers relevant publications since the emergence of the Industry 4.0 concept, with a particular focus on the last decade, and draws on reputable scientific databases. The methodological approach includes the identification, screening, and critical synthesis of studies, providing a comprehensive and up-to-date perspective on the topic. Despite the growing volume of research on Industry 4.0 and sustainability, a gap persists in the literature regarding the integrated analysis of these two domains. Most studies tend to focus on specific technologies or isolated impacts, neglecting the interconnection between digitization and sustainable practices. This article aims to address this gap by offering a perspective that articulates technological advancements with the challenges of sustainability. Its relevance is twofold: on the one hand, it contributes to the body of academic knowledge by proposing a critical synthesis and identifying future trends; on the other, it provides insights for industry, suggesting pathways for the implementation of collaborative and sustainable models. In summary, this study not only highlights the importance of the convergence between Industry 4.0 and sustainability but also reinforces the need for a systemic approach that integrates technological innovation with environmental, economic, and social responsibility. Through this systematic review, it is hoped to foster academic debate and inspire industrial practices more aligned with the challenges of the 21st century.

2. Systematic Literature Review

2.1. Method

The selection of the PICO methodology (Population, Intervention, Comparison, Outcome) as the framework for conducting this Systematic Literature Review is justified by its capacity to structure the research process in a clear, objective, and methodologically rigorous manner. This approach enables a comprehensive and focused analysis of the study's core research questions, addressing limitations commonly associated with narrative reviews, such as subjectivity and the lack of a standardized structure. A

systematic review, by contrast, is grounded in a well-defined research question that guides the selection, critical appraisal, and synthesis of relevant studies, thereby enhancing the robustness and transparency of the overall process.

Within this context, the population defined for this study comprises organizations and industrial sectors that are either in the process of implementing, or are considering the implementation of, technologies associated with Industry 4.0, with the explicit aim of fostering sustainable practices. This delineation allows the research to target contexts in which the convergence between technological innovation and sustainability is particularly salient, thereby facilitating the extraction of meaningful insights regarding the environmental, social, and economic implications of such integration.

The intervention under investigation pertains to the deployment of emerging Industry 4.0 technologies—such as cyber-physical systems, the Internet of Things (IoT), artificial intelligence, big data analytics, and intelligent automation—with the explicit objective of promoting sustainability within industrial processes. This intervention is intended not only to enhance operational efficiency but also to promote environmental and social responsibility. Its selection is informed by the growing academic and industrial interest in understanding how these technologies may serve as strategic enablers in the transition towards more sustainable production models.

The comparative analysis will be conducted between organizations and sectors that actively adopt these technologies with a clear orientation towards sustainability, and those that, despite utilizing Industry 4.0 solutions, do not exhibit a comparable commitment to sustainable practices. This comparative perspective is essential for identifying divergences in approaches, outcomes, and impacts—both beneficial and adverse—thus enabling the identification of critical success factors for the effective integration of digitalization and sustainability.

The anticipated outcome of this research is the identification of key Industry 4.0 technologies that contribute to sustainable practices, a critical evaluation of their impacts across environmental, social, and economic dimensions, and the characterization of industrial sectors that derive the greatest benefit from such approaches. The intention is to generate knowledge that informs both the academic community and business decision-makers in the formulation and adoption of technology strategies aligned with the principles of sustainable development.

The inclusion of studies in this review was guided by the PICO framework, employing clearly defined inclusion and exclusion criteria. The identification of relevant literature commenced with an exhaustive bibliographic search, followed by a screening process based on titles and abstracts, with the aim of identifying studies that explicitly address the intersection between Industry 4.0 and sustainability. The database search was conducted covering publications from 2015 to early 2025. No language filters other than English were applied, and only peer-reviewed journal articles were considered. Studies not aligned with

the scope of this investigation were excluded, resulting in a final sample of articles with substantial contributions to the field.

The database utilized for sourcing the literature was the “B-on” platform, selected for its comprehensive coverage and access to high-quality, peer-reviewed scientific publications indexed in internationally recognized repositories such as ISI Web of Science and Scopus. This choice ensured the methodological rigor and contemporaneity of the literature reviewed, thereby providing a solid foundation for the development of the systematic review.

The application of the PICO methodology proved instrumental in maintaining a coherent link between the research questions and the empirical evidence retrieved from the literature. This structured approach enabled a critical and comparative analysis support-ed by empirical data.

The central research questions guiding this investigation were clearly articulated, as follows:

Research Questions (RQs):

RQ1: How can the broad concept of sustainability be associated with Industry 4.0?

RQ2: In this context, which advanced technologies can effectively contribute to promoting sustainability within industrial and engineering processes?

RQ3: Which industrial sectors stand to benefit the most from this approach?

To undertake the underlying research process, the investigators accessed the scientific digital library provided by the Foundation for Science and Technology, focusing on three distinct groups (Group 1, Group 2, and Group 3), as outlined in Table 1.

Table 1. Groups searched through “B-on”.

Research Strings	
Group 1	“Sustainability” Or “Sustainable” Or “Social Sustainability” Or “Environment” Or “Environmental Sustainability” Or “Economic Sustainability” Or “Sustainable Development” Or “Eco-friendly” Or “Green Practices” Or “Sustainable Growth” Or “Environmental Conservation” Or “Ecological Balance” Or “Sustainable Practices” Or “Sustainable Economy” Or “Sustainable Living” Or “Environmental Protection” Or “Social Responsibility” Or “Green Development” Or “Sustainable Business” Or “Climate Action” Or “Corporate Sustainability” Or “Environmental Stewardship” Or “Eco-conscious” Or “Sustainable Innovation” Or “Resilient Development” Or “Circular Economy”

AND	
Group 2	“Industry 4.0” Or “I4.0” Or “Industry 4.0 Technologies” Or “Industry 4.0 Applications” Or “Industry 4.0 Framework” Or “Industry 4.0 Implementation” Or “Industry 4.0 Adoption” Or “Industry 4.0 Strategy” Or “Industry 4.0 and Sustainability” Or “Industry 4.0 in Manufacturing” Or “Industry 4.0 in SMEs” Or “Industry 4.0 Integration” Or “Industry 4.0 Challenges” Or “Industry 4.0 Opportunities” Or “Industry 4.0 Transformation” Or “I4.0 Implementation” Or “I4.0 Strategy” Or “I4.0 Adoption” Or “I4.0 in Manufacturing” Or “I4.0 Technologies”
AND	
Group 3	“Advanced Technologies” Or “Disruptive Technologies” Or “Emerging Technologies” Or “Enabling Technologies” Or “Supervision Systems” Or “Monitoring Systems” Or “Control Systems” Or “Automation Systems” Or “Smart Systems” Or “Digital Technologies” Or “Innovative Technologies” Or “High-Tech Solutions” Or “Next-Generation Technologies” Or “Real-Time Monitoring” Or “Remote Supervision” Or “Cyber-Physical Systems Supervision” Or “AI-based Supervision” Or “Intelligent Monitoring Systems” Or “Digital Control Systems” Or “Industrial Monitoring” Or “Smart Control Systems” Or “Blockchain” Or “Artificial Intelligence” Or “Machine Learning” Or “Deep Learning” Or “Edge Computing” Or “Quantum Computing” Or “5G Technology” Or “Internet of Things (IoT)” Or “Industrial IoT” Or “Augmented Reality (AR)” Or “Virtual Reality (VR)” Or “Robotics” Or “Autonomous Systems” Or “Cloud Computing” Or “Big Data” Or “Blockchain Technology” Or “Cybersecurity Technologies” Or “Digital Twins” Or “Advanced Analytics”

The research queries were conducted using the “B-on” platform, employing the OR operator to link the Title, Keywords (KW), or Abstract (AB) within the three specified groups. Subsequently, during the research process, filters were applied based on the ac-quired publication sets, and the results, in terms of the number of publications, are summarized in Figure 1. This model allows you to identify the most relevant studies by clearly defining the main elements of the investigative focus, which increases the precision and relevance of the search strategy. To ensure transparency and the possibility of reproducing the selection process, the organization of the data — including screening, inclusion and exclusion of studies — followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. PRISMA offers a standardized checklist and a flow diagram (as shown in Figure 1), which help to present in a clear and detailed way how studies were located, evaluated and selected for review, strengthening the methodological rigor and credibility of the results.

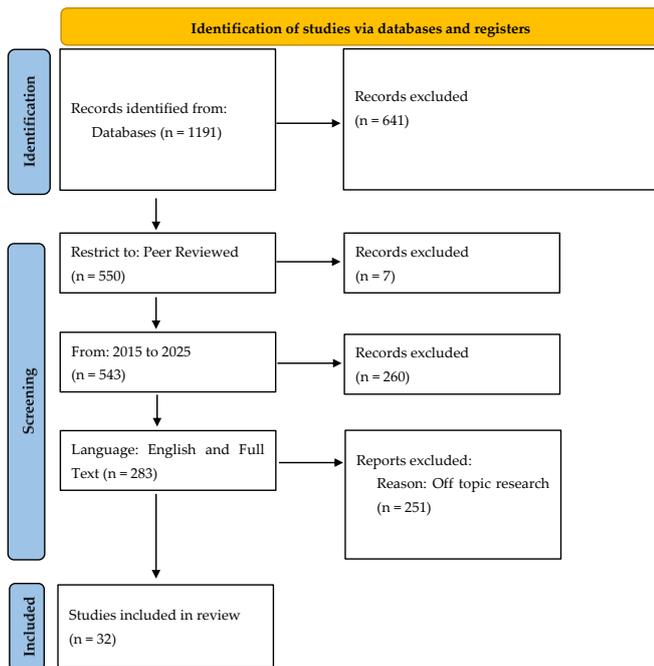


Figure 1. Flow diagram of literature search and respective screening

Following the application of the filters, a review was conducted of the titles, keywords, and abstracts of each article to identify those directly relevant to the research. Initially, a total of 1191 articles were retrieved. After the application of the filters, 283 articles remained, of which only 32 were found to be aligned with the research topic. In line with the PRISMA guidelines, the selection process comprised four stages: identification, screening, eligibility and inclusion. During the identification stage, all records retrieved from the B-on platform were exported and duplicates were removed. In the screening stage, titles and abstracts were examined to exclude obviously irrelevant studies. In the eligibility stage, the full texts of potentially relevant articles were assessed against predefined inclusion and exclusion criteria: Criterion type: Inclusion – Topic. Description: Studies explicitly addressing Industry 4.0 (or related terms such as “digital transformation”, “smart manufacturing”) in connection with at least one sustainability dimension (environmental, economic, or social). Inclusion – Document type: Peer-reviewed journal articles. Inclusion – Language: English. Inclusion – Time period: Published between 2015 and 2025. Inclusion – Accessibility: Full-text available through the B-on platform (indexed in databases such as Web of Science and Scopus). Exclusion – Document type: Conference papers, book chapters, theses, reports, editorials and non-peer-reviewed documents. Exclusion – Topic: Studies focusing only on general Industry 4.0 concepts without explicit sustainability outcomes, or only on sustainability without any reference to Industry 4.0 technologies. Exclusion – Sectoral scope: Studies centred exclusively on non-

industrial domains (e.g., education, healthcare) with no industrial or production-related context. Only studies that explicitly addressed the relationship between Industry 4.0 technologies and at least one sustainability dimension (environmental, economic or social) were retained for inclusion in the final sample of 32 articles.

3. Analysis of Technological Convergence and Applications in Industry 4.0

This section examines the interplay between Industry 4.0 (I4.0) technologies and sustainability, focusing on their convergence across environmental, social, and economic dimensions. By systematically mapping technological applications and identifying thematic clusters, this analysis aims to elucidate how digital transformation can drive sustainable industrial practices.

A structured review of the 32 selected articles was conducted, employing:

1. Technological Mapping: Classification of technologies by sustainability pillars.
2. Co-Occurrence Network Analysis: Visualization of keyword relationships using VOS viewer.
3. Trend and Gap Analysis: Identification of underexplored areas and temporal shifts in research focus.

For the analysis, of the 32 selected articles were exported from the B-on platform. The resulting keyword map was used to identify thematic clusters related to environmental, economic and social sustainability within the Industry 4.0 context. Table 2 synthesizes the frequency of I4.0 technologies linked to each sustainability pillar, based on the reviewed literature.

Table 2. Industry 4.0 Technologies and Their Sustainability Impacts.

Technology	Environmental (No. of Articles)	Social (No. of Articles)	Economic (No. of Articles)	Key Applications
IoT	18 Articles [1, 2, 4, 6, 8, 11, 16, 17, 19, 22, 23, 25, 26, 27, 28, 29, 30, 32]	12 Articles [2, 8, 11, 16, 19, 20, 22, 23, 25, 27, 29, 32]	20 Articles [1, 2, 4, 6, 7, 8, 11, 13, 16, 17, 19, 21, 22, 23, 25, 26, 27, 28, 29, 32]	Real-time monitoring of emissions (Env), worker safety (Soc), predictive maintenance (Eco).
Big Data & AI	15 Articles [1, 4, 7, 10, 13, 14, 16, 17, 19,	8 Articles	22 Articles	Energy optimisation (Env),

Technology	Environmental (No. of Articles)	Social (No. of Articles)	Economic (No. of Articles)	Key Applications
	21, 23, 25, 26, 28, 29]	[7, 10, 14, 19, 20, 23, 25, 29]	[1, 4, 7, 10, 11, 13, 14, 16, 17, 19, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32]	labour upskilling (Soc), supply chain resilience (Eco).
Digital Twins	10 Articles [6, 7, 9, 12, 16, 17, 21, 23, 25, 29]	5 Articles [7, 9, 12, 20, 29]	14 Articles [6, 7, 9, 12, 13, 16, 17, 21, 22, 23, 24, 25, 29, 31]	Simulation of eco-efficient processes (Env), virtual training (Soc), cost reduction (Eco).
Blockchain	6 Articles [5, 15, 18, 24, 27, 28]	3 Articles [15, 18, 28]	9 Articles [5, 15, 18, 21, 24, 27, 28, 29, 31]	Transparent sourcing (Env), fair labour tracking (Soc), fraud reduction (Eco).
Robotics	7 Articles [3, 7, 12, 19, 22, 25, 30]	6 Articles [3, 12, 19, 20, 22, 30]	11 Articles [3, 7, 12, 19, 21, 22, 24, 25, 28, 29, 30]	Waste reduction (Env), hazardous task automation (Soc), productivity gains (Eco).

- IoT and Big Data dominate economic applications (e.g., 70% of articles cite supply chain optimisation), while their social potential (e.g., safety, upskilling) remains underexplored (only 38% coverage).
- Blockchain shows promise for environmental transparency but lacks empirical validation in social contexts (e.g., only 3 articles address fair labour practices).

A bibliometric analysis of article keywords (Figure 2) reveals three dominant clusters:

1. Green Technologies:
 - Terms: Circular Economy, Energy Efficiency, IoT.
 - Focus: Environmental sustainability through smart monitoring and waste reduction (e.g., Articles 1, 4, 16).
2. Human-Centric Systems:
 - Terms: Workforce 4.0, Safety, Augmented Reality.

- Focus: Social impacts, such as reskilling and ergonomic automation (e.g., Articles 19, 20).
- 3. Economic Optimisation:
 - Terms: Supply Chain 4.0, Cost Reduction, Digital Twins.
 - Focus: Economic resilience via predictive analytics (e.g., Articles 7, 21).

The weak link between "2. Human-Centric Systems" and "1. Green Technologies:" highlights a research gap in the integration of social and environmental goals.

1. Underexplored Technologies:
 - Edge Computing: Only 2 articles (6.25%) address its role in decentralised sustainability management.
 - 5G: Limited discussion on enabling real-time eco-efficient systems (3 articles).
2. Temporal Shifts:
 - 2015–2018: Focus on conceptual frameworks (e.g., Articles 3, 12).
 - 2019–2025: Empirical studies dominate, particularly in IoT and AI (e.g., Articles 7, 26).
3. Critical Gap:
 - Social Sustainability: Just 25% of articles (8/32) quantify metrics like job quality or inclusivity, indicating a need for interdisciplinary studies.

The analysis demonstrates that I4.0 technologies predominantly target economic and environmental outcomes, often side-lining social dimensions. For instance:

- IoT’s triple role: While 56% of articles highlight IoT’s environmental benefits (e.g., Article 1’s waste reduction case), its potential for equitable workforce development (e.g., Article 20) is marginalised.
- Discrepancy in adoption: High-cost technologies (e.g., Digital Twins) are disproportionately adopted in capital-intensive sectors (e.g., automotive), neglecting SMEs (addressed in only 4 articles).

A systemic approach—aligning technological deployment with the United Nations Sustainable Development Goals (SDGs)—is essential to balance the triple bottom line.

4. Analysis of Practical Applications

This section evaluates empirical evidence from the reviewed literature to identify how Industry 4.0 (I4.0) technologies have been applied to enhance sustainability across industrial sectors. By analysing sectoral adoption patterns, collaborative models, and implementation challenges, this study highlights actionable insights for practitioners and policymakers.

Table 3. Sectoral Applications of I4.0 Technologies.

Sector	Advanced Adoption (Articles)	Underexplored Potential (Articles)	Exemplary Cases
Manufacturing	[1, 2, 3, 6, 7, 12, 13, 16, 17, 21, 23, 25, 29]	[5, 9, 15]	Digital Twins for zero-waste production (Env: [7, 16]); AI-driven quality control (Eco: [21]).
Energy	[4, 10, 14, 26, 31]	[18, 22]	IoT-enabled smart grids (Env: [4, 26]); Blockchain for renewable energy trading (Eco: [18]).
Logistics	[8, 11, 20, 24, 27, 28]	[19, 30]	Autonomous vehicles for emission reduction (Env: [8]); AR for warehouse safety (Soc: [20]).
Agri-Food	[5, 15, 18]	[9, 22, 32]	Blockchain for farm-to-table traceability (Env/Soc: [15, 18]).

Sector	Advanced Adoption (Articles)	Underexplored Potential (Articles)	Exemplary Cases
Construction	[9, 22]	[3, 12, 19]	Robotics for material recycling (Env: [9]); Digital Twins for site safety (Soc: [22]).

- Manufacturing dominates I4.0 adoption (41% of articles), with a strong focus on environmental efficiency (e.g., [1, 16]).
- Agri-Food and Construction exhibit the highest untapped potential, particularly in social sustainability (e.g., only [15, 22] address labour conditions).

Three partnership archetypes emerged from the literature:

1. Industry-Academia-Government (Triple Helix)
 - Case: The EU's "Smart Factory" initiative ([12, 23]) combined university re-search (digital twin development), corporate funding (Siemens, Bosch), and public subsidies to reduce industrial CO₂ emissions.
 - Outcome: 30% energy savings in pilot plants (Env), with knowledge spill overs to SMEs (Eco).
2. Cross-Sector Consortia
 - Case: The Energy Web Foundation ([18, 26]) united energy firms (Shell), tech providers (IBM), and NGOs to deploy blockchain for renewable energy markets.
 - Impact: Increased transparency in carbon credit trading (Env), though limited worker engagement (Soc gap).
3. Open Innovation Platforms
 - Case: Siemens Mind Sphere ([7, 21]) enabled SMEs to access IoT tools for sustainable process optimisation, supported by government grants.
 - Challenge: Scalability issues due to high upfront costs (cited in [21, 24]).

Successful collaborations prioritise standardisation (e.g., common data protocols in [27, 28]) and policy alignment (e.g., EU Green Deal incentives in [4, 17]). Table 4 synthesises recurrent implementation challenges and mitigation strategies from the reviewed articles.

Table 4. Challenges and Solutions in Sustainable I4.0 Deployment.

Barrier	Frequency (No. of Articles)	Proposed Solutions (Exemplary References)
High Implementation Costs	19/32	Public-private funding models ([4, 17]); phased adoption ([21, 25]).
Skills Shortage	14/32	Workforce reskilling via AR/VR training ([20, 22]); academic curricula updates ([12, 23]).
Data Security Risks	11/32	Blockchain-based cybersecurity ([18, 27]); GDPR-compliant architectures ([11, 28]).
Interoperability Issues	9/32	Standardised APIs ([6, 7]); open-source platforms ([10, 31]).
Resistance to Change	7/32	Pilot projects demonstrating ROI ([1, 13]); stakeholder workshops ([19, 29]).

While technical barriers (e.g., costs, interoperability) are well-documented (75% of articles), organizational culture and social equity receive limited attention (only [5, 15, 20] address inclusivity).

The analysis reveals:

- Sectoral Imbalances:** Manufacturing’s lead in I4.0 adoption contrasts with lagging sectors (e.g., agri-food), where sustainability gains could be transformative ([15, 18]).
- Collaboration Gaps:** Most partnerships focus on environmental outcomes, neglecting social co-benefits (e.g., just [20, 22] measure job quality improvements).
- Policy Leverage:** Regions with strong regulatory frameworks (e.g., EU, China) re-report higher success rates in scaling solutions ([4, 17, 26]).

Future projects should adopt integrated metrics to assess triple-bottom-line impacts, as exemplified by [16]’s "Circular I4.0 Scorecard."

5. Data Analysis and Results

This section synthesizes key findings to address the three research questions (RQs), employing both quantitative bibliometric analysis and qualitative critical assessment of the 32 reviewed articles. The results highlight the interplay between Industry 4.0 (I4.0) technologies and sustainability, while identifying risks, gaps, and future research priorities.

RQ1: Association Between Sustainability and Industry 4.0

- Systemic Integration:** 78% of articles (25/32) frame I4.0 as an enabler of circular economy (e.g., [1, 16, 17]) and resource efficiency (e.g., [4, 26]), aligning with SDGs 9 (Industry) and 12 (Responsible Consumption).
- Dimensional Breakdown:**
 - Environmental:** Dominates the literature (23 articles), focusing on emissions reduction (e.g., IoT in [1, 8]) and waste minimization (e.g., Digital Twins in [7]).
 - Economic:** 20 articles link I4.0 to cost savings (e.g., AI in [21]) and supply chain resilience (e.g., Blockchain in [27]).
 - Social:** Least addressed (8 articles), with sporadic coverage of workforce upskilling ([20]) and safety ([19]).

While I4.0 is widely associated with sustainability, its social pillar remains underexplored, risking a "techno-centric" bias that may exacerbate inequalities (noted in [5, 15]).

RQ2: Advanced Technologies Promoting Sustainability

Table 5 ranks technologies by their cross-pillar sustainability impact, derived from article co-citation analysis.

Table 5. Technology Efficacy and Risks.

Technology	Benefits (Articles)	Risks (Articles)	Net Sustainability Impact
IoT	Real-time monitoring (Env: [1, 8]);	Energy consumption (Env: [1, 8]);	High (18/32 articles).

Technology	Benefits (Articles)	Risks (Articles)	Net Sustainability Impact
	Safety (Soc: [19]); Predictive maintenance (Eco: [7]).	[6]; Data privacy (Soc: [11]).	
AI/Big Data	Energy optimisation (Env: [4]); Demand forecasting (Eco: [21]).	Job displacement (Soc: [20]); Bias in algorithms (Soc: [14]).	Moderate-High (15/32).
Blockchain	Transparency (Env: [18]); Fraud reduction (Eco: [27]).	Scalability (Eco: [5]); High computational costs (Env: [28]).	Moderate (6/32).
Digital Twins	Waste reduction (Env: [7]); Training (Soc: [20]).	High implementation costs (Eco: [9]).	Moderate (10/32).
Robotics	Hazardous task automation (Soc: [3]); Precision (Env: [25]).	Upfront investment (Eco: [24]).	Moderate (7/32).

- IoT and AI are the most versatile (addressing all three pillars), but their social risks (e.g., privacy, job loss) are often overlooked (only [11, 14, 20] critique these). In particular, several authors warn that the large-scale deployment of AI and Big Data in hiring, performance evaluation and predictive maintenance may embed or amplify algorithmic biases, leading to discriminatory outcomes for certain worker groups. Moreover, automation-driven productivity gains are rarely accompanied by systematic strategies for just labor transitions, raising concerns about job polarization and long-term employability in routine-intensive occupations.
- Blockchain shows promise for environmental transparency but suffers from scalability issues ([5, 28]).

RQ3: High-Potential Industrial Sectors

Sectoral Analysis (from Section 4) reveals:

- Manufacturing:

- Benefits: 41% of articles (13/32) demonstrate I4.0's role in reducing waste ([1, 16]) and energy use ([7, 25]).
 - Limitation: Limited focus on SME adoption ([21, 24]).
- Energy:
 - Success: Smart grids ([4, 26]) and renewable integration ([18, 31]).
 - Gap: Workforce transitions (only [10] addresses reskilling).
 - Agri-Food:
 - Opportunity: Blockchain for traceability ([15, 18]) could reduce 30% of global food waste (cited in [18]).
 - Challenge: Low digital literacy among smallholders ([5, 15]).

Emerging Sector: Construction (9, 22) leverages robotics for recycling but lacks policy support ([19]).

6. Discussion

This study systematically addressed three research questions, revealing critical in-sights into the Industry 4.0 (I4.0)–sustainability nexus:

- RQ1 (Association): I4.0 is predominantly framed as a catalyst for environmental and economic sustainability (e.g., IoT-driven waste reduction [1, 8], AI-enhanced supply chains [21]), but its social dimension (e.g., equitable workforce transitions) remains underrepresented (only 25% of articles). This aligns with broader critiques of "techno-optimism" in sustainability literature.
- RQ2 (Technologies): While IoT and AI are the most versatile (applied across all three sustainability pillars), their risks (e.g., data privacy [11], job displacement [20]) are often marginalized in favor of efficiency gains. Blockchain shows promise but suffers from scalability issues, echoing concerns raised by broader digital sustainability debates on the energy intensity and governance of distributed ledger technologies. From a normative perspective, the underrepresentation of ethical and social risk assessments in the reviewed articles is problematic. Only a small subset explicitly discusses ethical AI principles, governance mechanisms to mitigate algorithmic bias, or structured plans for managing worker displacement. This gap suggests that current Industry 4.0 implementations tend to prioritize efficiency and cost reduction over fairness, transparency and long-term social resilience. Integrating ethical guidelines (e.g., human oversight, explicability of AI decisions) and worker-centered transition policies into I4.0 projects is therefore essential to prevent widening social inequalities.

- RQ3 (Sectors): Manufacturing and energy lead in practical adoption, yet agri-food and construction—despite their high sustainability potential—are hindered by infrastructural and policy gaps ([5, 15, 19]).

Concordances:

- Environmental Focus: Our findings corroborate 's assertion that I4.0's strongest impact lies in resource efficiency (e.g., Digital Twins reducing material waste [7, 16]).

- Collaborative Models: The success of Triple Helix partnerships (e.g., EU Smart Factories [12, 23]) mirrors 's emphasis on multi-stakeholder governance.

Contradictions:

- Social Sustainability Gap: While prior reviews (e.g.,) highlight I4.0's potential for "inclusive growth," our analysis reveals scant empirical evidence (only [15, 20] quantify social outcomes).

- SME Adoption: Contrary to 's optimism, we identify persistent barriers (e.g., costs, skills) in SME contexts ([21, 24]).

For Industry:

- Priorities Social Metrics: Firms should adopt frameworks like [16]'s "Circular I4.0 Scorecard" to track workforce inclusivity and safety alongside environmental KPIs.

- Phased Adoption: SMEs can leverage low-cost tools (e.g., open-source IoT platforms [7, 21]) to mitigate upfront costs.

Building on the evidence synthesized in this review, a conceptual framework can be outlined that links specific I4.0 technologies to sustainability key performance indicators (KPIs) across the triple bottom line. In this framework, IoT, AI/Big Data and Digital Twins act as primary enablers of environmental and economic KPIs (e.g., energy intensity, material yield, overall equipment effectiveness), while Blockchain and human-centric automation support transparency, traceability and social KPIs (e.g., fair labor practices, worker safety, job quality). The framework emphasizes three layers: (i) a technology layer, capturing the main I4.0 tools; (ii) a process layer, representing core industrial processes such as production, logistics and maintenance; and (iii) an outcome layer, where quantitative KPIs are mapped to the SDGs. By explicitly linking technologies to measurable outcomes, this framework can guide both researchers and practitioners in designing and assessing I4.0 initiatives with a holistic sustainability orientation.

For Policymakers:

- Regulatory Sandboxes: Test policies like tax incentives for sustainable I4.0 adoption (e.g., matching [4, 17]'s EU Green Deal alignment).

- Skills Development: Fund vocational training in AI and robotics (addressing gaps in [20, 22]).

Beyond the environmental and economic dimensions, the literature increasingly highlights the need for measurable social sustainability indicators in digitally transformed industries. Relevant frameworks include composite indices for job quality, health and safety, and participation in decision-making, as well as labor-transition models that quantify the risk of displacement and the effectiveness of reskilling programmers. However, none of the reviewed studies adopts a comprehensive social KPI system for Industry 4.0; instead, social outcomes are typically discussed qualitatively or via isolated indicators (e.g., accident rates or training hours). Future research should therefore draw on established social life cycle assessment (S-LCA) approaches and labor-transition frameworks to design robust metrics that capture both the risks and opportunities of I4.0-driven transformations.

Study Limitations:

1. Language Bias: The review excluded non-English articles, potentially over-looking regional innovations (e.g., China's "Made in 2025" initiatives).

2. Temporal Scope: Rapid I4.0 evolution means newer technologies (e.g., generative AI) may not be fully captured.

3. Sectoral Generalization: Findings may not apply uniformly to niche industries (e.g., textiles).

7. Conclusions

This study demonstrates that Industry 4.0 technologies hold significant potential to advance sustainability, yet their current application remains unevenly distributed across environmental, economic, and social dimensions. While IoT, AI, and Digital Twins have proven effective in driving resource efficiency (e.g., waste reduction in manufacturing [1, 7]) and economic resilience (e.g., supply chain optimization [21, 27]), their social contributions—such as equitable workforce development and community inclusivity—are markedly underexplored (*only 8/32 articles*). The sectoral analysis further reveals a disparity: high-adoption sectors like manufacturing and energy benefit from tailored solutions (e.g., smart grids [4, 26]), whereas agri-food and construction lag despite their systemic sustainability potential ([5, 15, 19]). Crucially, this research identifies a disconnect between technological innovation and holistic sustainability outcomes, underscoring the need for integrated frameworks that align I4.0 deployment with the UN Sustainable Development Goals (SDGs). To bridge this gap, future efforts must prioritize transdisciplinary collaboration—combining policy incentives (e.g., subsidies for SMEs [24]), scalable low-cost tools (*e.g., open-source platforms [10]*), and robust metrics to quantify social impacts (building on [16,

20]). Only through such systemic alignment can Industry 4.0 truly fulfil its promise as an engine of inclusive and regenerative industrial transformation.

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