Review

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Abstract

This study examines how the Internet of Things (IoT) acts as a key enabler of sustainability in industrial production systems within the Industry 4.0 paradigm, addressing the fragmented understanding of the mechanisms linking digital technologies to environmental, operational, and emerging human-centric outcomes. A systematic literature review was conducted following PRISMA 2020 guidelines using the Web of Science Core Collection. After applying explicit inclusion and exclusion criteria, 69 peer-reviewed studies published between 2016 and 2026 were analyzed through qualitative thematic synthesis and comparative analysis. The findings reveal that IoT functions as a foundational digital infrastructure enabling real-time monitoring, operational transparency, and data-driven decision-making in production environments. Four dominant application domains are identified: (i) energy and resource efficiency, (ii) production monitoring and control, (iii) predictive maintenance and asset management, and (iv) emerging human-centric production systems aligned with Industry 5.0. While IoT consistently improves operational reliability and resource efficiency, its contribution to the social dimension of sustainability remains comparatively underdeveloped. This study advances existing literature by providing a mechanism-oriented synthesis that explains how IoT-enabled infrastructures generate sustainability outcomes across production systems. Furthermore, it establishes a conceptual bridge between Industry 4.0 digitalization and the transition toward human-centric and resilient manufacturing models associated with Industry 5.0. From a practical perspective, the results highlight that IoT adoption contributes to reducing energy consumption, optimizing resource utilization, and enhancing operational performance, while also supporting safer and more adaptive working environments. However, challenges related to data integration, workforce adaptation, and digital capability gaps persist, underscoring the need for inclusive and strategically aligned digital transformation processes.

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1. Introduction

Sustainability has established itself as a central strategic axis in contemporary production systems, driven by increasing regulatory pressure, resource scarcity, rising energy costs and social expectations around the environmental and operational performance of the industry. In this context, the Industry 4.0 paradigm has emerged as a key framework for the transformation of production systems, by integrating advanced digital technologies with the purpose of improving efficiency, flexibility and industrial competitiveness [1,2]. However, beyond the digitalization of processes, questions remain about how these technologies effectively contribute to the integral sustainability of production systems [3].

Among the enabling technologies of Industry 4.0, the Internet of Things (IoT) takes center stage by enabling the interconnection of machines, sensors, and systems throughout the production environment. By facilitating data capture, real-time monitoring, and two-way communication between physical assets and digital platforms, IoT enables greater visibility into processes and more accurate management of energy, material, and operational resources [4,5]. These capabilities position it as a strategic enabler for sustainable production systems, enabling waste reduction, energy optimization, and improved operational performance [6,7].

However, the literature on IoT and industrial sustainability is fragmented. Numerous studies focus on specific technological applications or device-level developments, without systemically addressing the mechanisms by which IoT impacts concrete indicators of sustainable performance [8]. Likewise, although potential benefits are reported in terms of efficiency and traceability, there is limited articulation between technological adoption and verifiable environmental, economic, and social sustainability metrics within production systems [9].

In parallel, the recent debate on Industry 5.0 introduces a complementary approach that emphasizes the centrality of the human being, resilience and the creation of sustainable value [10]. This conceptual evolution raises the need to examine how Industry 4.0 technologies, particularly IoT, can contribute not only to production efficiency, but also to the development of safer, more resilient systems oriented towards human well-being. In this sense, the transition to human-centric production models requires integrating digital capabilities with explicit criteria of sustainability and operational resilience.

Despite the growing volume of research on IoT, Industry 4.0 and sustainability, there is still a lack of systematic reviews that synthesize existing knowledge in a structured way from the perspective of production systems. In particular, a gap is identified in the literature regarding studies that analyze the IoT as a transversal enabler of operational sustainability, articulating its applications, operating mechanisms and effects on the performance of production systems in a coherent framework.

To address these gaps, this systematic review is guided by the following research questions (RQ):

RQ1: How does the Internet of Things (IoT) act as a key enabler of sustainability in production systems within the Industry 4.0 paradigm?

RQ2: What are the main technological trends, approaches, and thematic clusters in IoT-enabled sustainable production systems?

RQ3: What are the implications of IoT adoption for the transition toward human-centric and resilient production models in the context of Industry 5.0?

Finally, this article is part of the contemporary research agenda on sustainable production, industrial resilience and smart resource management in the digital age. In an environment characterized by operational volatility, resource constraints, and increasing regulatory and societal demands, understanding the role of the Internet of Things (IoT) in transforming production systems is critical. In this context, this review offers a relevant contribution by providing a mechanism-oriented synthesis that positions IoT as a central enabler of sustainability in production systems. It also explicitly integrates the environmental, economic and social dimensions of sustainability, the latter being still incipiently developed in the literature, and establishes a conceptual link between

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Industry 4.0 practices and the transition to a more human-centric and resilient paradigm, characteristic of Industry 5.0.

This study contributes to the literature in four main aspects. First, it provides a systematic, mechanism-oriented synthesis of how IoT technologies enable sustainability outcomes in industrial production systems. Second, it identifies the main operational domains through which IoT contributes to sustainability, including energy and resource efficiency, monitoring and control, predictive maintenance, and emerging human-centric production systems. Third, the study analyzes the technological evolution of the field, evidencing the transition from architectures focused on connectivity to production configurations intensive in analytics and decision support. Finally, the review establishes a conceptual link between Industry 4.0 practices and the transition towards more human-centric and resilient production paradigms associated with Industry 5.0, highlighting relevant gaps in the social dimension of sustainability.

2. Literature Review

2.1. IoT for Energy Resource Efficiency in Production Systems

The transition to sustainable production systems has consolidated Industry 4.0 and the Internet of Things (IoT) as key technological enablers to simultaneously improve the environmental, energy and operational performance of production processes. Beyond their role as digitization tools, IoT systems enable continuous data acquisition, real-time monitoring, and operational feedback, critical elements for reducing resource consumption, emissions, and waste in complex industrial environments [11–14].

Various studies agree that the main contribution of IoT to sustainability in production systems lies in its ability to transform operational data into actionable information for decision-making [11,15,16].

Through distributed sensors, communication platforms and analytics systems, organizations can monitor critical variables such as energy consumption, material utilization, operating conditions and equipment performance, facilitating the alignment of production processes with sustainability objectives linked to responsible production and efficient use of energy [11,17,18].

From an Industry 4.0 perspective, smart production systems integrate IoT, cyber-physical systems, and control architectures to improve operational efficiency and flexibility, while reducing environmental impacts [12,15,19]. The literature shows that IoT-based monitoring and control increases the transparency of the production process, reduces manual intervention, and allows dynamic adjustments that optimize the use of resources in smart factories and flexible manufacturing systems [12,20–22]. These capabilities are especially relevant in contexts characterized by high variability, personalization, and energy constraints.

IoT monitoring also plays a central role in predictive maintenance and asset management, contributing to sustainability by extending the life cycle of equipment and reducing unplanned failures [15,23,24]. The integration of industrial sensors with analytical platforms makes it possible to detect early anomalies, prevent unexpected stoppages and minimize material and energy losses associated with operational failures. In energy-intensive production systems, these strategies have demonstrated significant reductions in energy consumption and waste [11,15,25].

At the system level, the convergence of IoT, cloud computing, and edge computing has resulted in digital production ecosystems that support holistic sustainability [11,26]. These ecosystems allow information to be coordinated between production, maintenance and logistics, facilitating more coherent and timely decisions. However, the literature points out that the benefits of these approaches are not homogeneous and depend on factors such as interoperability, data quality, and the digital maturity of organizations [26,27].

IoT has also been identified as an enabler of circular economy practices within production systems, by facilitating material tracking, product lifecycle control, and optimization of closed flows [12,23]. Through continuous monitoring and real-time data analysis, IoT systems make it possible to track the use of resources throughout the entire production chain, supporting strategies aimed at reducing waste, reusing components, remanufacturing, and logistics optimization. These capacities simultaneously strengthen the environmental and economic sustainability of production systems [12,19].

Additionally, recent research highlights the role of IoT in supporting energy-efficient production systems by integrating it with advanced data analytics, machine learning, and optimization techniques [11,28]. These approaches allow multiple energy, environmental and operational performance indicators to be evaluated simultaneously, dynamically adjusting the parameters of the production system based on predefined sustainable objectives. However, a significant proportion of studies focus on specific application cases or experimental validations in controlled environments, limiting the generalizability of results to larger-scale or more complex industrial contexts [28].

Despite the documented advances, the literature agrees that relevant challenges persist for the consolidation of sustainable production systems based on IoT.

Among the main challenges are the integration of heterogeneous data sources, the scalability of technological solutions, the security and privacy of information, as well as the explicit link between the data generated by IoT and the sustainability indicators of the production system [26,27,29]. Consequently, the need for more integrative approaches that position IoT not only as a technological infrastructure, but as a structural component in the design, management and evaluation of sustainable performance within the Industry 4.0 paradigm is evident.

2.2. IoT-Driven Monitoring and Control for Sustainable Manufacturing

Within the framework of Industry 4.0, the IoT has established itself as the infrastructure that allows production systems to be instrumented for continuous measurement and systematic control of critical operating variables. Unlike traditional approaches based on periodic inspections or aggregated data, IoT systems enable real-time data acquisition at the machine, process, and system level, enabling a dynamic representation of production and energy performance [12,30–32]

The literature shows that its main contribution lies not only in the digitization of assets, but also in the continuous measurement of variables such as energy consumption, operating statuses, cycle times, vibrations and environmental conditions [26,33]. These measurements make it possible to identify operational deviations and inefficiency patterns that are not detectable by conventional schemes [33].

Based on this instrumentation, the IoT enables more advanced control architectures by integrating the captured data with analytics platforms and cyber-physical systems [30,34]. In this context, several studies report the use of digital twins powered by IoT data to reproduce the dynamic behavior of production systems and evaluate the impact of operational adjustments before their physical implementation [34,35]. This approach makes it possible to analyze alternative operating scenarios, anticipate bottlenecks, and evaluate the effect of control decisions on indicators such as energy consumption, process stability, and resource utilization [35].

From a systems engineering perspective, IoT acts as an integrator between operational levels and production management systems. The integration of IoT data with MES and ERP platforms makes it possible to link the information generated in the plant with planning, scheduling and control decisions, reducing the gap between operation and management [36,37]. In particular, the literature points out that the availability of real-time operational data facilitates the incorporation of energy and environmental constraints into production decision-making processes, displacing approaches based exclusively on cost or time criteria [37]

Likewise, IoT systems support the automation of operational decisions by incorporating data analysis, machine learning, and optimization techniques [38,39]. These tools allow large volumes of heterogeneous data to be processed to detect anomalies, classify operating states and adjust process parameters according to defined objectives, such as reducing energy consumption, reducing downtime or improving the stability of the production system [38]. In this sense, IoT does not replace decision models, but provides the necessary data for their effective application in real environments.

IoT-based monitoring also forms the foundation for predictive maintenance and asset management strategies, enabling early detection of degradation and incipient failures [40,41]. The literature documents that the continuous monitoring of variables such as vibrations, temperature and energy consumption is used to anticipate failures and plan maintenance interventions, reducing unscheduled stoppages and losses associated with waste of materials and energy [41].

These applications are particularly relevant in production systems where the reliability of the equipment directly impacts the overall efficiency of the system.

However, the studies reviewed agree that the effectiveness of IoT-based monitoring and control systems depends on additional technical and organizational factors [40,42]. Key challenges include the integration of heterogeneous data sources, interoperability across platforms, data quality and reliability, and the ability of staff to interpret and use the information generated [42,43].

Consequently, the adoption of IoT does not guarantee improvements in the sustainable performance of the production system, if it is not accompanied by robust decision models, adequate analytical capabilities, and aligned organizational processes.

In addition, a significant proportion of the studies analyzed are based on specific application cases or controlled environments, which limits the extrapolation of the results to production systems of greater scale or complexity [35,40]. This fragmentation highlights the need for more integrative approaches that look at IoT as a structural component of the design and operation of sustainable production systems, rather than considering it solely as a one-off technology solution.

2.3. IoT and Predictive Maintenance for Sustainable Production Systems

Predictive maintenance enabled by the Internet of Things (IoT) has established itself as one of the most relevant applications of Industry 4.0 for the sustainability of production systems. Unlike traditional reactive or preventive approaches, predictive maintenance is based on the continuous measurement of the real state of productive assets, allowing failures to be anticipated, interventions to be planned and losses associated with unscheduled stoppages, reprocesses and unnecessary energy consumption to be reduced [44–48].

The literature reviewed shows that the main contribution of IoT to predictive maintenance lies not only in data acquisition, but also in the transformation of physical signals into actionable indicators for decision-making. Variables such as vibration, temperature, pressure, electrical current and energy consumption are captured by industrial sensors and used to characterize degradation patterns and anomalous operating states [26,49–53]. This data allows for the estimation of formal reliability metrics, such as mean time between failures and remaining operating time before a failure, which are used to prioritize maintenance interventions and coordinate decisions with the production operation [47,54,55].

Various studies report cyber-physical architectures in which IoT data is integrated with analysis platforms and industrial information systems, such as MES and ERP, to support maintenance decisions at the production system level [47,54,56,57]. In these approaches, the actual state of the equipment is explicitly incorporated into production planning and control processes, bridging the gap between the plant floor and operational decisions. Empirical evidence shows that this integration reduces the time spent on manual monitoring and reporting activities, as well as improves the coherence between maintenance, scheduling, and availability of productive resources [47,57].

A recurring aspect in the literature is the use of energy consumption as an indirect diagnostic variable in IoT-based predictive maintenance. In energy-intensive production systems, anomalous deviations in electricity consumption are used as early indicators of equipment degradation, allowing timely interventions before the occurrence of critical failures [38,52,58]. This approach strengthens the link between predictive maintenance and sustainability by reducing energy losses associated with catastrophic failures, prolonged shutdowns and material waste [57,58].

The recent evolution of predictive maintenance incorporates advanced analytics techniques, machine learning, and digital twins as mechanisms to improve diagnostic accuracy and failure anticipation [12,54,59–61]. In particular, the integration of real-time monitoring and predictive

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maintenance within digital twin frameworks aligned with industry standards is documented, allowing to simulate the dynamic behavior of assets, evaluate degradation scenarios and support decisions before their implementation in the physical environment [12,58,62]. These approaches strengthen the decision-making capacity of the production system, although their effectiveness depends on the quality of the data and interoperability between platforms [44,63]

From a quantifiable sustainability perspective, some studies report measurable impacts of IoT-enabled predictive maintenance on operational and environmental indicators. In reliability-centered maintenance frameworks supported by Industry 4.0 technologies, improvements are documented in metrics such as mean time between failures, mean time to repair, availability, and overall equipment effectiveness, along with reductions in energy consumption, carbon footprint, and water use [49,56,57]. These results are particularly relevant because they explicitly link maintenance decisions to the environmental and operational performance of the production system [49,56,64].

However, the literature also identifies technical and organizational challenges that condition the adoption and scalability of IoT-based predictive maintenance. Key challenges include the quality and reliability of the data captured, the integration of multiple heterogeneous sources, the scalability of analytical models, and the need for sufficient computational capabilities for near-real-time processing [44,54,65,66]. Likewise, limitations related to the dependence on human intervention to close the decision cycle, staff training, organizational acceptance and, in some cases, concerns associated with the security and privacy of information are reported [46,56,63,67].

2.4. IoT, Human-Centric Production Systems and Sustainability (Industry 5.0 Bridge)

Although the Internet of Things (IoT) has been widely studied as an enabler of operational efficiency, monitoring and predictive maintenance in production systems under the Industry 4.0 paradigm, recent literature increasingly recognizes the need to expand this approach towards more human-centric, resilient and socially sustainable production models, in line with the emerging principles of Industry 5.0 [58,68–70]. In this context, IoT is no longer conceived exclusively as a technological infrastructure oriented towards automation to position itself as a facilitator of human-system interaction, assisted decision-making and improvement of working conditions in complex production environments [71,72].

The studies reviewed indicate that the contribution of IoT to human-centric production systems is manifested primarily through its ability to increase operational visibility and reduce the cognitive load on staff by providing contextualized information in real time [12]. By integrating data from sensors, machines, and processes, IoT systems support operational and maintenance decisions that traditionally relied on individual expertise, reducing operator exposure to unsafe environments and reducing the need for reactive interventions under high-pressure conditions [73,74].

From the perspective of social sustainability, the literature indicates that the use of IoT in production systems can contribute to improvements in safety, ergonomics and operational reliability, by facilitating the early detection of anomalous conditions, potential risks and equipment degradation [69,75,76].

These mechanisms are particularly relevant in production systems where unexpected failures generate not only economic and energy losses, but also direct risks for personnel. However, empirical evidence shows that these contributions are often addressed indirectly and lack standardized metrics that allow their social impact to be assessed systematically [77].

A critical aspect identified in the literature is that many IoT systems continue to be designed with a predominantly technological focus, prioritizing system efficiency over human-technology interaction [77]. Several studies report that, even when the IoT provides detailed information on the state of the production system, final decision-making continues to depend on human intervention, which can generate information overload, dependence on specialized skills, and organizational resilience if it is not accompanied by adequate interfaces and structured training processes [12,75]. This situation shows a gap between the availability of data and its effective use to support human decisions in real industrial environments.

Within the framework of the transition to Industry 5.0, the need to reconceptualize the role of IoT as an enabler of collaborative production systems, in which humans and smart technologies coexist in a complementary way, is highlighted [68]. The literature suggests that integrating human-centric principles into the design of IoT architectures involves considering not only the technical performance of the system, but also factors such as information transparency, the explainability of analytical models, and adaptability to human capabilities [73,77,78]. However, these aspects remain underexplored in most of the studies reviewed.

Figure 1 synthesizes the relationships between IoT infrastructure, operational mechanisms, and sustainability outcomes in production systems, highlighting the transition of Industry 4.0 to a more human-centric paradigm characteristic of Industry 5.0.

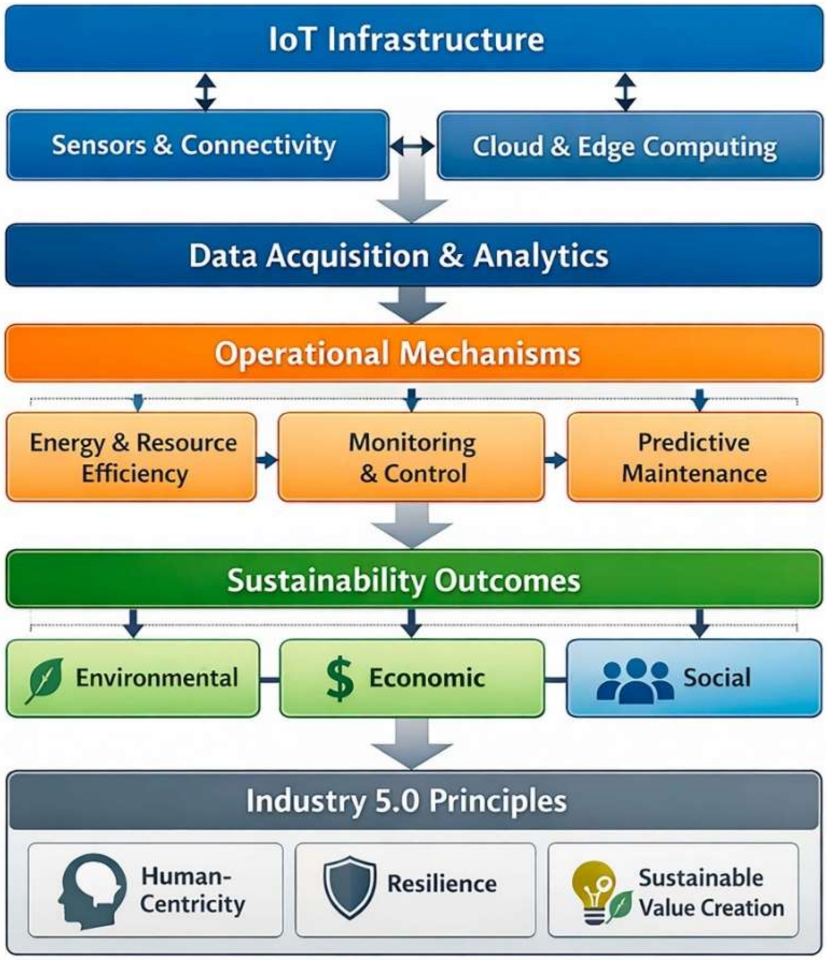

Figure 1. Conceptual framework of IoT-enabled sustainable production systems.

3. Methodology

The present study was developed under a systematic review of the literature, following the methodological guidelines proposed by [79] and the criteria established by the PRISMA 2020 declaration [80]. The objective of the review was to identify, analyze and synthesize in a structured way the most relevant research on the enabling technologies of Industry 4.0, with special emphasis on the Internet of Things (IoT) and its contribution to sustainability in industrial and manufacturing production systems.

The research team, made up of the authors, collaboratively defined the objectives of the review, the inclusion and exclusion criteria, the search terms and the scope of the analysis, to ensure methodological coherence, transparency and reproducibility of the study. The methodological

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process was structured in three main stages: (1) identification of the literature through systematic searches, (2) selection and critical evaluation of relevant studies, and (3) data extraction and qualitative synthesis of the results.

To ensure transparency and reproducibility of the review process, the completed PRISMA 2020 checklist is provided as Supplementary Material. In addition, a predefined review protocol supporting this study was registered in the Open Science Framework (OSF) prior to data extraction (https://doi.org/10.17605/OSF.IO/6UKN7).

3.1. Literature Search and Database Selection

The literature search focused on empirical and applied studies published in peer-reviewed scientific journals addressing qualitative, quantitative or mixed approaches related to Industry 4.0, sustainability in production systems and the Internet of Things (IoT) as an enabler of smart and sustainable manufacturing. In order to guarantee methodological rigor, quality of sources and reproducibility of the process, the Web of Science (WoS) Core Collection was selected as the main database.

WoS was chosen due to its extensive coverage of high-impact journals in key areas for this study, such as industrial engineering, advanced manufacturing, production systems, environmental sciences, and technology management, where the intersection between IoT, Industry 4.0, and sustainability is actively analyzed. WoS also offers robust citation indexing and advanced filtering tools, making it easy to identify influential and methodologically sound studies. Previous systematic reviews in the fields of Industry 4.0 and sustainability have used WoS as the main source, supporting its use as a consolidated database for this type of analysis.

The search strategy combined keywords aligned with the analytical axes of this review (resource efficiency, monitoring and control, predictive maintenance, and human-centric systems), using Boolean operators (DNA, OR) and field tags to optimize the retrieval of relevant literature. The search was carried out during the analysis period defined for the study and was restricted to articles published between 2016 and 2026, considering only documents classified as "Article" or "Review". Table 1 summarizes the overall configuration of the search strategy.

Table 1. Search configuration and query used in Web of Science (WoS).

	Search Configuration
Database	Web of Science Core Collection
Timespan	2015–2026
Document types	Article, Review
Keywords	Industry 4.0, IoT, sustainability, manufacturing
Field tags (TS)	“Industry 4.0” AND “Sustainability” AND “IoT” AND “manufacturing” OR “production system”

To ensure the transparency and reproducibility of the process, it is specified that all terms were searched using the Topic (TS) field in Web of Science (WoS), which simultaneously scans titles, abstracts, author keywords and Keywords Plus®. The final reproducible query was:

TS = (“Internet of Things” OR “IoT” OR “IIoT”)
AND (“sustainable manufacturing” OR “production sustainability”
OR “environmental performance” OR “resource efficiency”)
AND (“Industry 4.0” OR “I4.0” OR “digital transformation”)

Likewise, the use of the Topic field allows us to retrieve studies in which search terms appear in titles, abstracts or keywords, which increases the probability that the relationship between the variables analyzed is relevant within the focus of the study. However, the final conceptual relevance of each article was verified during the selection and eligibility evaluation phase.

Although the inclusion of other databases, such as Scopus or Engineering Village, could expand the documentary coverage, this review was deliberately based on the Web of Science Core Collection in order to ensure consistency in indexing standards, homogeneity in the quality of metadata and reliability in citation analysis. The selection of a single database also contributes to the traceability of the search process and the replicability of the study.

However, it is recognized that this controlled approach, while strengthening methodological consistency and transparency of the procedure, may limit the breadth of coverage and exclude relevant studies indexed exclusively in other databases. This restriction is explicitly acknowledged as a limitation of the study and is discussed in greater detail in the relevant section.

3.2. Inclusion and Exclusion Criteria

To ensure the transparency, reproducibility, and methodological rigor of the systematic review, explicit inclusion and exclusion criteria were defined before the study selection process, in accordance with the PRISMA 2020 recommendations. The systematic application of these criteria made it possible to ensure that the selected articles were relevant, methodologically sound and aligned with the objectives and research questions posed.

The inclusion criteria:

Studies that simultaneously met the following criteria were included in the review:

- Articles published in peer-reviewed scientific journals, classified as Article or Review in the Web of Science database (WoS).
- Studies published in the period 2016 - 2026, corresponding to the consolidation of the Industry 4.0 paradigm and the industrial expansion of IoT.
- Publications written in English or Spanish.
- Studies with an explicit focus on the Internet of Things (IoT) or enabling technologies directly associated with IoT within the framework of Industry 4.0.
- Research that addresses sustainability in industrial or production system contexts, considering at least one of its dimensions (environmental, economic and/or social).
- Empirical studies, based on models, industrial case studies, pilot implementations or mixed approaches that reported clearly described data, applications or methodologies related to operation, maintenance, resource management or decision-making in production systems.

The exclusion criteria:

Documents that presented any of the following characteristics were excluded:

- Non-peer-reviewed material (e.g., conference proceedings, books, book chapters, theses, technical reports, editorials, or opinion papers).
- Studies without access to full text.
- Research focused on IoT applications in non-industrial environments (such as smart homes, smart cities, education or agriculture), without a direct link to production systems or manufacturing contexts.
- Articles that addressed Industry 4.0 or sustainability in a general way, but without an explicit discussion of IoT or IoT-enabled technologies.
- Purely conceptual or opinion-based works that lack methodological transparency, empirical evidence or applied analysis relevant to sustainability in production systems.
- Studies focused exclusively on technical aspects of the IoT (e.g., communication protocols or algorithmic design) with no connection to sustainability outcomes or implications.

The application of these criteria sought to ensure that the included studies provided relevant evidence on applications, mechanisms and challenges of IoT in sustainable production systems, maintaining coherence with the objectives of the review and with the analytical domains developed in Section 2.

3.3. Screening, Selection, and PRISMA Flow

Following the application of the Web of Science (WoS) Core Collection search strategy, 453 records published between 2016 and 2026 were initially identified. Since the review was based on a single database, no duplicate records were identified at this stage. Consequently, all 453 articles were subjected to the initial screening process by titer.

During the screening phase by title, 257 articles that did not meet the inclusion criteria were excluded, mainly because they did not address the Internet of Things (IoT), were not related to industrial production systems or focused on contexts outside the objectives of the review. As a result, 196 articles were selected for further evaluation.

Subsequently, 196 were evaluated at the abstract and full text level. In this phase, 127 articles were excluded for the following reasons: (i) lack of alignment with the review objective (n = 36); (ii) focus on non-industrial populations or non-productive contexts (n = 24); (iii) applications not related to sustainable production systems or industrial IoT (n = 41); and (iv) low relevance or insufficient methodological depth for the analysis (n = 26). No unrecovered items were recorded.

Finally, 69 studies met all inclusion criteria and were considered eligible for in-depth analysis within the systematic review. The entire process of identification, screening, eligibility and inclusion is represented by a PRISMA 2020 flowchart (Figure 2), ensuring transparency, traceability and reproducibility of the selection process.

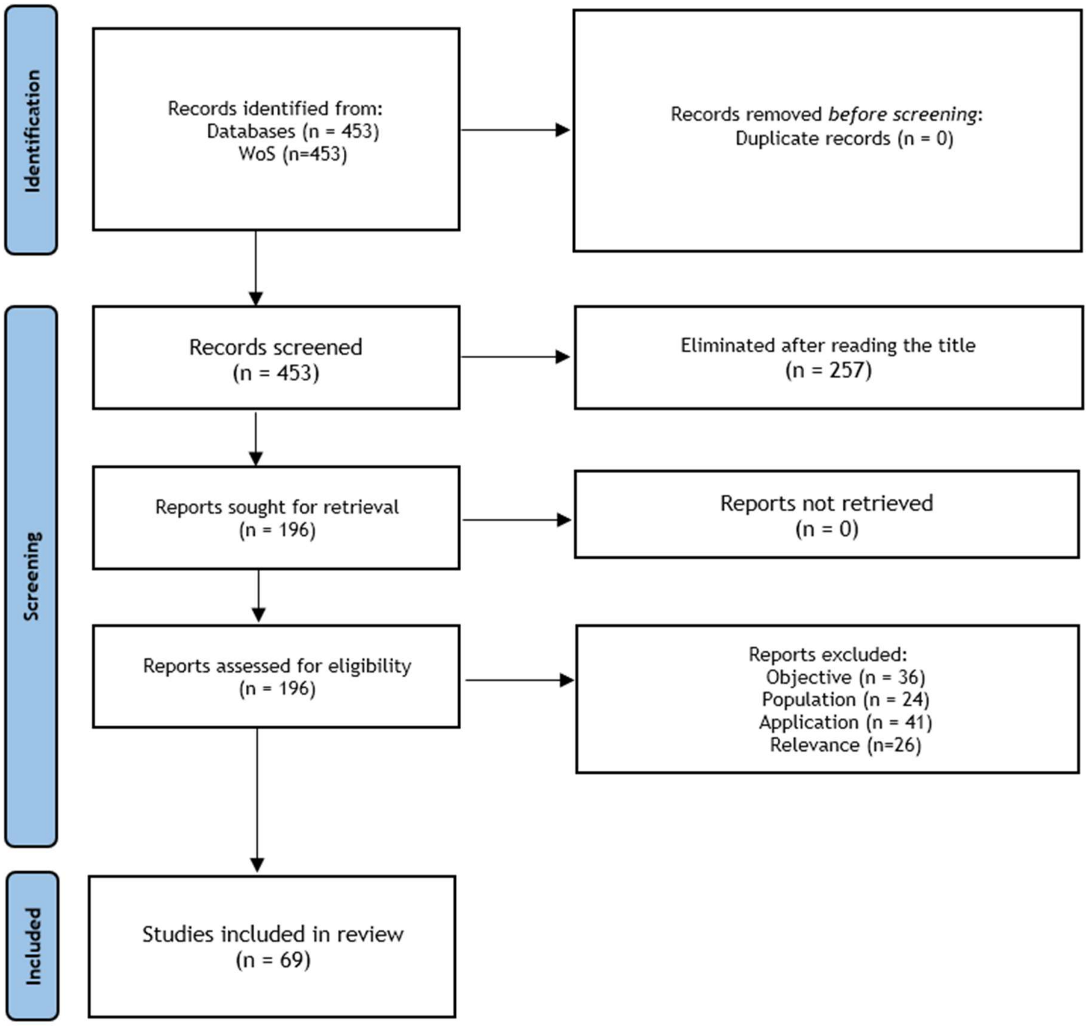

Figure 2. Systematic review PRISMA.

Due to the heterogeneity of the included studies in terms of research methodologies, covering case studies, conceptual frameworks, analytical methods, and mixed approaches, as well as the absence of standardized outcome metrics across the sample, conducting a statistical meta-analysis was not feasible. Consequently, a qualitative thematic synthesis was carried out to integrate and analyze the findings of the included studies, following the methodological recommendations associated with systematic reviews reported under the PRISMA guidelines.

3.4. Quality Assessment of Included Studies

To strengthen the methodological rigor of the review, all the articles included were subjected to a quality evaluation process, based on five fundamental criteria: (1) clarity in the design of the research and methodological transparency; (2) adequacy and reliability of data collection methods; (3) coherence between the objectives set, the methods used and the results reported; (4) robustness and validity of the analytical procedures used; and (5) degree of empirical support for the studies, distinguishing between experimental validations, industrial case studies, and results based exclusively on simulation.

Quality assessment was applied systematically to all included studies. Each article was analyzed qualitatively considering methodological clarity, coherence between objectives, methods and results, as well as the level of empirical evidence reported. Although a formal quantitative scoring system was not implemented, a structured qualitative assessment framework was applied to ensure consistency in evaluating methodological rigor, empirical validity, and relevance of the included studies.

During the synthesis of the findings, aspects such as insufficient methodological descriptions, limited industrial contextualization or potential replicability difficulties were critically considered. In this way, studies that presented experimental validations, industrial applications or more robust empirical evidence had a greater interpretative weight within the qualitative analysis of the results, particularly in the discussion of the impacts of IoT on the sustainability of production systems.

4. Results

4.1. Synthesized Findings Across Application Areas

The distribution of the 69 articles included in this systematic review reveals four dominant and interrelated application domains within IoT-enabled sustainable production systems (Table 2):

Energy and Resource Efficiency in Production Systems
IoT-Driven Monitoring and Control for Sustainable Manufacturing
Predictive Maintenance and Asset Management
Human-Centric Production Systems and the Industry 5.0 Transition

This classification reflects the structural organization of the reviewed literature and synthesizes the main mechanisms by which IoT technologies contribute to sustainability outcomes in industrial environments. In the set of studies analyzed, the IoT consistently acts as the fundamental layer of digital infrastructure for the acquisition of real-time data, operational transparency and the integration of information throughout production systems.

The first three domains energy efficiency, monitoring and control, and predictive maintenance demonstrate a strong empirical orientation, focusing on operational optimization, improving system reliability, and obtaining measurable improvements in environmental performance. In contrast, the fourth domain highlights the emerging transition to Industry 5.0, in which IoT-based applications begin to address dimensions related to occupational safety, ergonomic support, and human-machine collaboration. However, in this area the available empirical evidence remains comparatively limited.

Table 2 summarizes the methodological approaches, technological configurations, industrial contexts, and sustainability contributions of the 69 studies analyzed, providing a consolidated view of how IoT-enabled Industry 4.0 production systems are evolving towards more integrated and potentially human-centric sustainability frameworks. Due to space limitations, only a representative subset of ten studies is presented in the main manuscript, while the full table including all 69 studies is provided as supplementary material.

Table 2. Description of the results of the articles in the review process.

Lead Author	Objective of the Research	Method Used	4.0 Technologies Aligned with SDGs/Sustainability	Results, Scope or Contributions
Akinrebiyo, F. [28]	Strengthen sustainability in the cement industry, identifying challenges and levers for improvement.	Applied sectoral report/study.	Industrial sustainability, energy efficiency, decarbonization, process modernization.	It proposes guidelines to strengthen the sustainable performance of the cement sector and guide improvement decisions.
Ali, M. [12]	Develop/apply Industry 4.0 related technologies for custom manufacturing in an intelligent yogurt filling system.	Prototype/Applied Intelligent System Development.	Automation, sensors, intelligent control, customized manufacturing.	Demonstrates the viability of an intelligent filling system for customization and operational improvement.
Aliyari, M. [27]	Analyze technologies, applications, potentials and challenges of digitalization for sustainable buildings.	Review/conceptual contribution.	Smart buildings, digitalization, energy management.	Summarizes digitalization opportunities and barriers for sustainable buildings.
Alkhodair, M. [41]	Analyze how Industry 4.0 drives smart manufacturing and logistics in SMEs for sustainable supply chains.	Analytical/Applied Article.	Smart manufacturing, smart logistics, sustainable supply chain.	Shows how SMEs can move towards more resilient and sustainable chains with I4.0.
Allahloh, A. [40]	Integrate IIoT and digital twin for multi-loop intelligent control in oil and gas processes.	Technology integration development.	IIoT, digital twin, process control, oil & gas.	Demonstrates a proposal to improve control, diagnostics and operational efficiency.
Al-Mashhadani, A. [17]	Analyze the development of digital manufacturing ecosystems for sustainable performance based on two decades of research.	Literature review.	Digital manufacturing, digital ecosystems, sustainability.	Integrates historical lessons and research gaps for sustainable manufacturing ecosystems.
Alnahhal, M. [69]	Analyze the impact of emerging Industry 4.0 technologies on sustainability dimensions.	Analytic article/review.	I4.0, economic, environmental and social sustainability.	Provides a comprehensive view of the effect of emerging technologies on sustainability.
Alvares, A. [58]	Implement Digital Twin-Enabled Process Monitoring in an Additive Manufacturing Robotic Cell.	Experimental/Applied Development.	Digital twin, robotic, additive manufacturing.	Demonstrates real-time process tracking and improved additive manufacturing control.

Anang, A. [42]	Review the role of artificial intelligence in Industry 5.0 to improve human-machine collaboration.	Literature review.	AI, human-machine collaboration, Industry 5.0.	Highlights the transition to more human-centric approaches supported by AI.
Assad, F. [52]	Propose a component-based design approach for energy flexibility in cyber-physical manufacturing systems.	System Design/Modeling.	CPS, energy flexibility, smart manufacturing.	Provides a modular design to manage energy and support manufacturing sustainability.

Beyond thematic categorization, the temporal evolution of the technologies addressed in the 69 articles reviewed offers additional perspective on how IoT-enabled sustainability research has matured between 2015 and 2024. Figure 3 illustrates the annual frequency of Industry 4.0 technologies identified in the selected studies.

In line with qualitative synthesis, IoT clearly emerges as the fundamental and most persistent technology throughout the review period. From the first years analyzed, IoT appears as a central facilitator of sensing, monitoring and connectivity, and its presence becomes increasingly stable from 2018 onwards. This confirms its structural role as a data acquisition layer that underpins applications such as sustainable production monitoring, predictive maintenance, and efficient resource management.

Artificial Intelligence (AI) and Machine Learning (ML) show a notable increase from 2019, reflecting a transition from implementations driven primarily by connectivity to sustainability strategies based on advanced data analytics. Rather than isolated IoT deployments, the latest studies are increasingly combining IoT with AI-based optimization techniques, anomaly detection, energy prediction, and decision support systems. A similar upward pattern is seen in big data analytics and cyber-physical system (CPS) architectures, reinforcing the consolidation of integrated digital ecosystems in which IoT functions as the primary source of data for higher-level analytical intelligence and operational coordination.

Digital twins, blockchain, AR/VR, and additive manufacturing appear less frequently and mainly in the last years of the review period. Its presence is concentrated in specific domains, such as advanced maintenance architectures, traceability frameworks, collaborative production or human-machine interaction. This suggests that these technologies continue to play a complementary or emerging role within sustainability-oriented production systems, rather than being dominant drivers of transformation.

Finally, topics related to digital governance, circular economy applications and human-centric perspectives of Industry 5.0 show gradual growth from 2019 onwards. However, compared to operational and environmental applications, their empirical density remains lower, reinforcing the research gap identified in the social dimension of sustainability.

Taken together, the temporal trends depicted in Figure 3 confirm a clear evolution in the field: from early IoT-focused monitoring deployments to more integrated, advanced analytics-oriented, and partially human-centric Industry 4.0 configurations. This progression supports the interpretation of the four application domains discussed below and aligns with the conceptual framework proposed in Section 2.

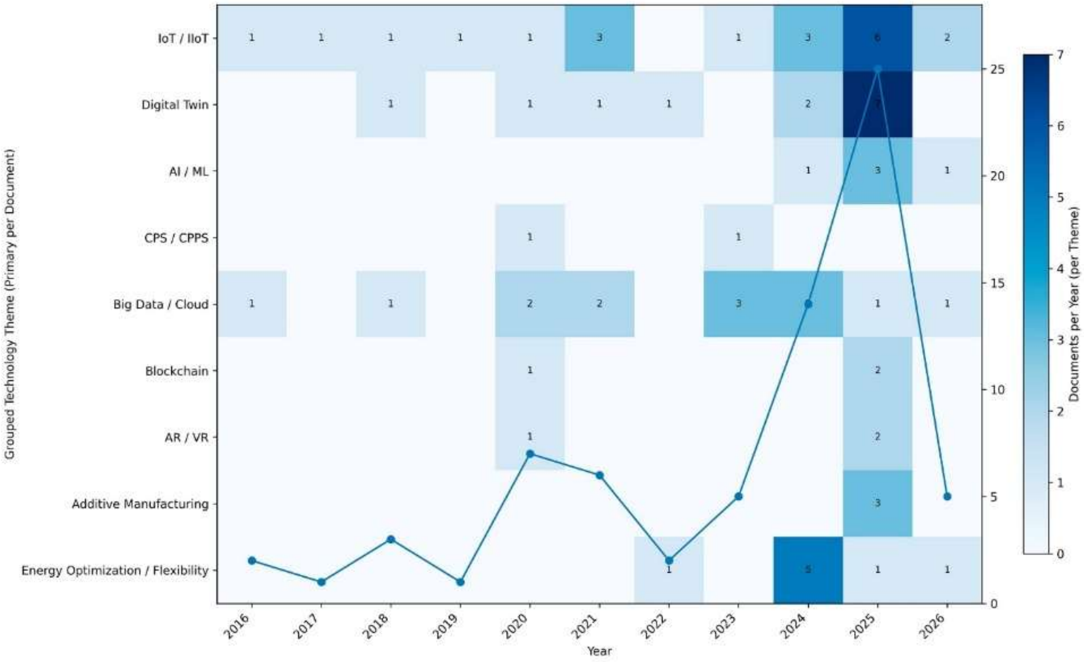

Figure 3. Temporal evolution of industry 4.0 technologies addressed in the reviewed articles (2016-2026).

Taken together, the temporal dynamics depicted in Figure 3, based on the 69 studies reviewed, reveal a structured evolution in research on IoT-enabled sustainable production. More than just linear growth, the pattern identified shows an early phase dominated by fundamental IoT deployments focused on monitoring and connectivity, followed by a consolidation phase in which complementary technologies such as AI/ML, digital twins, cyber-physical systems (CPS), and data-driven architectures take on progressive relevance.

Since 2018, the IoT has maintained a stable and central presence in all application domains, confirming its role as the structural backbone of data acquisition of sustainability configurations associated with Industry 4.0. However, the notable increase in advanced analytics-oriented technologies from 2019-2020 indicates a transition towards more integrated production systems based on analytical intelligence. This shift reflects the maturation of digital ecosystems, in which IoT-generated data is increasingly leveraged for operational optimization, predictive maintenance, energy management, and multi-criteria decision-support.

Emerging technologies such as blockchain, augmented reality and virtual reality (AR/VR) and additive manufacturing appear more selectively and mainly in the last years of the period analyzed, suggesting that their role continues to be complementary and context-dependent rather than structural within sustainable production systems. In parallel, the gradual emergence of human-centered and Industry 5.0-related topics from 2019 onwards reinforces the ongoing transition from an exclusively efficiency-oriented digitalization to broader socio-technical approaches to sustainability.

Taken together, Figure 3 confirms that the field has evolved from initial IoT-based monitoring implementations to more integrated, analytics-intensive, and partially human-centric Industry 4.0 configurations. This technological intensification and diversification directly guide the interpretation of the four application domains discussed below, showing that sustainability outcomes increasingly depend on the interaction between IoT infrastructure and complementary digital capabilities, rather than on the isolated adoption of individual technologies.

- Sustainable Production Monitoring

This domain represents one of the most empirically robust groups within the 69 studies reviewed. Most of the contributions deploy IoT-enabled sensing infrastructures for machine health monitoring, real-time production tracking, and energy consumption measurement in industrial environments. The evidence consistently informs improvements in operational visibility, anomaly detection, and process transparency, confirming the structural role of IoT as the backbone of data acquisition in sustainable production systems.

The temporal dynamics illustrated in Figure 4 reinforce this finding, as the IoT maintains a stable and central presence throughout the review period. Although operational advances are well documented, several studies highlight persistent interoperability challenges and fragmented architectures, suggesting that monitoring capabilities alone do not guarantee a systemic transformation into sustainability.

- Process and Operational Optimization

Table 2 shows that IoT-powered process optimization frequently appears in combination with complementary technologies such as artificial intelligence and machine learning (AI/ML), cyber-physical system (CPS) architectures, cloud platforms, and advanced data analytics tools. As reflected in Figure 4, the prominence of these complementary technologies increases markedly after 2019–2020, indicating a transition from deployments focused primarily on connectivity to more analytics-intensive and decision-support-oriented configurations.

The empirical studies reviewed report significant improvements in operational efficiency, predictive maintenance accuracy, energy management, and performance in production planning. However, the strength of the evidence remains heterogeneous. While experimental and case-based studies demonstrate measurable advances in the performance of production systems, contributions based on simulations or conceptual frameworks tend to generalize the potential benefits without long-term industrial validations.

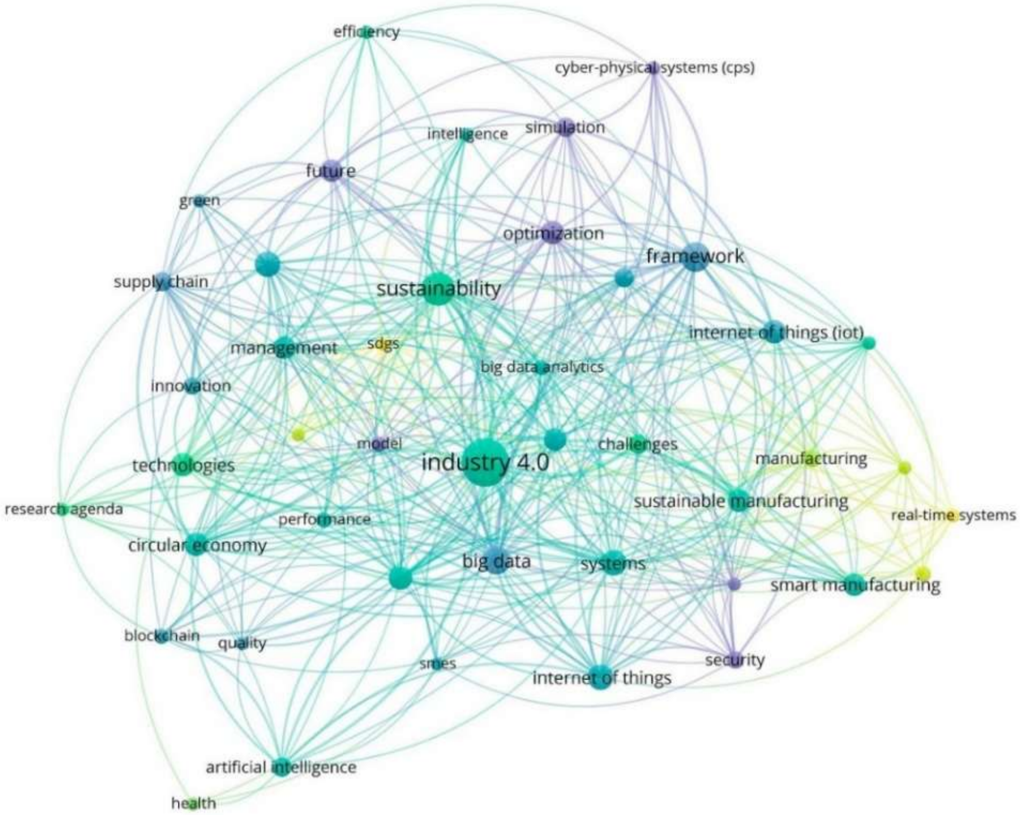

Figure 4. Keyword Co-occurrence network of IoT and sustainability research in the industry 4.0 Era (2016-2026).

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- Predictive maintenance and assets management

This domain consolidates IoT applications aimed at improving operational reliability and optimizing the life cycle of industrial assets. The grouping of keywords in Figure 5 reveals strong associations between "predictive maintenance", "big data", "artificial intelligence" and "cyber-physical systems", reflecting the increasing analytical maturation of this line of research.

In the articles reviewed, IoT-enabled predictive maintenance shows measurable reductions in equipment downtime, improvements in reliability indicators such as MTBF (Mean Time Between Failures), and indirect environmental benefits derived from reduced energy waste and extended equipment lifespan. However, the complexity of implementation and the costs associated with the integration of these solutions continue to be relevant barriers, particularly for small and medium-sized enterprises (SMEs), limiting their widespread adoption in industrial contexts.

- Human-centric and industry 5.0-oriented systems

Compared to the previous domains, human-centric applications remain relatively underdeveloped within the dataset of 69 studies analyzed. Figure 5 reveals weaker clustering of terms associated with social sustainability, indicating that this dimension occupies a marginal yet emerging position in the current literature.

Most contributions in this area are conceptual or framework-oriented, discussing the potential of IoT to enhance worker safety, ergonomic monitoring, collaborative robotics, and decision-support systems. Empirical validation remains limited, and the reported findings are heterogeneous. While some studies document improvements in workplace safety and enhanced human–machine interaction, others raise concerns related to data privacy, digital surveillance, and technostress associated with increasing levels of workplace digitalization.

Overall, this uneven evidence base highlights a significant research gap in the socio-technical dimension of IoT-enabled sustainability systems, particularly regarding the systematic evaluation of social sustainability outcomes within industrial production environments.

4.2. Overall Synthesis

The combined evidence in Table 2, the temporal dynamics illustrated in Figure 4, and the thematic clustering presented in Figure 5 confirm that the IoT functions as the structural backbone of sustainable systems associated with that of Industry 4.0 in the 69 studies reviewed. However, the contribution of IoT is not uniform across the different domains analyzed. Its impact is highly dependent on the degree of integration with complementary technologies, such as artificial intelligence and machine learning (AI/ML), cyber-physical systems (CPS), and digital twins, as well as the maturity of organizational data management practices.

The strongest empirical evidence focuses on monitoring, energy efficiency, and predictive maintenance applications, where measurable operational and environmental improvements are consistently reported. In contrast, studies aimed at process optimization show more heterogeneous levels of validation, while human-centered sustainability remains comparatively underexplored, with limited validation based on longitudinal studies or implementations in real industrial environments.

The temporal progression identified in Figure 4 shows a clear technological intensification from 2019 onwards, characterized by the increasing incorporation of architectures oriented towards advanced analytics and data intelligence. However, the thematic distribution represented in Figure 5 shows that social sustainability and the constructs associated with Industry 5.0 continue to occupy a peripheral position within the predominant discourse on IoT and sustainability.

Taken together, the findings suggest that sustainability outcomes in the context of Industry 4.0 do not derive solely from IoT adoption, but from systemic integration between digital infrastructures, analytical capabilities, and organizational transformation mechanisms. This synthesis provides an analytical basis for discussing future lines of research and moving towards more human-centered and socio-technical approaches to sustainability.

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5. Discussion

The Internet of Things (IoT) and the technologies associated with Industry 4.0 contribute to sustainability in production systems. Based on the analysis of 69 peer-reviewed studies, the results show that IoT consistently functions as the fundamental digital infrastructure that enables real-time monitoring, predictive maintenance, and optimization of resource use. This responds directly to RQ1, confirming that IoT acts not only as a connectivity layer, but as a structural enabler of data-driven sustainability mechanisms within industrial production systems.

However, the evidence also expands on previous research by showing that sustainability outcomes depend more on the systemic integration of technologies than on isolated technology adoption. As can be seen in the temporal evolution presented in Figure 3, the field has evolved, especially after 2019, towards increasingly analytics-intensive configurations, characterized by the integration of artificial intelligence and machine learning (AI/ML), cyber-physical systems (CPS), digital twins and cloud architectures. This technological intensification suggests a maturation phase in which IoT-generated data is increasingly used for advanced optimization, predictive control, and multi-criteria decision support.

Despite these advances, the findings also reveal significant heterogeneity in empirical validation. While areas such as energy efficiency, process monitoring, and predictive maintenance report measurable improvements in operational and environmental performance, studies aimed at process optimization are often based on simulations or conceptual frameworks without longitudinal industry validation. This uneven evidence base challenges overly optimistic narratives about universal advances in sustainability and highlights the importance of contextual factors such as digital maturity, technological interoperability, and organizational capabilities.

A particularly relevant contribution of this review lies in the systematic analysis of the gap in the social dimension of sustainability, identified in the introduction and linked to RQ3. Although the emerging Industry 5.0 discourse emphasizes the importance of human-centered production systems, the keyword co-occurrence analysis presented in Figure 4 shows that constructs related to social sustainability and human-centric approaches occupy relatively peripheral positions within the overall landscape of IoT and sustainability research. Most studies that address aspects such as workplace well-being, ergonomic monitoring or ethical governance remain at the conceptual level, with limited empirical support in real industrial contexts.

This imbalance reflects deeper structural patterns within literature. Environmental and operational indicators tend to be prioritized due to their greater measurability and the availability of quantitative data, while results associated with social sustainability lack standardized and comparable metrics across studies. In addition, IoT research continues to be predominantly technocentric, with a strong emphasis on efficiency and optimization over comprehensive socio-technical approaches. Consequently, the transition to Industry 5.0 seems, at this stage, more normative than empirically grounded.

Taken together, the results of this discussion suggest that IoT-enabled sustainability in production systems has achieved significant technological consolidation but remains dimensionally unbalanced. Achieving a real sustainable transformation requires not only advanced digital integration, but also organizational adaptations, workforce capacity building, ethical data governance, and the development of robust indicators to assess the social performance of production systems.

Research Gaps and Future Directions

Based on the synthesis of the evidence presented in this review, three main gaps in research are identified that guide future study agendas.

- Human-centered sustainability mechanisms remain empirically underdeveloped.

The human-centric dimension of sustainability continues to be poorly supported by empirical evidence. Although some studies explore the potential of IoT to improve occupational safety, ergonomic monitoring or human-machine collaboration, most of these contributions remain at the conceptual level. Future research should employ longitudinal designs, mixed methodological approaches, and multi-sector industry studies to systematically assess how IoT-enabled systems influence variables such as worker well-being, digital stress, safety performance, skills development, and organizational culture.

- Optimization claims require stronger empirical validation.

Many studies report improvements in simulation environments or controlled analytical frameworks; however, implementation in real industrial contexts remains limited. Future research should focus on evaluating these solutions in heterogeneous operating environments, considering conditioning factors such as the digital maturity of small and medium-sized enterprises (SMEs), technological infrastructure limitations, and interoperability challenges between platforms.

- Integrated socio-technical architecture remains under-theorized.

While IoT often coexists with technologies such as artificial intelligence, cyber-physical systems, digital twins, and cloud platforms, the mechanisms by which these integrated configurations jointly generate sustainability outcomes remain insufficiently conceptualized. Future research should adopt system-level modeling approaches that allow for analysis of the interactions between multiple technologies, rather than focusing solely on isolated or tool-level applications.

6. Conclusions

This systematic review provides a structured, mechanism-oriented synthesis of how Industry 4.0 technologies enabled by the Internet of Things (IoT) contribute to sustainability outcomes in production systems. Based on the analysis of 69 peer-reviewed studies published between 2016 and 2026, this research advances literature beyond descriptive technology mapping and positions the IoT as the structural backbone that enables data-driven sustainability transformations.

In relation to RQ1, the findings confirm that IoT acts as a fundamental digital infrastructure that enables real-time monitoring, predictive maintenance, energy optimization and resource efficiency. However, advances in sustainability do not stem solely from IoT adoption, but from its systemic integration with complementary technologies such as artificial intelligence and machine learning (AI/ML), cyber-physical systems (CPS), and digital twins.

With respect to RQ2, the temporal and thematic analysis reveals a clear trajectory of technological maturation. Early research focused on connectivity and monitoring architecture, while post-2019 studies show a transition towards integrated digital ecosystems that are intensive in advanced analytics. This evolution reflects a shift from mere operational transparency to intelligent decision-support configurations capable of addressing multi-criteria sustainability optimization.

As for RQ3, the results show a persistent asymmetry in the sustainability dimensions addressed. While improvements in environmental and operational performance are consistently validated, the social dimension remains empirically underdeveloped. Although human-centric and Industry 5.0-aligned applications are emerging, these remain predominantly conceptual, indicating the need for longitudinal research and more robust field studies on the socio-technical implications of IoT-enabled production systems.

The main theoretical contribution of this study lies in the proposal of an integrative conceptual framework that articulates IoT infrastructure, operational mechanisms and sustainability results from a socio-technical perspective. This framework clarifies that sustainability in Industry 4.0 environments is not an automatic technological outcome, but an emerging property that arises from the alignment between digital architecture, organizational capabilities, governance mechanisms, and human-centered design principles.

From a managerial perspective, evidence suggests that IoT investments must be accompanied by robust data governance strategies, workforce competency development, interoperability planning, and ethical oversight, in order to translate digitalization into measurable sustainable improvements. For policymakers, the findings underscore the importance of regulatory frameworks that facilitate digital adoption by small and medium-sized enterprises, while protecting data integrity and workers' well-being.

Ultimately, IoT-enabled sustainable production should be understood as a dynamic process of socio-technical co-evolution. The transition from Industry 4.0 to Industry 5.0 will depend not only on technological intensification, but on the balanced integration of environmental efficiency, economic viability and social responsibility within digitally interconnected production ecosystems.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org, PRISMA 2020 Checklist.

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