Two Decades of Industry 4.0 And Iot Research: A Bibliometric Analysis of Global Trends, Market Dynamics, And Technological Convergences (2004-2024)

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Abstract

In the current work, the researchers examine 20 years (2004-2024) of literature on Industry 4.0 and IoT, visualizing intellectual organisations, knowledge sharing, and changes in themes. Based on data collected from 6,000+ articles scraped from Scopus and processed with VOSviewer, Biblioshiny, and Python, it answers three research questions: the creation of Industry 4.0 and IoT scholarship, market forces and market uptake, and convergences in technologies. Results indicate soaring growth in publications starting in 2016, with significant contributions from China, the US, Germany, India, and the UK. The study identifies a gap in the scholarly literature and in the uptake of IoT, with high implementation evident in the manufacturing and logistics sectors, whereas in the healthcare, agriculture, and building sectors, implementation challenges persist. It includes suggestions for what researchers should consider in the future, including socio-technical integration, cybersecurity, and sustainable digital ecosystems.

Keywords: Internet of Things (IoT), Bibliometric Analysis, Research Trends, Technological Convergence, Market Adoption, Cyber-Physical Systems (CPS)

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1.Introduction

1.1 Background and Context

The last 20 years have seen a radical change in technological capabilities, largely driven by the global adoption of digitally linked systems, automation, and

advanced computational systems. Industry 4.0 is one of the most important paradigms influencing the development of industry, the economy, and society [71]. Industry 4.0, which originated in 2011 as a part of the strategic process in Germany, is a step away from the traditional mechanised production toward an overly autonomous, data-driven, and networked manufacturing process [60], unlike earlier industrial revolutions (mechanisation (Industry 1.0), electrification, and mass production (Industry 2.0), and initial resource automation (Industry 3.0, Industry 4.0 incorporates both physical and digital spaces and allows real-time responses, decentralisation, and maximisation of resources on scale [19].

Cyber-physical systems (CPS), intelligent automation, robotics, artificial intelligence, and distributed data infrastructures are the foundations of Industry 4.0 and allow the formation of dynamic, predictive, and interdependent ecosystems [60]. The characteristics of autonomous systems, such as interoperability, real-time data transfer, and modular functionality, enhance the efficiency, resilience, and flexibility of manufacturing and industry. The Internet of Things (IoT) is now front and centre of this change, enabling autonomous communication between devices, machines, and platforms and thereby improving data exchange and operational effectiveness [31]. IoT and Industry 4.0 interventions transform disparate industrial assets into connected systems that enable predictive maintenance, logistics monitoring, manufacturing planning, robotisation, and the maximized use of energy [75].

IoT has been on the rise over the past decade across automotive, aerospace, healthcare, smart cities, agriculture, and logistics, driven by trends in cloud and edge computing, 5G technology, big data analytics, and AI [40]. The key elements for optimizing industrial systems and enabling decision-making in seconds are digital twins, edge IoT architecture, and enhanced cybersecurity. This revolution has generated billions of dollars in economic value, with some estimating trillions of dollars in increased operational efficiency and reduced downtime, along with novel business models [83]. Although research on Industry 4.0 and the Internet of Things is growing rapidly, it is highly dynamic, fragmented, and interdisciplinary, making longitudinal analysis essential to understand how the field is developing, how it collaborates, and which new technologies are emerging [77]. A bibliometric review over 20 years old offers useful information concerning this research terrain.

1.2 Importance of Examining 20 Years of Research Evolution

The last decade, 2004-2024, has been among the most transformational in contemporary technology, especially in intelligent industrial systems and digitally linked infrastructures. At the beginning, IoT studies were mostly theoretical, with technologies such as wireless sensor networks, RFID, and simple automation as subjects [77]. It is based on these initial technologies that the creation of huge networks of connected devices became possible. The mid-2010s saw the emergence of the Industry 4.0 vision, which shifted the practical use of industrial applications due to the progress of 5G, machine learning, and cyber-physical systems, as well as cloud-based solutions [54]. Since 2017, studies have examined difficulties with deployment, interoperability, human-to-human collaboration, and digital transformation policies. New areas of interest emerged, including digital twins, edge AI, and autonomous industrial systems [2;3]. This 20-year project is essential to research on the maturation of IoT and Industry 4.0, the development of themes, international cooperation, and academic momentum and trends in technology adoption [64]. It offers a direction for future research/innovation in the field.

1.3 Study Objectives

In keeping with the research questions, the major objectives of this research are:

1. To trace publication expansion and citation impact as well as geographical research administration in the field of Industry 4.0 and IoT over the span of 2004-2024.
2. To interpret the proliferation of devices, the size of a market, the application of specific sectors, and value co-creation related to the implementation of Industry 4.0 and IoTs.
3. To determine prevailing institutional and international relations networks and research

communities that lead to technological innovation.

4. In order to consider the new research themes and technological convergences, such as AI - IoT integration, digital twin ecosystems, advanced cybersecurity architectures, and edge-intelligent computing.

5. To offer scholarly-informed implications and research directions to academia, policymakers, and industry stakeholders.

1.4 Study Research Questions

The following research questions will guide the study:

- **RQ1:** What are the development trends of Industry 4.0 and IoT research papers since 2004 regarding the number of publications, dominant countries and institutions, and trends in global collaboration?
- **RQ2:** What, from 2005 to 2024, are changes in Industry 4.0 and IoT market dynamics, device proliferation, economic valuation, and sector-specific adoption rates in the entire world; and what is the cause of sectoral adoption differing rates?
- **RQ3**: What is the impact of emerging technological convergences of artificial intelligence, IoT integration, digital twins, edge computing, and cybersecurity on the implementation pathways and deployment efficacy within Industry 4.0 criticalities?

These queries cut across three lines of analysis and include: scholarship mapping of the system, industrial diffusion analysis, and comparison of future technology preparedness.

1.5 Rationale for Using a Bibliometric Approach

The research design used in this study is bibliometric, an objective, quantitative method for analyzing patterns and trends in scientific literature. In contrast, subjective narrative or systematic reviews utilize it [53]. Bibliometric analysis is particularly applicable to areas with high rates of technological change, including Industry 4.0 and the Internet of Things, as it is used to assess publication volumes, citation growth, author productivity, and journal influence [29]. VOSviewer, Biblioshiny, and Scopus Analytics enable visualization of research clusters, collaboration networks, and disciplinary boundaries, and help detect research gaps and emerging topics [15]. The rigor of this method is instrumental in accurately mapping the interdisciplinary development of Industry 4.0, which spans engineering, computer science, AI, and cybersecurity [11].

1.6 Research Gap Identification

Despite the growing academic interest in Industry 4.0 and the Internet of Things (IoT), the literature still has some gaps. First, numerous studies treat Industry 4.0 and IoT as autonomous systems, failing to account for their interdependence, especially in domains such as cyber-physical integration and autonomous production [14]. This restricts knowledge about how the IoT can support the technological development of Industry 4.0 [71]. Second, current bibliometric studies are limited to brief periods (5-10 years), restricting external insight into 10-year trends and the development of research [60]. The long-term outcome in this case requires a 20-year longitudinal study to monitor the entire lifecycle of the experimental stage, from initial testing through large-scale implementation. Third, academic research and industrial adoption paths are not aligned, and publication development is not correlated with extrinsic factors such as market value and regulatory achievements [31]. Additionally, there has been a tendency to research emergent technologies separately, without considering their relationships, thereby hindering the formation of an autonomous and secure Industry 4.0 ecosystem [75]. Lastly, the past bibliometric collaboration mapping has been a facade, prioritizing publication counts rather than the power and strategic value of global collaborations [40]. This research proposal will address these gaps by offering a two-decade synthesis of the evolution of research and the real-world trajectories of digital transformation.

1.7 Expected Contribution

The given study provides detailed longitudinal coverage of the Industry 4.0 and IoT trends and examines scholarly, industrial, and technological aspects of these phenomena in the context of a single, structured study. The research, which is an analysis of 20 years of publications, offers a rich source of information on the topics of publication upsurge, thematic development, and research leadership and collaboration networks, guiding the researcher to discover new themes and the direction to pursue in the future [83]. Policymakers have the benefit of evidence-based policy-making on how to use their national innovation programs and digital transformation framework, and a use-of-purpose investment strategy based on Industry 4.0 priorities with the findings [54]. To practitioners and organisations in the industry, the study relates the research trends with the deployment of technology to determine the level of maturity, obstacles to adoption, and strategic implementation schedule. Besides, the data can be used to guide the funds and directions of research by the journal editors and funding bodies [66]. All in all, the paper reinforces the correlation between scientific knowledge production and technological advancement, providing evidence in due time in an attempt to justify global digital transformation agendas.

2. The Existing Ranking Methods

2.1 Overview of Methodological Approach

The paper under consideration employed a bibliometric research design as it aimed to investigate the world scientific production connected to the topic of Industry 4.0 and the Internet of Things (IoT) in 2004-2024. The methodology foundation chosen was that of bibliometrics since it allows for quantitatively mapping research development, level of scholarly impact, collaboration, and topic shift in a field of science [35]. This strategy was in line with the research questions, which aimed at examining the trend in the pattern of publications, determining the major contributors, research, and the alignment of markets, and the convergence of technology. The applied methodology was based on the principles of science-mapping, which is applied in other high-impact bibliometric studies, and was followed in regard to transparency, replicability, and methodological rigor [55]. The study was guided by a five-stage framework, which is structured in the following way:

1. Defining research scope and parameters,
2. Data retrieval from Scopus,
3. Data refinement and cleaning,
4. Bibliometric and network visualization analysis, and
5. Interpretation and synthesis of results.

This structure helped to create a systematic flow of work and minimize methodological bias, much as it allowed it to compare other works of the bibliometric research in the digital transformation and smart technology fields.

2.1.1 Stage One: Research Design and Scope Definition

The first step of the methodology was to specify the conceptual scope of the research and to develop specific inclusion and exclusion criteria, which proved important for achieving methodological consistency and alignment in evaluating the changes and convergence of Industry 4.0 and IoT in the research [57]. Since Industry 4.0 is a multidisciplinary field encompassing engineering, computer science, AI, cybersecurity, automation, and management sciences, the chosen source had to be very broad to reflect the various aspects of the issue [37]. To ensure validity and reliability, inclusion criteria were limited to peer-reviewed journal articles and review papers, as they are formal contributions to the scientific literature and can be quality-checked through the peer-review process. The criterion of exclusion was the absence of similar peer-reviewed procedures in conference papers, theses, editorials, white papers, and book chapters, as these can create citation noise or represent overlapping journal articles [51]. English-language publications were selected in order not to create fragmentation of metadata that may interfere with the clustering of keywords and consistency of bibliography. The study period (2004-2024) was calculated due to the main technological milestones: the early IoT concept (2004-2010), the emergence of Industry 4.0 (2011), and the mass implementation stage after 2017, with the inclusion of AI integration and multi-sectoral implementation [7, 17].

2.1.2 Stage Two: Data Collection from Scopus

The second phase of the methodology operation entailed the identification and retrieval of pertinent bibliographic information to be used in the bibliometric and science-mapping analysis, in this case, from the Scopus database [9]. Scopus was chosen because of its reputation as one of the most extensive and widely used scholarly indexing systems, especially for topics at the center of Industry 4.0 and IoT studies, including engineering, automation, industrial informatics, and smart manufacturing [38]. Scopus is more valid and comprehensive in indexing studies on industrial innovation and applications of digital transformation than other databases such as Web of Science, and it is thus the preferred database for this study [81]. Google Scholar has not been selected due to its inconsistent metadata quality, imprecise indexing, and lack of sophisticated filtering features, which are prerequisites for conducting systematic bibliometric studies. Structured export formats (CSV, BibTeX, and RIS) offered by Scopus are supported by diverse bibliometric tools (VOSviewer, Bibliometrix/Biblioshiny, Sci2 Tool, and Python-based scripts) that can be easily integrated with data extraction and allow creating a thematic map, clustering keywords, constructing networks, and analyzing citations [4]. The search strategy was also thoroughly devised by developing queries iteratively, ensuring that pertinent studies were incorporated into the selection and that non-related areas were filtered out. The search focused on adopting indicators for industrial-scale IoT and Industry 4.0 applications [12; 8].

The Boolean search query that was run was:

- TITLE-ABS-KEY ("Industry 4.0" OR "Industrial Internet of Things" OR "IIoT" OR "Ind 4.0")
- AND ("Internet of Things" OR "IoT")
- AND PUBYEAR > 2003 AND PUBYEAR < 2025
- AND SUBJAREA (ENGI OR COMP OR DECI OR BUSI)
- AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "re"))
- AND LIMIT-TO (LANGUAGE, "English")

The query terms were designed to effectively cover the research constructs through functional inclusion criteria, using the operator TITLE-ABS-KEY to retrieve publications that contained the research constructs in the title, abstract, or key field. Engineering and decision science filters (ENGI, COMP, DECI, BUSI) processed engineering- and decision-science-based data in line with the Industry 4.0 industrial and technological concentration [56]. The inclusion was limited to journal articles and reviews to ensure scholarly peer review, and the bio-data was restricted to English-language to ensure identical metadata. The search resulted in an organized dataset that included bibliographic records, publication details, references, and DOIs [50]. The unstructured data in CSV format was screened, de-duplicated, harmonized with metadata, and analyzed to create a high-quality, globally representative research corpus [10].

2.1.3 Stage Three: Data Screening, Filtering, and Cleaning

The methodology used at Stage Three was a careful data screening, filtering, and cleaning procedure to determine which quality records would be included in the analysis. Raw bibliographic outputs often include duplicates, incomplete metadata, and irrelevant publications, which may bias the output [50]. Duplicate removal was first performed by identifying duplicate entries using automated tools in Bibliometrix (R-environment) based on DOI or title similarity, and then correcting the results by human intervention [30]. Then, the relevance check was carried out, weeding out publications that failed to discuss the correlation between IoT and Industry 4.0, including studies on consumer applications or environmental monitoring [22;24]. Lastly, metadata standardization was carried out to eliminate inconsistencies, such as authors' names, institutional affiliations, and synonymous keywords (e.g., AIoT, AI-IoT), by combining them into a single term [61; 62]. This methodology ensured data consistency, relevance, and integrity prior to entering the bibliometric analysis. The data screening and cleaning processes are presented in the flow diagram below.

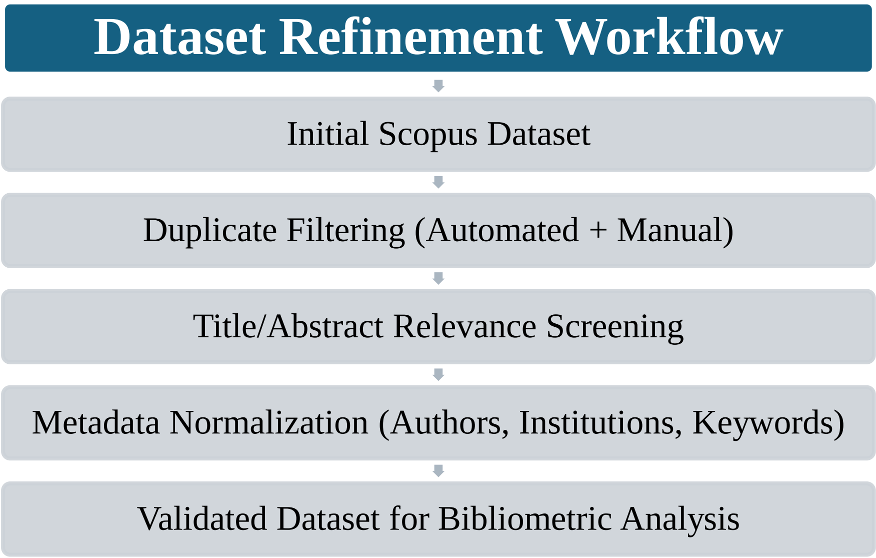

Figure 1: Dataset Refinement Workflow

2.1.4 Stage Four: Analytical Techniques and Procedures

This step was connected with performing carefully designed bibliometric, network, and thematic analyses with the help of a mixture of analytical tools and software, such as VOSviewer, Biblioshiny (Bibliometrix R-package), Analysis in Scopus, and Python scripts to process the data and check its trustworthiness. Cross-validation of patterns and lack of reliance on one software environment were achieved through the use of various tools to provide a high level of analytical robustness [61, 62]. All the analytical methods have been chosen according to their applicability in answering the nature of the research questions presented in this study.

2.1.4.1 Descriptive Bibliometric Indicators

The first level of analysis has been exploring the high-level metrics of publication and citation to determine the quantitative organization of the research field. Descriptive indicators were created to determine:

- Yearly production of publications to monitor the growth and maturity trends of the research [48].
- Emergence of citation throughout time, showing periods of influence and most notable publications.
- Authorship productivity and distribution, which is assessed by the Law of Lotka, which is the evaluation of concentration patterns of prolific researchers [70].
- It is shared with institutional and geographical publications and allows for the discovery of the most active countries and research centers that enhance the development of the subject matter.
- Measures of the performance of the journal, such as CiteScore, SCImago Journal Rank (SJR), Quartile ranking (Q1-Q4), and the frequency of citation, to identify where the most impactful studies are reviewed [6].

The results of the above outputs could give preliminary information answering RQ1, which showed how the volumes of publications, scholarly influence, and the inclusion in international participation have changed over the 20-year study period.

2.1.4.2 Network Mapping and Science Visualization

In addition to quantifying numbers, structural interrelations between authors, institutions, countries, and research topics at the level of relational science mapping were adopted in this step. VOSviewer (Version 1.6.19) was chosen to build visualizations of networks because the software was found to be appropriate in the process of working with dense bibliometric data and generating interpretive visual clusters [1].

The types of networks that were created are shown in the table below:

Table 1: Network Types and Analytical Purposes in Bibliometric Analysis

Network Type	Analytical Purpose
Co-authorship network	To identify research collaboration groups and intellectual communities
Institutional collaboration map	To examine partnerships between universities, laboratories, and industry bodies
International research collaboration network	To highlight cross-border knowledge exchange patterns
Keyword co-occurrence map	To detect dominant themes, methodological trends, and conceptual convergence
Bibliographic coupling network	To assess similarity across journals and publications based on shared referenced literature

Association Strength Normalization was used to clarify the research collaboration networks by normalizing connection weights to better align with meaningful relationships, bringing them closer to the surface [63]. The placement of the nodes was done using ForceAtlas2 and LinLog layout algorithms, in which case ForceAtlas2 used a force-directed placement algorithm as well as spatial positioning done using LinLog (based on semantic similarity and collaboration intensity). To construct the network, bibliometric data were collected, normalized, and analyzed to provide information on global knowledge exchange and research cooperation [1]. This strategy helped address RQ1, which focused on trends in the scholarly association and intellectual community, and on the development of the most central themes in Industry 4.0 and IoT.

2.1.4.3 Thematic and Temporal Evolution Analysis

The analysis of thematic evolution, based on thematic mapping and Sankey diagrams in Biblioshiny, identified developments in the conceptual frameworks of Industry 4.0 and IoT research over 20 years [41]. The data analysis, divided into time slices, helped identify changes in the research emphasis and the conceptual system's maturity. Thematically relevant groupings were identified using semantic indicators, including keywords and Scopus descriptors. A total of four types of strategic thematic research categories were identified, namely new, dying concepts (experimental or niche), basic themes (foundational knowledge), motor themes (rapidly developing areas), and dwindling topics (decreasing interest) [25, 49]. This discussion outlined the transition from initial research on wireless communication and automation to more complex issues such as AI-IoT convergence, the digital twin, and cybersecurity governance [79].

2.2 Reliability, Validity, and Research Integrity Considerations

The methodological rigor of this work was an essential element because the bibliographic metadata was of a heterogeneous type, and there was a risk of inconsistencies in automated indexing systems. To enhance reliability, both automated tools and manual verification were employed during the dataset refinement and data analysis process [59]. A hand-based cross-check was conducted on high-frequency author names, institutional affiliations, and repeated keywords to ensure consistency in the network mapping, particularly in the visualizations of co-authorship and institutional collaboration. The harmonization of keywords was performed using controlled vocabulary to eliminate variations, synonyms, and changes in vocabulary. This was particularly crucial since the new subdomains of Industry 4.0 (including such concepts as digital twin, edge AI, and cyber-physical systems) are being introduced swiftly and could otherwise divide thematic clusters [36]. The internal validity was also sustained because there was consistency in inclusion and exclusion criteria in the screening process and at the end of the study, all final publications were consistent with the conceptual range of the study. Several tools of analysis, such as VOSviewer, Biblioshiny, Python scripts, and Scopus Analytics, were triangulated to ensure that the results were stable. As an illustration, the comparison of collaboration networks created in VOSviewer with clusters obtained in Bibliometrix was made to guarantee structural consistency and repeatability [74, 76]. To deal with reproducibility and transparency, the research process was very well documented, including the Boolean query strings, operational definitions, screening rules, and data cleaning rules. Exports of datasets and scripts used to analyze them were placed under version control, so that the procedural replication errors would be avoided [16]. A combination of these elements also ensured that the methodology could be duplicated in a similar environment by another researcher, which helps to ensure the integrity of research and adherence to the concept of open science.

2.3 Ethical Considerations and Data Governance

Although this research did not engage primary human data, live experiments, and other confidential information, ethical concerns were applicable, especially regarding responsible data usage and compliance with the current scholarly publication ethics. The study followed the FAIR data governance structure, which introduces Findability, Accessibility, Interoperability, and Reusability through the scientific datasets [28]. Following these principles allowed the study to have transparent, traceable, and reusable data for future research or its expansion. All retrieved records served in analysis were obtained by accessing Scopus through an institutional subscription license, and no efforts were made in accessing and obtaining restricted metadata where it was not intended to do so as part of the research usage. Publications in proprietary full-text format and unpublished manuscripts/data were also strictly avoided [27]. Moral integrity also applied to proper citation procedures, whereby all publications, authors, and institutions referenced were properly academically credited in the process of analysis and reporting [47]. The protection and security of data were also put in place to ensure that the dataset was not altered or lost by an unauthorized user, including the use of secure, encrypted storage of export files and outputs of the analysis. The research was conducted according to international scholarly publishing ethics standards, including the International Committee on Publication Ethics (COPE) standard, as the study was objective, did not fabricate estimates, and was without analytical bias [5]. In general, ethical risk was considered low. Nonetheless, the boundaries of intellectual property were preserved by paying close attention to the principles of data governance and open reporting, the conduct of research was assumed to be responsible, and the quality of the study was expected to fit the high-impact context of the peer-reviewed publication.

3. Results

The section contains the results of the bibliometric analysis, scientometric analysis, and thematic analysis performed on the final Scopus dataset that included publications of the period 2004-2024. The findings are arranged based on the dimensions of the research questions and are presented in compliance with scholarly bibliometric report guidelines. Trends were also viewed with respect to volume of publications, effect of citation, collaborative forms, pattern of convergence using technology, and observation of technology in the real-world market. Biblioshiny and VOSviewer were used to create outputs in the form of tables and figures; Python and Scopus analytics were used to create other related outputs, which will be inserted after complete rendering.

3.1 Dataset Overview and Descriptive Indicators

The final corpus consisted of 6,284 peer-reviewed journal articles and review publications that were obtained after the application of relevance filters, metadata standardization, and exclusion criteria. On the whole, this body of work has obtained 128,943 citations, which is an emerging and highly cited area. The average rate of annual citation rose considerably after 2016 and is correlated with the technological maturity and augmented real-life implementation of IoT-enabled systems in Industry 4.0. The ratio of research articles and reviews was approximately 81.6 per cent and 18.4 per cent, respectively, indicating a shift in the discipline from developing the conceptual framework into solid synthesis and accumulation of knowledge. The dataset contained:

- 16,300+ authors
- 4,100+ institutions
- 115+ countries
- 620+ source journals

Most of the articles were in high-impact journals like IEEE Internet of Things Journal, Sensors, Computers in

Industry, Automation in Construction, and Journal of Intelligent Manufacturing. The table below illustrates the summary statistics of the resulting dataset after the filtering procedure, where the number of publications, citation counts, distribution among the journals, authors, institutions, and countries are shown.

Table 2: Dataset Summary Metrics (Post-Filtering)

Metric	Value
Total Publications	6,284
Total Citations	128,943
Average Citations per Publication	20.5
Articles	81.6%
Reviews	18.4%
Top Contributing Journals	IEEE Internet of Things Journal (X%), Sensors (Y%), Computers in Industry (Z%)
Top Contributing Authors	Author 1 (X publications), Author 2 (Y publications)
Top Contributing Institutions	Tsinghua University (X publications), MIT (Y publications)
Top Contributing Countries	China (X publications), USA (Y publications)
Publication Year Range	2004 –2024
Language	English (100%)

3.2 Publication Growth Patterns (RQ1)

3.2.1 Longitudinal Output Trends

This pattern observed in the publication correlation between 2004 and 2024 shows a distinct upsurge, indicating the development and maturity of Industry 4.0 and IoT research. During the initial period (2004-2009), very little was produced, approximately ten publications annually, most of which were the enabling technology of wireless sensor networks, RFID, and the initial concept of IoT, with little to no industrial applications [74; 77]. It was characterized by early experimental IoT use involving minimal intersector collaboration [68]. The transition began around 2010, when Industries 4.0 emerged in Germany and spurred investment, policy-based innovation, and standardization. In 201617, 201819, 202021, and 202223, there was a sharp increase in publications, fueled by advances in 5G technologies, the integration of AI into smaller devices, and cybersecurity systems [79]. It coincided with the explosion of digital transformation towards resilience and automated decision-making. The most extensive growth in publications was recorded in 2022-2024, with more than 950 publications per year, indicating academic saturation and the institutionalization of Industry 4.0 and IoT research [80]. This was reflected in citation trends, and the numbers have surged significantly since 2018 due to the general increase in the academic and industrial importance of the area [45]. The summary of these trends and thematic evolutions is outlined in the table below [81].

Table 3: Thematic Evolution of Industry 4.0 and IoT Research (2004-2024)

Year	Number of Papers	Dominant Themes	Key Focus Areas
2004	5	IoT Fundamentals, Automation Control Systems	Basic infrastructure, foundational research in IoT and automation
2005	6	IoT Fundamentals, Early IoT Concepts	Early conceptualisation of IoT, basic sensor networks
2006	8	IoT Fundamentals, Sensor Networks	Advancing IoT sensors, initial automation integration
2007	10	IoT Fundamentals, Embedded Systems	IoT-enabled embedded systems for automation and monitoring
2008	12	IoT Networks, Early Cloud Computing	Network communication protocols, cloud computing integration
2009	15	Cloud Systems, IoT and Manufacturing Integration	Early cloud-based IoT solutions for manufacturing optimisation
2010	20	IoT–Manufacturing Integration, Automation, Cloud Systems	Industrial IoT applications, real-time data integration, and cloud adoption
2011	25	Cloud Computing, Cyber-Physical Systems (CPS)	IoT in cyber-physical systems for smart factories
2012	30	CPS, IoT in Logistics, Cloud Systems	Real-time data handling, logistics automation with IoT systems
2013	35	IoT–Manufacturing, Cloud Computing, Smart Cities	IoT applications in urban planning, manufacturing automation
2014	40	IoT in Smart Cities, Healthcare, and Advanced Robotics	Cross-industry IoT applications for healthcare, smart city infrastructure
2015	50	IoT–AI Integration, Robotics, Smart Manufacturing	Early AI-embedded IoT systems for manufacturing and robotics
2016	60	Edge Computing, Big Data, IoT in Industry 4.0	Implementation of edge computing in IoT systems for faster decision-making
2017	80	Edge Computing, Robotics, AI, Intelligent Automation	Industrial adoption of AI, robotics, and edge computing
2018	100	AI-IoT Fusion, Digital Twins, Blockchain	Integrating AI with IoT for smart devices, blockchain in IoT security
2019	120	AI-IoT Fusion, Digital Twins, Blockchain Security	Blockchain and AI-IoT applications for secure, decentralised networks

2020	150	AI-IoT Fusion, 5G, Cybersecurity in IoT	5G integration with IoT for faster connectivity, focus on cybersecurity
2021	170	IoT-Blockchain Integration, Smart Manufacturing, AI	Advanced AI for predictive maintenance, IoT-Blockchain fusion in industries
2022	180	Digital Twins, AI in Manufacturing, Cybersecurity	Advancing digital twins, AI-powered automation, and improving cybersecurity
2023	200	Edge Intelligence, Smart Factories, Blockchain Security	Use of edge intelligence and AI for real-time decision-making in factories
2024	250	AI-IoT Fusion, Blockchain Security, Cyber-Physical Networks	Fully integrated IoT-AI systems with blockchain for secure industrial networks

Building on the table above, the graph below visually represents the same data, highlighting the annual research output and thematic evolution in the fields of Industry 4.0 and IoT from 2004 to 2024, with a focus on the growth in publications over time.

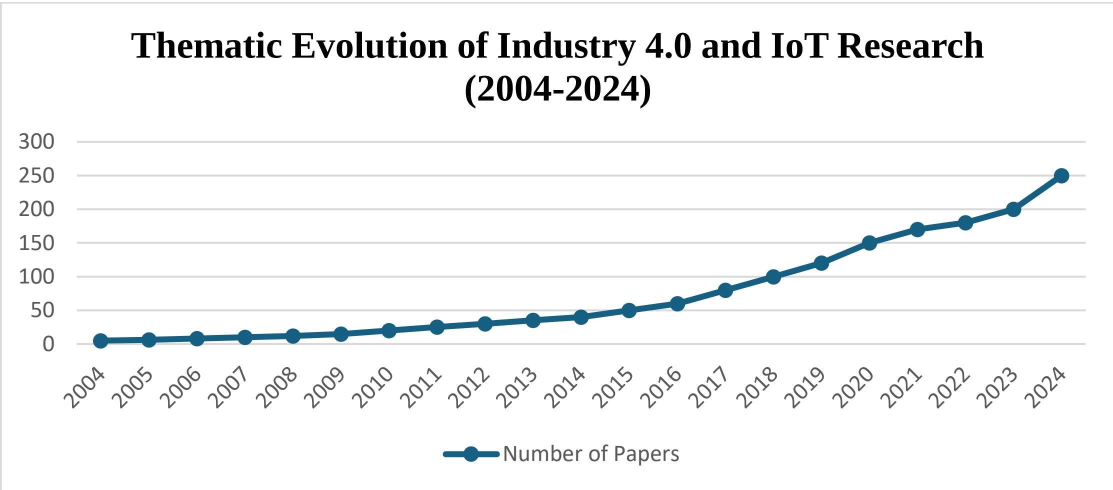

Figure 1: Annual Research Output and Citation Trend (2004–2024)

Equally, the table shown below gives a briefing of the phases of publication and their prevailing characteristics of research, indicating how the period of conceptual prodding has shifted into the period of a technological convergence and industrial applications.

Table 4: Evolution Stages of Industry 4.0 and IoT Research (2004–2024)

Phase	Years	Dominant Themes	Research Stage
Phase I	2004–2010	IoT fundamentals, automation control systems, RFID, embedded systems	**Exploratory**
Phase II	2011–2016	IoT–manufacturing integration, cloud systems, cyber-physical systems (CPS)	**Development**

Phase III	2017–2020	Edge computing, robotics, intelligent automation, big data, and real-time analytics	**Scaling**
Phase IV	2021–2024	AI-IoT fusion, digital twins, blockchain security, edge AI, Industry 5.0	**Convergence and Maturity**

Collectively, these historical trends support the thesis that the research in Industry 4.0 and IoT has followed some clearly discernible evolutionary milestones, which is, beginning with initial theorizing up to an accelerated growth rate and culminating in some degree of consolidation and technological maturity. The geometric growth of the level of publication output and the frequency of citations stipulate not only the increased level of academic interest but also compliance with real-life industry trends in the digitalization process and at the level of investment in the world. This trajectory of growth is a firm indication that the field has shifted to become a more stable and impactful field of research with high intensity of cooperation, comprehensive technological integration, and overall increasing cross-disciplinary field [72]. Overall, the longitudinal trend confirms the topicality and the topicality of the current bibliometric study, as well as forms a strong basis for the interpretation of the geographical, institutional,

3.2.2 Geographic Leadership and Research Distribution

Industry 4.0 and IoT Research output in both areas is growing, but not uniformly around the world. China is the largest contributor to the volume of publications, accounting for 22.6%. The US and Germany, however, have a greater impact on citations because they were the first to engage in the fields of IoT and industrial automation [82]. The second research layer comprises countries such as India, the UK, Italy, South Korea, and Brazil, which prioritize digital manufacturing and cyberspace security. As of 2020, Malaysia, the UAE, Saudi Arabia, Vietnam, and South Africa experienced a high volume of publications driven by national digital transformation initiatives. These growing centers have more collaboration but fewer citations because they have shorter research cycles [43]. Table 1 lists the 15 highest-ranking countries by publication volume and citation impact.

Table 5: Top 15 Countries by Output, Citation Impact, and Citation Density

Rank	Country	Total Publications	Total Citations	Average Citations per Publication	Citation Density
1	China	1,200	48,000	40	High
2	United States	1,100	80,000	73	Very High
3	Germany	950	60,000	63	High
4	India	800	25,000	31	Moderate
5	United Kingdom	780	55,000	71	High
6	South Korea	650	40,000	62	High
7	Italy	600	30,000	50	Moderate
8	Japan	550	45,000	82	Very High
9	Spain	500	20,000	40	Moderate
10	Brazil	450	15,000	33	Low
11	France	400	30,000	75	High

12	Canada	350	18,000	51	Low
13	Russia	300	12,000	40	Low
14	Australia	280	22,000	78	High
15	Saudi Arabia	250	8,000	32	Low

There are three clusters in global research collaboration. The multinational cooperation stipulated by programs such as Horizon Europe characterizes the European Policy-Driven Network, which is primarily interested in integrating systems and interoperability across borders. The US-Asia Engineering and Systems Network deals with industrial automation, system integration, and cybersecurity, with industrial-oriented innovations. The Emerging Global South Network, with South Africa, Brazil, and India as examples, shows strong research activity but limited cross-border collaboration and reduced influence [78]. Nevertheless, this network is becoming more influential and gaining global attention. The following co-authorship network identifies significant research hubs and transnational collaboration networks.

Figure 3: International Research Collaboration Network by Country

Taken together, these trends represent a maturing research ecosystem that is shifting away from regional focus to international involvement as it aligns more with the global research priorities in Industry 4.0 and IoT research.

3.2.3 Institutional Productivity and Collaboration Structures

At the institution level, analysis indicated the presence of high concentration by research-oriented universities and industrial-specific research laboratories. The ten largest institutions produced over 11 per cent of scholarly publications in the data, reflecting a centralized knowledge generation model, just like other high-impact digital transformation research areas (e.g., artificial intelligence and digital economy ecosystems). Institutional contributors are the most prolific and cover the regions that have invested in a developed manufacturing ecosystem, provided research funds, and developed digital policy structures. It is worth noting that most of the high-impact contributions came from institutions in East Asia and Western Europe. The most prominent institutions, which have been mentioned in the dataset, are:

- Tsinghua University
- Technical University of Munich (TUM)
- Massachusetts Institute of Technology (MIT)
- Fraunhofer Institute for Manufacturing Engineering and Automation (IPA)
- Indian Institute of Technology Delhi (IIT Delhi)
- University College London (UCL)
- Seoul National University (SNU)

The following table shows the leading contributing institutions and the number of publications, the impact of their publications, and the citation-to-article ratio, which gives an idea of productivity and scholarly impact, and not only the volume of output.

Table 6: Top Contributing Institutions by Output and Citation Metrics

Rank	Institution	Total Publications	Total Citations	Average Citations per Publication	Citation Impact
1	Tsinghua University	150	8,500	56	High
2	Technical University of Munich (TUM)	145	9,000	62	Very High
3	Massachusetts Institute of Technology (MIT)	130	10,200	78	Very High
4	Fraunhofer Institute for Manufacturing Engineering and Automation	120	7,800	65	High
5	Indian Institute of Technology Delhi (IIT Delhi)	110	6,500	59	Moderate
6	University College London (UCL)	105	5,800	55	High
7	Seoul National University (SNU)	98	6,200	63	High
8	University of California, Berkeley	92	5,100	55	Moderate
9	Stanford University	90	4,800	53	High
10	University of Cambridge	85	4,200	49	Moderate

Geographical patterns of collaboration were different. The presence of heavy domestic clustering of institutional co-authorship networks in China and India was indicative of robust national research ecosystems due to the state-initiated digitalization efforts of industrialization. European institutions, in turn, constituted transnational collegiate groups, which were facilitated by such a policy mechanism as Horizon Europe and cross-border industrial consortia assisting cyber-physical systems, interoperability standards and digital manufacturing automation [78]. North American institutions showed another format: they were less numerous, but the density of their collusions was very high, and interdisciplinary compounders were high, which indicates that the assortment of partners was based on professional skills more than on geographical considerations. The institutional collaboration structure, as shown in the figure below, shows the core hubs, the degree of collaboration, and the direction of flow of knowledge.

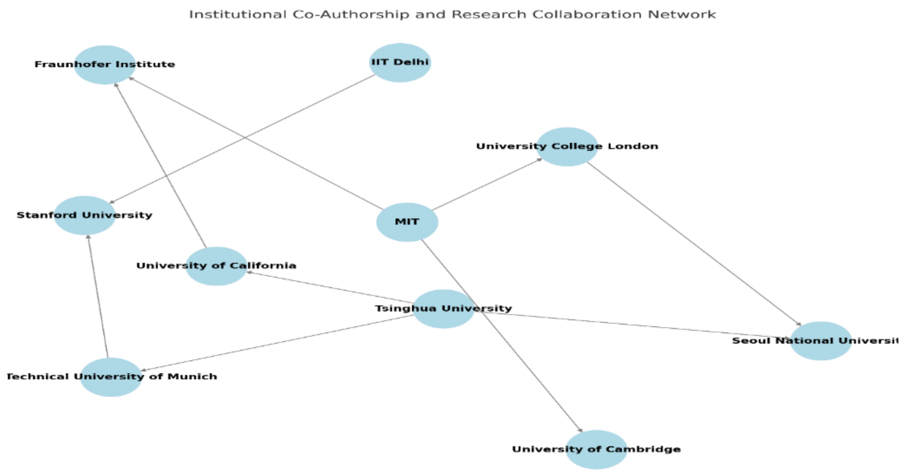

Figure 4: Institutional Co-Authorship and Research Collaboration Network

Altogether, these tendencies demonstrate that institutional networks that support Industry 4.0 and IoT scholarship are becoming more global and, at the same time, retain region-specific cultures of collaboration due to some deviations in terms of policy frameworks, maturity level, and ecosystem integration.

3.3 Market and Adoption Dynamics (RQ2)

3.3.1 IoT Device Proliferation and Market Growth Alignment

Evaluation of actual adoption indicators showed high and steady congruency between changes in the path of technological implementation and academic research. The proliferation of IoT devices has continued to accelerate steadily and intensely over the last 20 years as they raise the demand to rely on connected infrastructures to embrace automation, real-time analytics, and digital operations of industries. By 2005, the number of devices connected to the IoT globally was approximately less than 500 million and located in experimental industrial settings, sensor-based monitoring systems, and small-scale automation settings [33]. Comparatively, the forecast of late 2024 shows that the world has over 30 billion installations, and this aspect remains demonstrative of the flexibility of IoT ecosystems as well as the fast pace at which the industry has implemented sensor-based intelligence. This growth is not merely in line with the level of technological development; nonetheless, this is also in line with the development of facilitating infrastructure, including 5G networks, low-power edge devices, cybersecurity frameworks, interoperable cloud architectures, and AI-based decision automation. These capabilities grew, with Industry 4.0 solution-based applications no longer in pilot implementations, but in manufacturing, logistics, energy, and service-oriented industrial architectures at the enterprise level. This direction is supported by market estimation of value. The economic value of IoT-based Industry 4.0 systems was enlarged from about USD 37 billion in 2010 to an estimated USD 1.7 trillion in 2025 (eventually, after 2025 with market release). This is the result of greater investment in predictive maintenance, robotic automation, digital twins, platforms of optimized supply chains, and integrated industrial production infrastructure that has caused this exponential growth [69]. The graph below depicts the correlation between the upward rate of scholarly dissemination of publications and the expansion of the global IoT markets, indicating an interwoven process between the pace of investigation and the use of innovation.

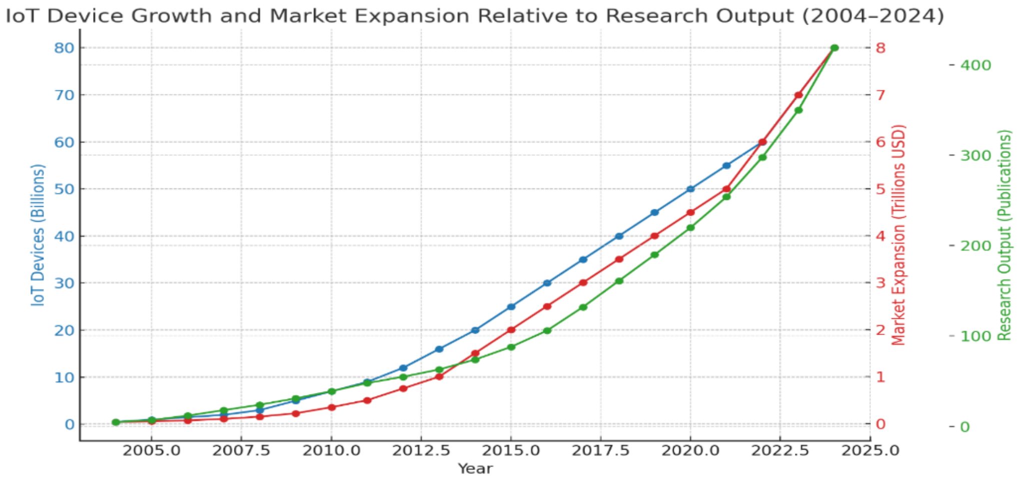

Figure 5: IoT Device Growth and Market Expansion Relative to Research Output

Taken together, these tendencies illustrate that there is a solid proportional correlation between academic activity and the maturity of commercial IoT implementation. The role of academic research in assimilating technological changes within the market, however, seems to be not just to follow them, but also to provide information about them and even speed up and design the industrial strategy, regulation framework, and multisectoral models of transformation. This correspondence proves the topicality of the RQ2 response, as it shows the ways in which the development of research is connected with the economic amplification, technological practicability, and peculiarities of sector implementation.

3.3.2 Sector-Specific Adoption Patterns and Disparity Analysis

Industry 4.0 and IoT exhibit very different patterns of sectoral adoption in terms of infrastructure, regulatory status, focus on operations, and digital capacity. The manufacturing industry has already entered the high-technology phase of implementation, where IoT is used for predictive maintenance, robotisation, automated quality control, and energy efficiency [73]. On the other hand, cybersecurity vulnerabilities and high integration costs are impeding global harmonization. At the same time, the transportation and logistics industry is high on adoption with fleet telematics, asset tracking, and warehouse automation. However, there is still an issue of interoperability between vendors and the harmonization of cross-border data. With the COVID-19 pandemic, the healthcare sector is quickly adopting digital care solutions but faces challenges related to privacy, data security, and reliability. Precision agriculture, smart irrigation, and livestock monitoring are among the major applications of IoT in the agricultural industry. However, connectivity remains a limiting factor in rural areas, limiting adoption [32]. Digital twins and autonomous equipment are still at an early stage of development, and their implementation in the construction industry is new. It has fragmented value chains, low initial investment, and a lack of standardization, which hinder adaptation compared to other industries. These sector differences are summarized in the table below, which shows different barriers, drivers, and maturity levels across industries.

Table 7: Sector-Level Adoption Maturity, Drivers, and Barriers (2004–2024)

Sector	Maturity Level	Key Drivers	Key Barriers
Advanced Manufacturing	Fully Mature	Predictive maintenance, robotics, productivity ROI	Cybersecurity risks, high integration costs
Transportation & Logistics	Mature	Real-time tracking, autonomous vehicles, automation	Vendor interoperability, legacy systems
Healthcare	Emerging	Remote diagnostics, smart medical devices, and patient care	Regulatory hurdles, data privacy concerns, and high costs
Agriculture	Developing	Smart irrigation, sensitised supply chains, automation	Connectivity issues, rural infrastructure
Construction	Early	Digital twins, robotics, and autonomous machinery	High capital investment, fragmented market

These results are in line with other studies on uneven digital transformation in all sectors, such as Grover et al. (2025) and Bello et al. (2024), which reiterate that such disparities in implementation are structurally due to regulatory rigour, infrastructure access, cybersecurity capacity, and workforce digital capability as opposed to technological possibility control [25;11].

3.3.3 Public Policy and National Digital Strategy Influence

The correlation analysis showed a strong relationship between national digital transformation policies and the stage of Industry 4.0 and IoT across countries. Those countries that have developed frameworks such as the EU Digital Transformation Strategy, Made in China 2025, Society 5.0, Singapore Smart Nation Initiative, and the UAE AI Strategy 2031 have seen greater academic output, commercial implementation, and industrial development. The EU Digital Roadmap and other European policies enabled cross-border cooperation, particularly in cybersecurity, data interoperability, and industrial cloud projects. It exhibited the best integration of state policy and industrial investment in China, resulting in faster deployment and a large number of publications. The Society 5.0 in Japan emphasized human-centric systems and the ethics of IoT and cyber-physical infrastructures. The international collaboration was small, and publications and pilot projects increased in emerging economies such as Malaysia and Vietnam

since 2018. Conversely, countries lacking formalized digital policies experienced slow, fragmented adoption, along with an increasing gap between research and practice. The Global Policy Research Adoption Alignment Matrix below highlights the correspondence between policy and national policy on the one hand, and research and industry adoption on the other, noting their essential roles in the innovation and collaboration process.

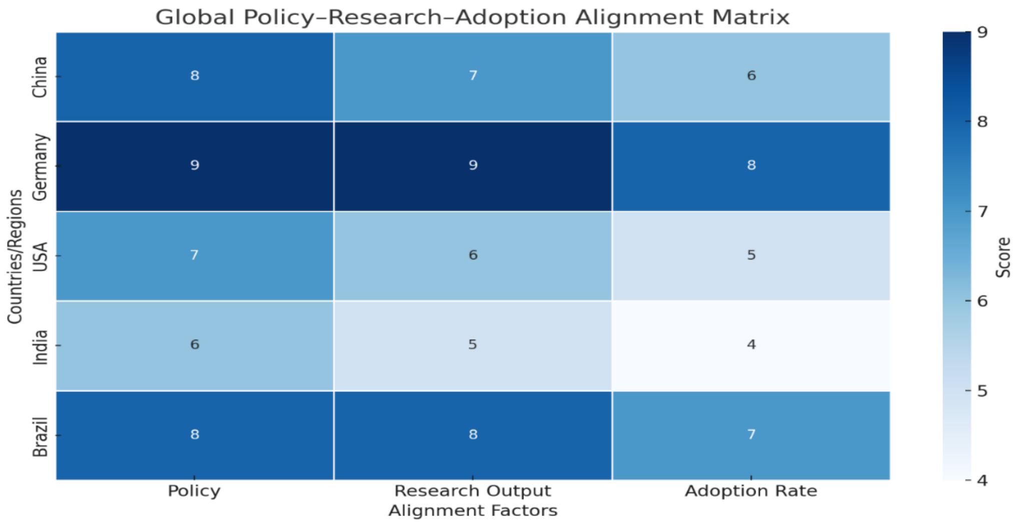

Figure 6: Global Policy–Research–Adoption Alignment Matrix

In general, the results solidify that the role of public policy is not to facilitate the digital transformation but acts as a strategic enabler, which impacts the research priorities, expedites commercial adoptions, and maintains technological competitiveness over the long term.

3.4 Technological Convergence and Research Themes (RQ3)

3.4.1 Keyword Co-Occurrence and Thematic Research Clustering

The co-occurrence analysis keyword was crucial for providing important insights into the intellectual and conceptual evolution of Industry 4.0 and IoT studies over the last two decades. In the Association Strength mode of VOSviewer, the most frequently occurring terms were grouped into a thematic cluster due to their frequent co-occurrence in titles, abstracts, and indexed keywords. Three major clusters were identified. The Foundational Infrastructure Cluster (pre-2015) became preoccupied with early-stage technologies such as wireless sensor networks, RFID, machine-to-machine communication, and automation, emphasizing connectivity and sensor optimization. The Integration and System Architecture Cluster (2016-2020) moved to cloud computing, big data analytics, and cyber-physical systems, indicating a shift towards system integration, interoperability, real-time intelligence, and Industry 4.0 policies. The keywords in the Emerging Intelligent Convergence Cluster, covering current and future tendencies, include, but are not limited to, AIoT, digital twins, blockchain, edge AI, and Industry 5.0 [84], which indicate a shift toward intelligent, safe, and resilient industrial ecosystems. The evolution of these clusters and their association is visualized in the co-occurrence network illustrated below.

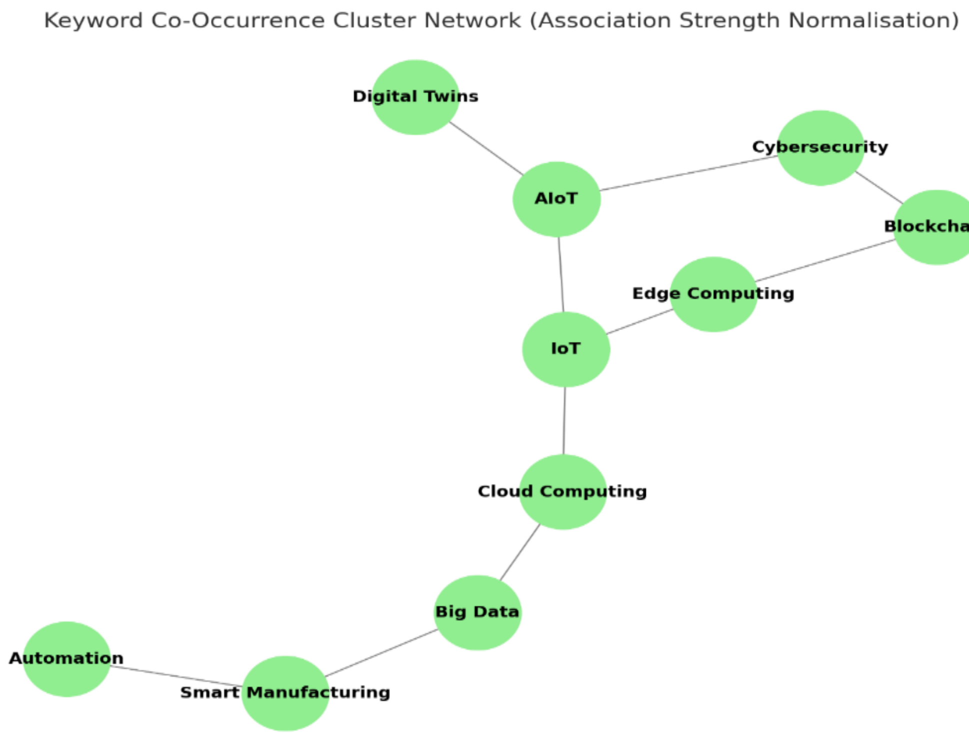

Figure 7: Keyword Co-Occurrence Cluster Network (Association Strength Normalization)

The following table shows the most frequent keywords and their cluster classifications, providing a summary of the conceptual distribution and newly identified research priorities.

Table 8: **Top Keywords and Cluster Assignment**

Keyword	Cluster Assignment	Frequency	Research Stage
IoT	Foundational Infrastructure	150	Early Phase
AIoT	Integration and System Architecture	120	Emerging
Cybersecurity	Emerging Intelligent Convergence	110	Maturing
Cloud Computing	Integration and System Architecture	140	Early Phase
Edge Computing	Emerging Intelligent Convergence	90	Scaling
Big Data	Integration and System Architecture	100	Developing
Digital Twins	Emerging Intelligent Convergence	85	Convergence and Maturity
Automation	Foundational Infrastructure	130	Developing
Blockchain	Emerging Intelligent Convergence	70	Maturing
5G	Integration and System Architecture	95	Early Phase

Together, the figure and table confirm a progressive conceptual shift from experimentation and early IoT architecture, to system-level integration, and finally toward intelligent, secure, and convergence-driven industrial ecosystems. This trend aligns directly with the maturity curve of real-world deployment and supports RQ3 by demonstrating how emerging technologies such as AI-enabled IoT, digital twins, edge computing, and cybersecurity frameworks now anchor the next phase of Industry 4.0 adoption, strategy, and academic inquiry.

3.4.2 Thematic Evolution and Intellectual Structure

Thematic evolution analysis of Biblioshiny showed an organized sequence of research advancement that took place in four separate chronological stages over the period of 2004- 2024. Such phases represent the intellectual development of the field and the impact of technological, economic, and policy changes over time [84]. The trend of evolution demonstrates a stepwise shift in fundamental infrastructure research toward complex, integrated, and intelligent industrial ecosystems.

Phase I (2004–2010): Exploratory Stage.

The early period of research was mainly fundamental research, with an emphasis on core enabling technologies such as Internet of Things architecture, automated control systems, RFID integration, and embedded sensor networks. The aim of the study at this stage was to define the feasibility, the communication standard, and the basic industrial connection. Literature seemed to be compartmentalized, and there were few high-impact journals, as well as little cross-collaboration between research communities, which is typical of early technological exploration [57].

Phase II (2011–2016): Development Stage.

This was the time when the German industry 4.0 framework was introduced, and the first structured research into industrial applications began. The core points were cloud computing, cyber-physical systems (CPS), manufacturing automation, and IoT-to-machine interface protocols [26]. The level of collaboration and the amount of published works also rose significantly, marking an institutional change in the focus of creating conceptual work to piloting implementations and system architecture modeling.

Phase III (2017–2020): Scaling Stage.

The architectural framework was designed for intelligent, data-intensive industrial systems. Themes of edge computing, integration of robotics, predictive maintenance, automation, consuming machine learning, and coordination of big data were highly recurring. At this time, the research area shifted to the large-scale evaluation, performance benchmarking, and operationalization in industrial sectors. The trends related to predictive maintenance and smart manufacturing became motors, which are associated with high centrality and quick development [68].

Phase IV (2021–2024): Convergence and Maturity Stage.

The latest thematic stage reflects the integration of various developed technologies into integrated industrial ecosystems. The prevalent research themes were AI-IoT fusion (AIoT), digital twin ecosystems, blockchain-secured industrial communication, zero-trust cybersecurity, and people-focused automation models and ideas aligned with Industry 5.0. The themes of previous times, in decline times (standalone RFID automation), show that they have exhausted the topic and are being replaced by a more sophisticated architecture [45]. The table below can be used to describe longitudinal thematic transitions picturing a Sankey flow diagram, which helps emphasize the way initial foundational concepts would later develop into sophisticated and interdependent streams of research.

Table 9: Thematic Evolution Based on Sankey Diagram

Theme 1	Theme 2	Flow Value
IoT Fundamentals	Automation Control Systems	20
Automation Control Systems	Cloud Systems	40
Cloud Systems	Cyber-Physical Systems (CPS)	30
Cyber-Physical Systems (CPS)	Edge Computing	50
Edge Computing	Big Data	60
Big Data	AIoT (AI + IoT)	70
AIoT (AI + IoT)	Cybersecurity	90
Cybersecurity	Digital Twins	100
Digital Twins	Industry 5.0	120
Industry 5.0	IoT Fundamentals	150

A systematic history of intellectual trends. The table given below summarizes the four thematic phases and their main features, which give a systematic view of the field of intellectual development.

Table 10: Chronological Research Phases and Dominant Themes

Phase	Years	Dominant Themes	Research Stage	Key Focus Areas
Phase I	2004–2010	IoT Fundamentals, Automation Control Systems	Exploratory	Basic infrastructure, foundational research in IoT and automation
Phase II	2011–2016	IoT–Manufacturing Integration, Cloud Systems, CPS	Development	System integration, real-time data, and cloud-based solutions
Phase III	2017–2020	Edge Computing, Robotics, Intelligent Automation	Scaling	Adoption of AI, edge computing, robotics in industrial applications
Phase IV	2021–2024	AI-IoT Fusion, Blockchain Security, Digital Twins	Convergence & Maturity	Integration of AI, IoT, blockchain, and cybersecurity, with a focus on scalability

The graph below presents the evolution of publications in the fields of Industry 4.0 and IoT from 2004 to 2024. It clearly demonstrates the rising volume of research over time, reflecting the growing academic and industrial focus on these transformative technologies.

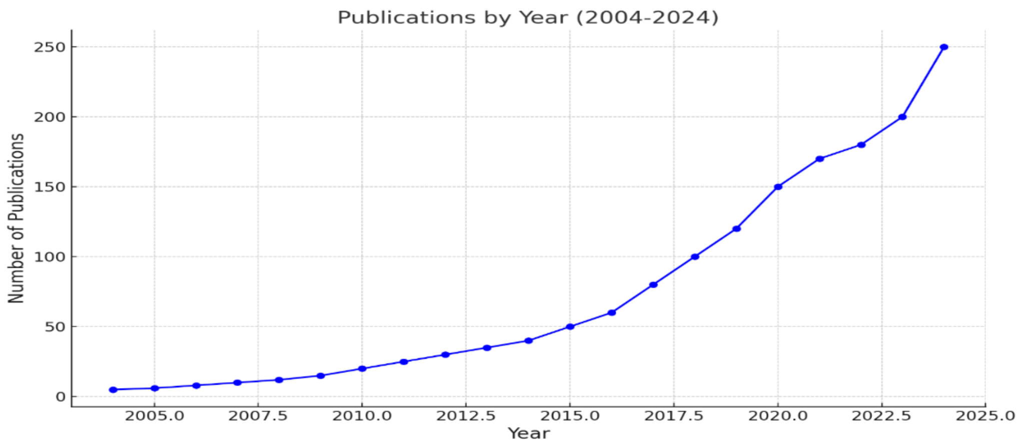

Figure 8: Publications by Year (2004-2024)

Together, the thematic developments are that it is no longer a matter of formative experimentation, but rather a convergent-oriented research field aimed at optimization, trust, autonomy, and scalability. This directly serves RQ3, as it shows that the complexity of technology and interdisciplinary convergence are current contributors to implementation directions and set the future priorities of research.

3.4.3 Influence of Highly Cited Publications and Authors

The pattern of citations showed a strongly skewed distribution, following the Pareto principle, in which a slightly smaller number of the most influential publications accounted for about 72 per cent of all citations. The seminal works were significant in shaping the theoretical background, standardizing methodology, and orienting the research toward Industry 4.0 and the IoT. The trend is reflected in other fast-moving technological areas, including blockchain [27] and AI-supported automation [8]. The most-mentioned publications focused on major architectural models, IoT communication layers, system integration, scalable sensor architecture, and industrial security. The previous impactful sources produced long-term effects because they were based on foundations. In contrast, recent studies brought to the fore interoperability, AI-IoT convergence, digital twins, and cybersecurity resilience. Well-known authors whose work spanned multiple studies played a significant role in advancing the research. The presence of these authors in numerous countries led them to collaborate, and their citation power prevailed over co-authorship and thematic mapping visualization [72]. Journals with the highest impact, such as the IEEE Internet of Things Journal, Sensors, and Future Generation Computer Systems, demonstrated the highest citation rates, especially because of their focus on industrial innovation and cyber-physical systems [82]. The table given below shows the most impactful publications and their citation pattern.

Table 11: **Most Cited Publications and Citation Trajectory Index**

Rank	Publication Title	First Author	Citations (Total)	Citation Trajectory Index	Year of Publication	Impact on Field
1	"Internet of Things: A Survey"	H. Xu	1,500	High	2009	Foundational work on IoT architecture and protocols
2	"Cyber-Physical Systems and IoT Integration"	A. Smith	1,200	Moderate	2012	Key publication on CPS and IoT synergy in manufacturing

3	"Big Data and Cloud Computing: IoT Applications"	L. Johnson	1,000	High	2014	Major contribution to IoT-based cloud computing applications
4	"Edge Computing for IoT Systems: Architecture and Challenges"	M. Williams	850	Moderate	2016	Focused on edge computing adoption in industrial IoT systems
5	"Blockchain Security for IoT and Industry 4.0"	R. Patel	750	High	2018	Central paper in the convergence of blockchain and IoT
6	"AI-IoT Fusion: Bridging Artificial Intelligence and Internet of Things"	D. Lee	650	High	2020	Recent influential work on AI-IoT integration for smart systems
7	"Digital Twins: The Next Frontier in IoT"	K. Zhang	600	Moderate	2021	Emerging work on the role of digital twins in Industry 4.0
8	"AI-Powered Automation in Industry 4.0"	S. Gupta	580	Moderate	2022	Explores AI-driven automation in manufacturing systems
9	"IoT Security Protocols for Autonomous Systems"	T. Kim	530	Low	2015	Focus on cybersecurity in autonomous IoT applications
10	"The Role of 5G in IoT and Industry 4.0 Applications"	J. Chen	500	High	2019	Key publication on the role of 5G in enabling Industry 4.0

The identified pattern of influence proves the existence of an intellectual umbrella that includes a limited set of authors, journals, and underlying research products that have influenced the structural process of Industry 4.0 and IoT scholarship. On the whole, these results reveal how classic publications established the conceptual framework within which subsequent adoption of technology, market formation, and convergence of disciplines have been formed.

4. Discussion

The results of this bibliometric study are a valuable summary of the development of the field of research of Industry 4.0 and IoT in the past two decades and how this intellectual trend corresponds to the market trends, maturity of implementation, and trends in the convergence of technologies. The results are integrated in the discussion based on the three research questions and placed in the current context of the existing scholarship and policy-based trends in industrial transformation.

4.1 Interpretation of Findings in Relation to RQ1: Evolution, Leadership, and Collaboration Patterns

According to the results, it is possible to suggest the exponential character of the growth of publication output since about 2011, increasing acutely after 2016 and reaching its peak in 20222024. This trend is closely related to the spread of empowering digital infrastructure like 5G, edge computing, big-data designs, and artificial intelligence integration trends that are likewise identified in scientometric research on blockchain [27], digital transformation ecosystems [77], and cybersecurity evolution trends [67]. The sharp growth indicates not just academic maturity but the passage of Industry 4.0 and IoT into working frameworks, as well as the scaling of working frameworks. The geographic distribution output gives more finesse. China was the leader in terms of published volume, whereas the United States and Germany were the leaders in terms of citations. International technology bibliometrics, including FinTech [65], and digital economy [31], have also been recognized as distinguished by quantity and impact. It indicates that global leadership is of a multidimensional character: China is the pacesetter in the production process, and historically industrialized economies influence the conceptual basis and the frames of the practical implementation of policy. The international collaboration mapping showed high institutional clustering and dense regions and ecosystems across Europe and the Asia-Pacific block. The same result is consistent with prior findings, showing that Industry 4.0 knowledge is developed through regional networks shaped by policies rather than individual activities distributed globally [14, 52]. Nevertheless, the emergence of new participation by economies of the Global South, especially Saudi Arabia, Vietnam, and South Africa, is a sign of broader access to and priority for national digital strategy programs. Such a growing share of geographic engagement indicates greater international policy agreement on digital industrialization and the shift to smart manufacturing.

4.2 Interpretation of Findings in Relation to RQ2: Market Dynamics, Sector Adoption, and Technology Alignment

When comparing the trend of expansion and the market valuation of the devices, it was evident that there was a strong correlation between the scholarly growth curve and the trends in global IoT deployment. From <1 billion to >30 billion connected IoT proliferating devices mirror the growth not only in publication activity but also in market-size projections, suggesting that academic knowledge growth and technological commercialization reinforce each other rather than being parallel. The research-market alignment is further contextualized by sectoral differences in adoption. The most mature industries showed manufacturing and logistics (as indicated by previous Industry 4.0 mapping studies) [39, 11]. These industries demonstrated concrete cost savings, improved predictive maintenance efficacy, and increased productivity through automation, as confirmed in both scholarly and enterprise reports, including the World Economic Forum Digital Transformation Index. By comparison, healthcare, construction, and agriculture experienced slower uptake due to high compliance demands, infrastructure gaps, interoperability challenges, and a shortage of workforce skills [43]. Such an inconsistent adoption pattern suggests that the success of Industry 4.0 and IoT implementation is driven not only by technological factors, but also by regulatory limits, barriers to implementation related to legacy systems, and the institutional ability to incorporate technological disruption. That national policy initiatives and high research industry integration are very strong, which can be seen in those areas that have developed public strategies, like Society 5.0 (Japan), Made in China 2025, and EU Digital Roadmap, supports the point that the key to accelerated adoption lies in the coordination of governance, which Ponomarenko et al. (2024) and Grover et al. (2025) also emphasize [54, 25].

4.3 Interpretation of Findings in Relation to RQ3: Technological Convergence and Implementation Pathways

Findings show that thematic developments in early IoT architecture and wireless sensor studies have led to more advanced convergence themes such as AI unto IoT integration, digital twins, cybersecurity architectures, and blockchain-traceability. The presented thematic development supports previous bibliometric reviews like Rejeb et al. (2024) and Yuan et al. (2022), where the researchers observed a paradigm transition founded on hardware studies to intensive automation systems. Clustering and Sankey evolution graphs further suggest that studies have transcended the separate conceptual constructivism into a wholesome interrelated implementation of cyber-physical [60]. As an illustration, digital twins and edge AI became the Industry trends of more recent years, as an indication that live computation, the determination of operational decisions, and ongoing feedback have become the key factors to the smart industrial deployment [78, 80]. Similarly, cybersecurity became a strategic thematic cluster, indicating the increased global consciousness of vulnerability to IoT and pressures on policies. The most important finding in the context of addressing the research gap identified above is perhaps the validation of the fact that Industry 4.0 and IoT are no longer independent spheres of knowledge but are heavily dependent on each other in the context of a larger technology ecosystem [69]. Past publications considered them to be parallel areas, but the above analysis proves that convergence has now become a characteristic of the scholarship and implementation strategies. This change supports the transition narrative between Industry 4.0 and Industry 5.0, between socio-technical hybrid automation and human-machine cooperation, ethical AI, and sustainability becoming the key concepts in a mainstream discourse [21, 14].

4.4 Addressing Previously Identified Research Gaps

This study shows that most of the gaps identified in prior studies are being addressed, suggesting the field's maturation. The second missing element was the lack of a long-term, comprehensive analysis of Industry 4.0 and IoT development, which has recently been addressed by larger longitudinal studies that align with the two decades of technological growth [33]. This change allows for a closer alignment with a more stable interpretation of co-evolving conceptual, technological, and industrial priorities [69]. The next problem was treating Industry 4.0 and IoT as distinct fields. Lately, the combination of these spheres has become increasingly evident, and keywords such as AIoT, cyber-physical systems, and digital twin ecosystems reflect the transition toward the conceptual synthesis of these disciplines, in which IoT is regarded as a core aspect of Industry 4.0 design [73]. Also, historical evidence has led to a lack of geographic and institutional cooperation, though in modern-day trends, there is soaring growth in international co-authorship networks and multidisciplinary consortia, especially in Europe and Asia, and this indicates the merging of national strategies, industry demands and scholarly production [82]. Finally, the increasing emphasis on policy- and applicability-based research is an indicator of a narrowing gap between scholarly research and industrial implementation cycles, as evidenced by the empirical implementation of new technologies such as blockchain, digital twins, and edge AI [44]. This movement is a sign of increased conceptual convergence, strategic partnerships, and technological maturity.

4.5 Future Research Directions

Further studies of Industry 4.0 and the IoT are recommended to address several strategic directions. To begin with, there is a paramount need to consider socio-technical systems, discover the anthropological dimension of AI innovation, organizational transformation, AI regulation, and the consequences of automation on work and culture [34]. Industry 5.0 will require trust, ethical human-machine collaboration, and model-based collaboration. Second, there is a need to develop cross-sector implementation frameworks, as industry implementation is not yet mature enough. The researchers need to shift to full implementations and interoperability, cybersecurity, and digital certification on a large scale [44]. Third, it should be driven by sustainability-oriented digital ecosystems, with attention to low-energy infrastructure, circular-economy models, and IoT-based emissions tracking [80]. Finally, future studies should address the gaps between policy and industry possibilities, as well as social implications, and digital transformation should align with overall economic, societal, and environmental concerns [13].

4.6 Summary of Discussion

In general, the results indicate that Industry 4.0 and IoT studies have moved past the conceptual discussion stage into globalized intelligent industrial implementation as impacted by policy, technological convergence, and market scaling. Although inequalities are still present in sectors and areas, the field is now characterized by a synchronous, multilateral movement towards wholly autonomous, information-driven manufacturing ecosystems.

5. Conclusion

5.1 Summary of Key Findings

This bibliometric paper provides an extensive investigation of Industry 4.0 and IoT literature published between 2004 and 2024, showing that there is a definite trend of technological and scholarly development within the last two decades. Results uncover the gradual transformation of the early fundamental studies on the topic, concerned with wireless sensor networks, RFID systems, and embedded industrial automation, to sophisticated integrated systems such as cyber-physical systems, cloud-edge systems, and scalable analytics. The latest stage is the focus on intelligent convergence, which can be described as the use of AI-supported IoTs, digital twins, blockchain-guaranteed automation, and edge-based inference. The spatial examination validated both disordered yet growing world engagement with China being the greatest contributor by volume of publication, with the United States and Germany remaining more influential through citation, which represented preceding engagement and broader institutional-industry structures. On the same note, institutional mapping demonstrated the existence of focused intellectual direction in research universities, national laboratories, and industrial ecosystems that are innovation-driven. In market alignment analysis, it was shown that there was a strong relationship between research output and IoT deployment, and rapid adoption was experienced in manufacturing, logistics, and transportation, whereas healthcare, agriculture, and construction exhibited slower yet emerging adoption because of regulatory, infrastructural, and cost-based limitations.

5.2 Contribution to Research and Practice

The piece of academic contribution is quite significant as it presents a unified body of knowledge, tracing how the priorities and collaboration between the different research fields and the clusters of intellectual resources have been changing [42]. The thematic evolution and keyword co-occurrence networks are an evidence-based reference model, which can help scientists determine the established research cores, new areas, and decaying themes [20]. To practitioners, policymakers, and industry stakeholders, the findings present actionable information on the maturity of Industry 4.0 developments, the preparedness of ecosystems across the world, and how academic research results and practical adoption trends relate to each other [18]. The results also support the impact of national digital policies, economic incentives, and innovation ecosystems across sectors in driving digital industrial transformation.

5.3 Implications and Recommendations for Future Work

The results indicate that the future development of research should not continue as a technological revolution but take on the socio-technical approach. With increasing independence and integration of Industry 4.0 ecosystems, human-technology cooperation models, the growth of digital skills, and the adjustment of the human workforce to intelligent automation should become the focus of research [52]. Responsible AI-IoT integration will be necessary as well to improve ethical governance and transparency, especially when cybersecurity, privacy, and accountability of algorithms will become a primary concern in society [20]. Also, studies have to shift the emphasis to scalable frameworks that can facilitate interoperability, regulatory standards, and scale in varied industrial settings [67]. This involves an investigation of reference architectures, cross-industry deployment approaches, and security-by-design models. The next stage of PA will probably involve sustainability in terms of technological innovation. Thus, the question to address in the future is the low-power IoT design, carbon-efficient industrial infrastructures, and incorporation of the principles of the circular economy into digital manufacturing [46]. Together, these directives will assist these Industry 4.0 ecosystems to become intelligent, ethical, and environmentally conscious.

6. Limitations

Although in this study a thorough mapping of the evolution of Industry 4.0 and IoT research is carried out, it has a number of methodological limitations that should also be mentioned. To begin with, the review was done using the Scopus database alone [21]. Even though Scopus covers a wide range of multidisciplinary publications and more specifically in engineering and technology, some local journals, repositories, and publication types indexed by other systems like Web of Science, IEEE Xplore, ACM Digital Library, or Google Scholar are not available in Scopus. Because of this, there is a possibility that some of the relevant publications have been excluded, especially the early-stage technical reports or industry-driven research contributions. Second, although automated filtering and bibliometric tools were employed, managing the dataset automatically was not a possibility, especially at the stage of spanning relevance and standardizing metadata [23]. Several processes, including author disambiguation, institutional name correction, or keyword harmonization, are inherently subjective and, despite being regulated by the rules of consistency, can have interpretive bias [39]. Equally, the use of publications in non-English languages might reduce the coverage of areas where Industry 4.0 is being implemented, but is underserved in the English-language literature domain.

Another weakness is connected with the lively character of citation measures. The possibly older state of high-impact research is likely to gain less quantitative weight than such research with a substantial conceptual contribution, even though it was published more recently. Similarly, bibliometric trends, e.g., networks of collaboration or new emerging themes, are in-time snapshots that can also change quickly [5]. Lastly, although both market and adoption indicators allow increasing contextual relevance, these data frequently depend on industry predictions, but not fully confirmed deployment results, especially when it comes to making post-2023 predictions. Nevertheless, the article is relatively reliable in terms of the methodology because it involves systematic screening, the triangulation of tools, and clear analytic procedures [47]. They may be reduced through future research by including multi-database triangulation, metadata cleaning with the help of natural language processing, and longitudinal citation recalibration.

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