I 4.0 and Quality Management.
A bibliometric review about challenges, drivers and trends for its adoption

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Abstract

Purpose: Industry 4.0 (I 4.0) enables companies to produce high-quality products and services at lower costs, making business processes more sustainable. By exploring this topic, the aim of the paper is to analyze the evolution of I 4.0 research, identifying the leading journals and influential papers that have shaped I 4.0 and Quality Management. We examine the conceptual structure and core topics within I 4.0 research, including the understanding of how advanced technologies drive transformation, promote sustainability, and evolve quality management practices.

Methodology: Our research explores the relationship between I 4.0 and quality management through bibliometric analysis. We started with an initial sample of over 400 papers and selected 209 for detailed analysis.

Findings: I 4.0 encourages the integration of advanced technologies into quality management. It highlights the importance of developing new skills, fostering a supportive culture, and increasing customer involvement to improve quality. However, more research is needed in areas like Big Data, Analytics, AI, and Skills Development to understand and fully address the transformative impacts of Industry 4.0. Contributions from countries such as India, the UK, China, and Italy indicate a global interest in using advanced technologies to boost economic growth and industrial development.

Research limitations/Implications: I 4.0 transforms quality management by integrating advanced technologies, enhancing competitiveness and sustainability. Ongoing research and strategic implementation are essential to maximise the benefits of this transformation, improving industrial processes and productivity. Future studies should focus on incorporating AI, Big Data, and cyber-physical systems into quality management, fostering a supportive culture, and enhancing customer-centric practices.

Originality/Value: Differently from previous literature analysis and bibliometric studies, this paper analyses the topic of I 4.0 and quality management in a comprehensive overview that integrates various aspects of I 4.0 and quality management. Unlike prior studies that may focus narrowly on specific elements or methodologies, this paper aims to synthesise findings across multiple dimensions, including technological advancements and main trends.

Keywords: I 4.0; TQM; Quality Management, Bibliometric Analysis

Type of paper: Bibliometric review.

1. Introduction

Industry 4.0 (I 4.0) outlines a fundamental change in manufacturing to meet the continuously growing customer demand by integrating high-quality products with digitalisation and traditional methods, including quality and Quality Management (QM) principles. Automation, real-time data analytics, predictive maintenance, and human-machine interaction impact decision-making across business functions, and they foster flexibility and efficiency, optimising the overall company value chains. The growing research on I 4.0 in recent years underscores the scholarly interest in comprehensively analysing such a transformation's impact, benefits and limitations. Papers have been offered to academic audiences focusing on key topics, tracing the development of I 4.0 research, and laying the foundations for understanding the technological drivers, sustainable practices, and evolutionary concepts such as Quality Management and future trends. Given the promising interest in the topic, both from practical and theoretical perspectives, bibliometric studies have been conducted, with a prevailing focus on specialised areas such as Agile development, Quality 4.0, maturity models, and environmental sustainability. Such a literature direction highlights, from one side, the need to identify, evaluate, and synthesise the phenomena of I 4.0 comprehensively and quantitatively in terms of impact and patterns of publications, but also, within such a direction, the missing analysis of the overall I 4.0's impact on quality management. Because of this gap, our study aims to analyse the current trends, influential papers, conceptual and intellectual framework, and country collaboration in I 4.0 and QM research. The paper is organised as follows: section 2 presents the research background and research questions, section 3 presents the bibliometric methodology and the main results, and section 4 presents the implications and conclusion.

2. Research Background and Research Questions

I 4.0 is a transformative paradigm that integrates traditional manufacturing processes with state-of-the-art industrial practices (Agarwal and Ojha, 2022), enabling companies to produce high-quality output and meet the increasing demands of customers (Rifqi et al., 2021). I 4.0 is based on interconnected systems driven by digital technologies (Zhong et al., 2017) that allow human-machine interaction and automate production chains, fostering flexibility and efficiency. Central to I 4.0 are principles emphasising quality and QM as core elements. QM is an approach which leads organisations to use their resources in an efficient way with continuous improvement to satisfy the customers' expectations and satisfactions. It has been an evolving concept since the Industrial Revolution, and the practices of the concept are changing via many researchers or practitioners (Rifqi et al., 2021). I 4.0 is highly connected with quality management and TQM (Ali et al., 2022; Canbay and Akman, 2023; Pongboonchai-Empl et al., 2023; Ali et al., 2022; Pongboonchai-Empl et al., 2023), and it could benefit from its principles based on fostering quality and continuous improvement culture, leadership commitment, and effective relationship management by refining existing knowledge and nurturing continuous improvement to identify short-term gains, streamlining value analysis and minimising waste (Davenport, 1993; Hammer and Champy, 1993). QM, through I 4.0 automation and real-time data analytics, can improve the decision-making process across business functions (i.e. production, marketing, maintenance, supply chain management and finance). An example is the efforts to support personalised marketing and efficient customer service practices, collectively enhancing the overall customer experience through access to real-time data and advanced analytics. Also, cost savings through a bottom-up strategy and statistical approach are pivotal in reducing performance variation and enhancing product consistency and customer satisfaction (Elibal and Özceylan, 2022; Maganga and Taifa, 2022; Prashar, 2023). In addition, companies can quickly adapt to market changes and customer demands by adopting predictive and prescriptive maintenance, optimised supply chains, and increased agility and resilience through flexible production systems and digital twins.

Growing research on I 4.0 shows scholars' increasing interest in analysing this phenomenon properly (Babatunde, 2020). Comprehensive empirical studies focus on I 4.0 concepts, definitions, and models,

including quality applications, which have already been taken in the literature. For instance, Alsadi et al. (2024) investigate the specific topic of Quality 4.0, focusing on specific key areas: agile product development, predictive quality algorithms, cloud databases, automation, reduced cost of quality and streamlined quality processes. Limitations include the novelty of the Quality 4.0 topic, which made finding academic material challenging, and the six-year analysis period, which may have restricted the coverage of more recent research developments.

Similarly, the review by Singhal et al. (2024) assesses the state and gaps in "Green-JIT," considering environmental sustainability with JIT under I 4.0. Their study is limited by the scope of environmental sustainability and JIT within the I 4.0 context. Finally, the study by Kucińska-Landwójtowicz et al. (2023) focuses on organisational maturity models (OMMs), their development, and classification, as well as identifying research gaps and potential development areas in the context of scientific research and management practitioners needs. Another interesting study (Khanuja et al., 2024) focuses on bibliometric analysis of the usage of I 4.0 technologies in healthcare and how they can help to improve services, efficiency, and patient care.

Therefore, few specific studies in the literature have quantitatively analysed the development and impact of I 4.0 and quality management, the key influential works, sources, and regions driving research, the foundational concepts, and the collaboration patterns to understand the global research network. While these studies provide valuable insights and identify opportunities and gaps for future research within their focused domains, they do not offer a comprehensive overview framework about I 4.0 and QM. Given this gap, we aim to explore the comprehensive landscape of I 4.0 in quality management. Particularly, we want to identify how I 4.0 research has developed over time and pinpoint the leading journals and influential papers that have shaped the field. Finally, we want to understand the conceptual structure and core topics within I 4.0 research, including how advanced technologies drive transformation, promote sustainability, and evolve quality management practices by shaping future directions.

Our Research Questions (RQs) are the following:

RQ1: What are the current trends, evolution, and key publications and citations about I 4.0 and quality management research?

RQ2: What are the country collaboration patterns and which countries are the most productive and influential in the field of I 4.0 and quality management research?

RQ3: What are the key topics and conceptual structure in I 4.0 and quality management research?

3. Method section: the search strategy

We adopt a bibliometric analysis to provide a more comprehensive understanding of I 4.0 and QM by collecting evidence from the literature, which is sparse in the various related research fields. Utilising bibliometric software (Alsadi et al., 2024), we perform quantitative analysis to explore and analyse research articles' metadata by operating an I 4.0 descriptive analysis, which includes the most cited papers and influential authors in the field, the volume and distribution of relevant I 4.0 papers, the network analysis through the co-authorship network to visualise collaboration patterns among researchers and the thematic analysis for generating a thematic map to identify key topics and their evolution in I 4.0 research. The articles were identified using the Scopus database, widely recognised as the world-leading database (Paschou et al., 2020). In particular, we use two sets of keywords related to the general concepts of ("Industry 4.0" or "I 4.0") and ("Quality Management") to search for relevant articles.

Initially, 426 studies were identified from the search process. Subsequent filtering based on criteria such as language (English), document type (original articles at the final stage), and research areas (business management, economics and engineering) resulted in a refined set of 209 articles for the bibliometric analysis.

4 Bibliometric analysis and findings

4.1 Main Statistics

This study conducted a comprehensive review of research on "I 4.0" in the context of quality management, covering a period from 2014 to 2024. A sample of 209 relevant studies, authored by 607 researchers, was examined, with an average of 17.43 citations per document. These studies were published in 100 different publication outlets. The analysis revealed that authors also participated in multi-authored studies, with 26.32% engaging in international co-authorships.

As depicted in Figure 1, published studies on I 4.0 and quality management have exhibited an annual growth rate of 38.52%. In terms of production and total citations per paper and year, we notice an exponential growth of topic interest after the first five years, indicating a rising relevance in the field.
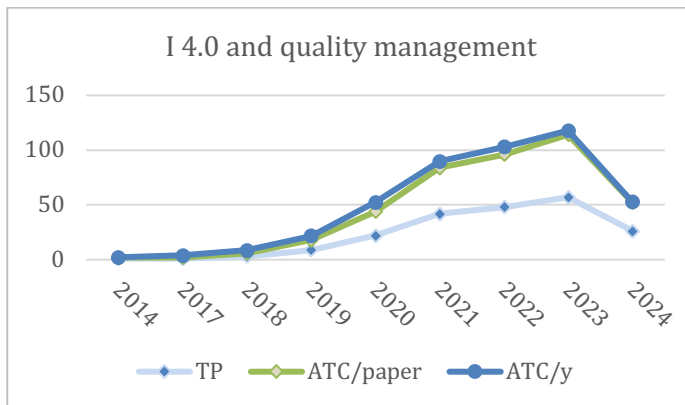

Figure 1: Annual growth of scientific production. TP = total global citation, ATC/paper = average global citation per document, ATC/y = average global citation per year.

4.2 Most relevant Journals, articles and countries

This section presents the most impactful journals, articles and countries in the field of I 4.0 and quality management studies. Table 2 summarises the top journals publishing research in this area, representing diverse academic disciplines encompassing strategy, business and management, operations management, environmental science, sustainability, engineering and decision science. Among the 100 journals identified, the TQM journal dominates with 24 articles and 711 citations. Only four other journals have published more than 10 articles in this emerging field: the International Journal for Quality Research (13 articles), TQM and Business Excellence (10 articles) and the International Journal of Quality and Reliability Management (Table 1).

Journal	h_index	TC	NP	PY_start
TQM JOURNAL	79	711	24	2020
INTERNATIONAL JOURNAL OF QUALITY AND RELIABILITY MANAGEMENT	97	211	10	2021
TOTAL QUALITY MANAGEMENT AND BUSINESS EXCELLENCE	94	206	10	2018
SENSORS	245	174	6	2021
INTERNATIONAL JOURNAL OF PRODUCTION RESEARCH	186	164	2	2022
INTERNATIONAL JOURNAL OF QUALITY AND SERVICE SCIENCES	39	120	3	2019
APPLIED SCIENCES	130	43	6	2021
TECHNOLOGICAL FORECASTING AND SOCIAL CHANGE	179	38	2	2022
INTERNATIONAL JOURNAL OF COMPUTER INTEGRATED MANUFACTURING	69	29	3	2021
COMPUTERS AND INDUSTRIAL ENGINEERING	161	21	2	2021

Table 1: Most influential journals. TC = total citation, NP = number of publications, PY = starting period.

Table 2 overviews the top significant studies in I 4.0 and quality management. The impact of these articles is indicated by total citations (TC). The three most prominent papers by Zonnenshain (2020), Sony (2020), and Chiarini (2020) highlight the importance of Quality 4.0 as a common topic. They

underscore the relevance of integrating technological innovations such as Big Data, analytics, artificial intelligence (AI), and cyber-physical systems into quality management practices by developing new skills and fostering a culture that supports Quality 4.0. This includes providing education and training on Quality 4.0 principles and practices, customer involvement in the value creation process and customer-centric quality improvements as a shared topic. The papers recognise the need for further research to explore and refine I 4.0 concepts from different angles, such as Quality 4.0 issues related to Big Data, Analytics, AI, Skills Development, and Data-Driven Innovation (Chiarini, 2020; Sony et al., 2020; Zonnenshain and Kenett, 2020). They also provide practical implications and guidance for organisations looking to implement Quality 4.0 models and emphasise the transformative impact of I 4.0 technologies and Quality 4.0 strategies on manufacturing and quality management (Javaid et al., 2022). They underscore the importance of leveraging digital tools, fostering organisational readiness and addressing implementation challenges to achieve enhanced quality, competitiveness, and innovation in the Fourth Industrial Revolution context (Psarommatis et al., 2023). The other papers collectively highlight integrating advanced technologies like machine learning and digitalisation to enhance manufacturing and engineering quality, efficiency, and competitiveness. Furthermore, they emphasise the need for evolving traditional quality models and methods, such as Zero Defect Manufacturing, to align with technological innovation (Benbarrad et al., 2021; Powell et al., 2022; Psarommatis et al., 2023).

Paper	Total Citations	TC per Year	Normalized TC
ZONNENSHAIN A, 2020, QUAL ENG	160	32,00	3,78
SONY M, 2020, TQM J	158	31,60	3,73
CHIARINI A, 2020, TQM J	132	26,40	3,12
PSAROMMATIS F, 2022, INT J PROD RES	125	41,67	5,93
POWELL D, 2022, COMPUT IND	96	32,00	4,55
BENBARRAD T, 2021, J SENS ACTUATOR NETW	80	20,00	3,49
PSAROMMATIS F, 2020, FRONTIER COMPUT SCI	80	16,00	1,89
FAN W, 2021, STRUCTURES	78	19,50	3,40
JAVAID M, 2021, SENS INT	76	19,00	3,31

Table 2: Top articles on "I 4.0 and QM"

Table 3 shows the most productive countries in the "I 4.0 and QM" literature. These countries have a high impact because they have contributed many research publications in this field.

Country	Articles	SCP	MCP
INDIA	21	18	3
POLAND	13	11	2
UNITED KINGDOM	13	7	6
CHINA	12	8	4
PORTUGAL	11	8	3
ITALY	8	5	3
CZECH REPUBLIC	7	6	1
GERMANY	7	5	2
SLOVAKIA	6	4	2

Table 3: Top Countries' Production and Most Cited Countries

Moreover, India, Poland, the UK, China, Portugal, Italy, the Czech Republic, Germany, and Slovakia emerged as the countries that produced the most publications with a good grade of authors collaboration (Fig. 2).
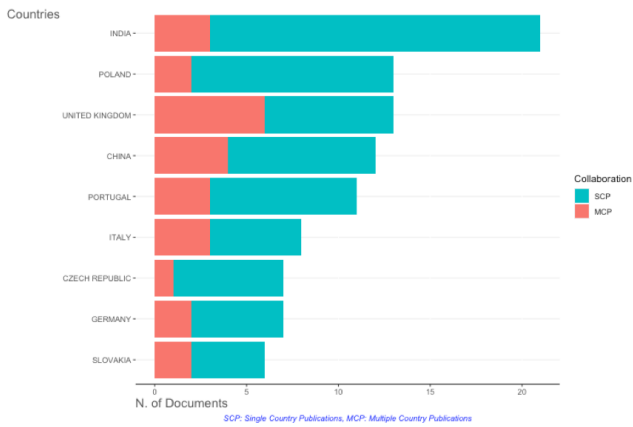
Figure 2: International authors' collaboration. (SCP: intracountry collaboration; MCP: intercountry collaboration)

4.3 Topic and Keywords Trends

In this subsection, we present a thematic analysis to detect the main research topics of the field through co-occurrence network analysis and thematic evolution using a thematic map.
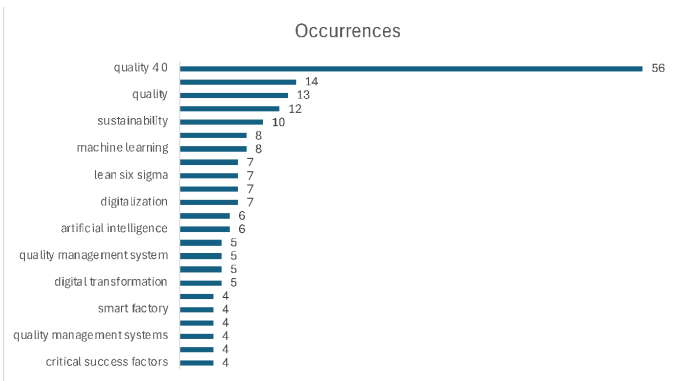

Figure 3: Most Relevant Words

Figure 3 shows the most frequent keywords in the dataset. Interestingly, "Quality 4.0", "digitalisation", and "machine learning" are on the top. This confirms the I 4.0 and QM trend towards the importance of digital transformation as a process that integrates and combines technological and organisational dimensions. Notably, the word "sustainability" appears on the top, highlighting the importance and awareness of sustainability for I 4.0 practices. The trend topic in Figure 4 explains the dynamics of trending subjects and classifies them, giving us an idea of the most frequently mentioned items and how their relevance has shifted. We classify the distribution according to three main topics:

a) Early Focus_(2020-2021): this thematic area revolves around the integration of I 4.0 technologies, such as the Internet of Things (IoT), machine learning, robotics, and cloud computing, with organisational performance, quality management systems (QMS), and Lean Six Sigma (LSS) methodologies. The core themes explored in these papers include the enhancement of organisational performance indicators, the evolution of quality management in the I 4.0 era (referred to as Quality 4.0), and the practical implications and strategies for implementing these technologies in various sectors.
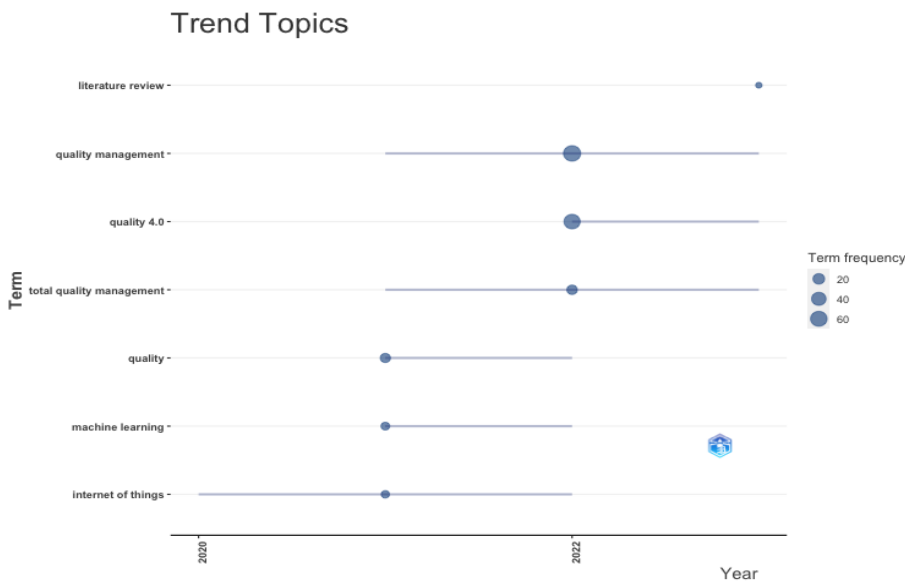
Figure 4: Evolution of trends topic over time

b) Growing Focus (2022-2023): this area covers a wide spectrum of topics related to Quality 4.0, encompassing conceptualisations, implementation strategies, technological innovations, human-centric approaches, sector-specific applications, environmental sustainability, analytical reviews, and specialised methodologies. This area reflects how Quality 4.0 is being researched, applied, and integrated across different industries and organisational contexts. "Quality 4.0," "Total Quality Management", and "Quality Management" showed an increasing trend from 2021 onwards, with a noticeable rise in importance up to 2023. This suggests that the concepts of Quality 4.0 are relatively new topics, but they quickly became significant.

c) Recent Focus (2024): "Literature Review and other themes" became notably relevant in 2024, indicating a new area of concentration or possibly a consolidation of past research efforts. This focus highlights the need and importance of systematising previous research and knowledge about advanced quality management practices with I 4.0 technologies. The focus spans from theoretical frameworks and literature reviews to practical applications, organisational readiness assessments, and sustainability considerations, reflecting the broad scope of research and development in Quality 4.0 within the context of industrial practices. The collection of studies and reviews underscores the multifaceted impact of Quality Management practices as they converge with I 4.0 technologies. Systematic literature reviews and bibliometric analyses reveal the evolving trends and factors influencing Quality 4.0 adoption, from the synergistic role of QM 4.0 in enhancing I 4.0 readiness to the development of predictive quality frameworks; these papers highlight the importance of both technological and socio-technical perspectives. Multiple case studies provide practical insights into the I 4.0 application and its impact on organisational performance.

4.4 Conceptual thematic map

Figure 5 provides the "thematic map" of our analysis. It integrates density and centrality, provides a comprehensive view of the distribution and importance of research topics, and enables the uncovering of patterns, trends, and strategic insights crucial for understanding and advancing research in the field of I 4.0 (Javaid et al., 2022). The analysis in this study utilises the Louvain algorithm and author keywords as the field of study.
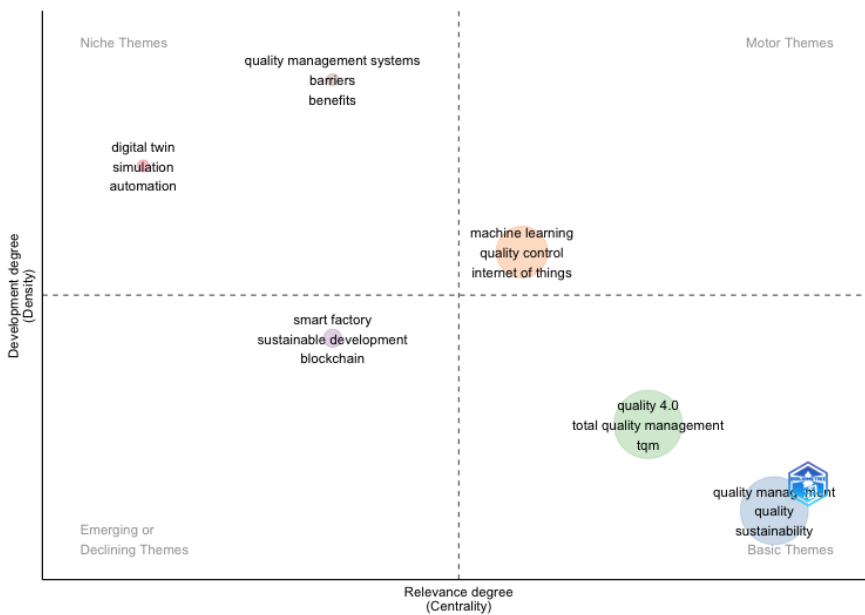
Figure 5: Thematic Map

Quadrant 1(Emeging Themes) encompasses topics characterised by lower occurrences of the mapped variables (low density) and not well-connected within the network context (low centrality). The key themes in this quadrant include smart factories, blockchain and sustainable development. This quadrant is related to the "growing focus" (2022-2023), and these themes lie on the borderline of centrality and density, suggesting the ongoing developments and their importance in the future, making smart factories, blockchain and sustainable development a pivotal aspect.

Quadrant 2 (Motor Themes) shows the highest centrality and density, establishing topics within this quadrant as mainstream themes. These topics are primarily concerned with integrating I 4.0 technologies such as IoT and machine learning, quality control, and organisational performance.

Quadrant 3 (Basic Themes) shows low-density but high-centrality topics, the foundational and cross-cutting subjects within I 4.0 research. Also, this cluster is aligned with the "growing focus" (2022-2023) as it encompasses a wide range of I 4.0 QM, quality and sustainability conceptualisations, implementation strategies, sector-specific applications and environmental sustainability. Such topics are not extensively covered in terms of publications or citations but are strategically important and influential within the broader research context. This concept highlights the significance of looking beyond the sheer volume of publications to identify pivotal areas that could drive future research directions and advancements.

Finally, Quadrant 4 (Niche Themes) is characterised by high density and low centrality. It highlights areas of research where there is a significant amount of published work but limited integration within the broader research network. It features studies focusing on specialised or niche themes, predominantly exploring the implementation issues of I 4.0, such as digital twin, automation, and I 4.0 barriers and benefits.

Co-occurrence of keywords

A network of keywords is shown in Figure 6 based on their co-occurrence to discover interpretable relationships and research topics. A node was labelled with a keyword, and the edge between the two nodes represented the co-occurrence between keywords. The size of a node and label indicates the frequency of a keyword in the dataset, whereas the thickness of an edge indicates the co-occurrence frequency between keywords. A greater thickness demonstrates that the keywords are closely related to each other. The node's colour shows the cluster with which the keyword is associated. Each cluster belongs to a research theme represented by the keywords and their links. From Figure 7, we can see four main clusters. We named the first cluster "Technological drivers", where the keywords "machine

learning", "quality control", "internet of things", "data analytics", and "predictive quality" indicate the prevailing use of digital tools on QM.

Integrating machine learning, quality control, the Internet of Things (IoT), data analytics, and predictive quality in industrial and manufacturing contexts represents a transformative approach to modern production processes and a significant advancement in the field of quality control. Combining such technologies and predictive quality allows the creation of a powerful framework for enhancing smarter, proactive and more efficient manufacturing and production processes. Focused themes are based on digital twins and advanced analytics (Chang et al., 2021; Lin and Li, 2021; Rácz-Szabó et al., 2020; Trauer et al., 2021; Velázquez de la Hoz and Cheng, 2021), machine learning and AI applications (Benbarrad et al., 2021; Elizondo-Noriega et al., 2021; Kasperovica et al., 2022; Mukherjee and Marozzi, 2021; Plank et al., 2021; Sariyer et al., 2021), Quality 4.0 and cybersecurity (Chang et al., 2021; Sariyer et al., 2021; Vo et al., 2020), and smart manufacturing with IoT applications (Črešnar et al., 2020; Lin and Li, 2021; Nedelko, 2021; Rácz-Szabó et al., 2020).
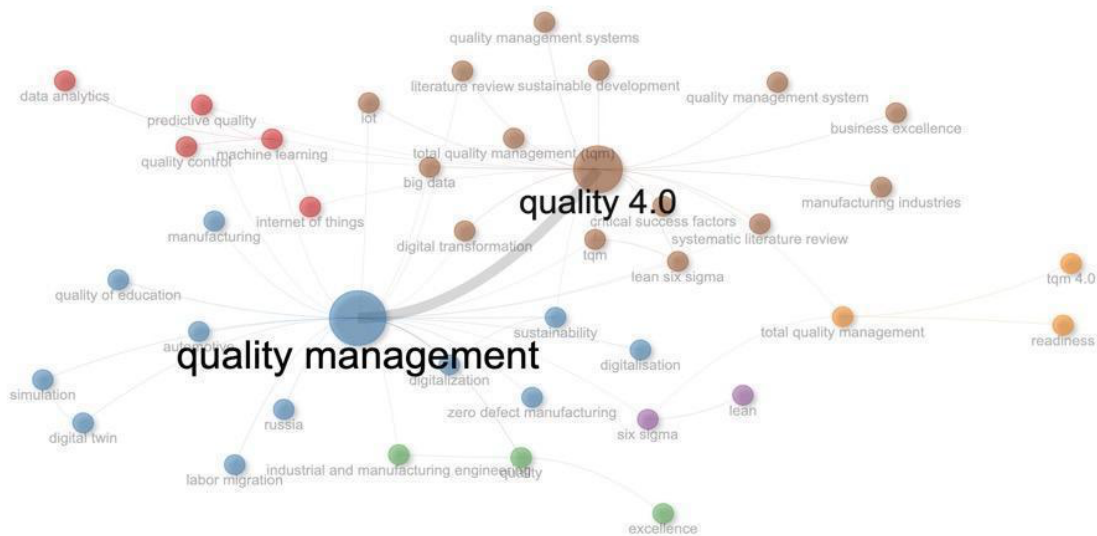

Figure 6: Co-occurrence network

According to the previous analysis, this cluster follows Quadrant 1. It encompasses topics such as smart factory, blockchain and sustainable development.

The second cluster is named "sustainable I 4.0", and it combines quality management, sustainability, digitalisation, and other advanced concepts in the context of I 4.0 manufacturing, particularly in the automotive industry, which can lead to significant improvements in efficiency, product quality, and environmental impact. Organisations can significantly improve product quality, operational efficiency, and environmental sustainability by integrating quality management, sustainability, digitalisation, digital twins, simulation, and zero-defect manufacturing, especially in the automotive industry. This holistic approach enhances competitiveness and aligns with the global move towards sustainable and digitalised industrial practices. According to temporal topics analysis, the attention of the studies focused on sustainable development and organisational ones (growing focus, 2022-2023). Overall, these themes collectively illustrate how I 4.0 technologies are being leveraged to foster sustainability, enhance quality management practices, drive economic development, and innovate across various industrial sectors in the pursuit of sustainable development goals. Sustainability can be harnessed in the following themes:

- "Integration of Sustainability and Technological Innovations", which explores technological advancements, such as AI, automation, and deep learning within the context of I 4.0, quality management systems, just-in-time practices Lean and Six Sigma methodologies, and how they can be harnessed to achieve sustainable supply chain management and enhance competitiveness through improved environmental practices and certifications (Chang et al., 2021; Sariyer et al., 2021; Vo et al., 2020).
- "Quality Management and Digital Transformation", which focuses on how I 4.0 facilitates advancements in quality management practices and drive sustainability performance, economic development, and sustainable food manufacturing practices, including integrating sustainability goals into quality management systems for economic security and sustainable development, also regarding areas like food manufacturing and small-to-medium-sized enterprises (SMEs) (Narkhede et al., 2024; Saha et al., 2022).

The third cluster is "Transformation in I 4.0 and TQM readiness". TQM is a comprehensive approach to improving the quality of products and services through continuous refinement in response to continuous feedback. The readiness for TQM involves preparing an organisation to adopt these principles effectively. The advent of I 4.0 has introduced new technologies and methodologies that are transforming traditional TQM practices into what is now referred to as TQM 4.0. The readiness of quality management systems to adopt TQM 4.0 is a priority. The readiness for TQM 4.0 involves a multifaceted approach encompassing technological, organisational, and cultural dimensions. Critical success factors include awareness, education, and workforce skills, such as competency in quality 4.0-enabled technologies and digital skills (Črešnar et al., 2020; Maganga and Taifa, 2022). However, industry-specific challenges include adoption barriers (Karanina et al., 2020), leadership, and top management support for Quality 4.0 initiatives (Ali and Waheed, 2024).

The fourth cluster is named "future trends": it highlights the importance of I 4.0's organisational aspect and the emphasis on literature reviews (Gonzalez Santacruz et al., 2024; Oliveira et al., 2024). Integrating Quality 4.0, TQM, Lean Six Sigma, IoT, and digital transformation advances quality management systems significantly. These approaches enhance efficiency, reduce defects, and promote sustainable development. Critical success factors such as leadership commitment, team member training, and data-driven decision-making are essential for successful implementation. Business excellence frameworks provide valuable guidance for achieving high performance in manufacturing industries (Carvalho et al., 2021; Duong Thi Binh et al., 2024; Hsueh and Hsu, 2024). Combining the previous concepts in the context of manufacturing industries can lead to a holistic and advanced approach to quality management. This comprehensive approach enhances product quality and improves operational efficiency, sustainability, and overall business performance.

4.5 Three-way plot

The interconnection between research journals, themes, and countries provides valuable insights into I 4.0 and TQM. Figure 7 depicts a Sankey diagram that represents the relationships among prominent journals (left), keywords (middle), and countries (right) within this research domain.
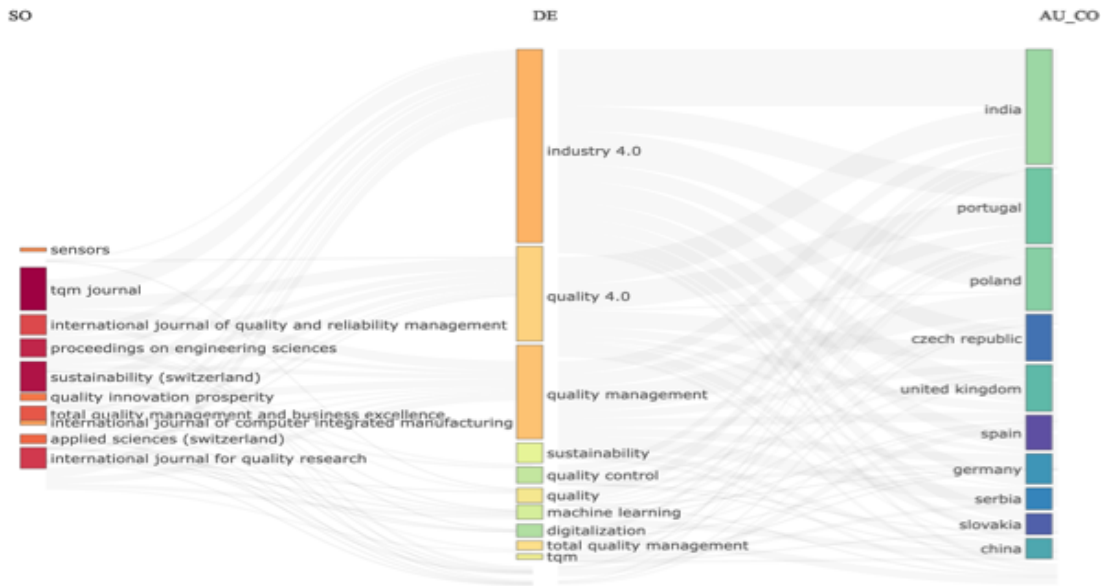
Figure 7: Three-field plot

The Sensors and TQM journals emerge as the primary outlet for significant studies on I 4.0. These studies predominantly analyse the transformative potential of Quality 4.0 in enhancing quality management practices through advanced digital technologies and digital transformation. They identify enablers, key readiness factors, and models that can guide successful implementation. The insights provided serve as a valuable resource for researchers and practitioners seeking to leverage Quality 4.0 for improved operational performance and competitive advantage. Scholars from India, Portugal, and Poland have contributed extensively to these journals.

5. Implications and conclusions

Our study provided several implications regarding the evolution and thematic trends to understand the usage patterns in the field of I 4.0 and quality management. The study used bibliometric analysis to understand trends and patterns of the most influential authors, papers and countries by examining the existing literature to see the current position and ideas for future research in I 4.0 and quality management.

First, by examining the existing literature over the past decade, we have observed that researchers and industry are recognising the importance and potential benefits of integrating I 4.0 technologies within TQM frameworks: an increasing trend of about 38,5% year-on-year highlights the relevant interest in the topics. This trend suggests the need for modernising traditional quality management practices through advanced technologies, potentially leading to significant improvements in efficiency, productivity, and overall organisational performance.

Second, according to the most influential works by Zonnenshain (2020), Sony (2020), and Chiarini (2020), Quality 4.0 is becoming a central theme, stressing the integration of cutting-edge technologies such as Big Cata, AI, and cyber-physical systems into quality management. These Authors emphasise the importance of cultivating new skills and fostering a supportive culture for Quality 4.0, advocating for education and training initiatives, customer involvement in value creation, and customer-centric quality enhancements. They also call for further research on Quality 4.0 topics like Big Data, Analytics, AI, and Skills Development, offering practical insights for organisations navigating I 4.0's transformative impacts on manufacturing and quality management (Chiarini, 2020; Sony et al., 2020; Zonnenshain and Kenett, 2020).

Third, the top contributing countries for this domain are India, Poland, the UK, China, Portugal, Italy, the Czech Republic, Germany and Slovakia, which produced the most publications with a good grade of authors collaboration from these countries. Our findings highlight that Poland, Portugal, Italy, Czech Republic, Germany, and Slovakia are EU countries which contribute to I 4.0 and its applications. At the same time, India and China represent the most productive countries, showing a strong interest in adopting cutting-edge technologies to sustain their rapid economic growth and industrial expansion in recent years.

Fourth, the thematic analysis showed the theoretical insights into the structure and evolution of I 4.0. The focus of I 4.0 on digital transformation, as highlighted by keywords such as Quality 4.0, digitalisation, machine learning, and IoT, suggests that I 4.0 is not merely about technological advancements but also on how these technologies integrate with organisational processes and strategies. This integration is essential for achieving comprehensive benefits such as improved quality, efficiency, and sustainability. The prominence of sustainability as a top keyword reflects a growing theoretical awareness and emphasis on environmental and social impacts within I 4.0 frameworks. This shift indicates that theoretical frameworks are expanding beyond operational efficiency to include broader societal concerns, aligning with global sustainability goals.

The thematic analysis reveals the diversity and evolving nature of I 4.0 research, urging a balanced approach to leverage established and emerging themes for advancing technological innovation and sustainable development in manufacturing and beyond. Emerging themes such as smart factories, blockchain, and sustainable development suggest their evolving importance (Quadrant 1). Mainstream topics like IoT, machine learning, and quality control reflect their established prominence in current research (Quadrant 2). Foundational subjects emphasise their strategic significance in shaping future directions of I 4.0 research, particularly in quality management and sustainability (Quadrant 3). Finally, niche areas such as digital twins and automation (Quadrant 4) indicate opportunities for enhanced collaboration and deeper integration into broader research networks.

The temporal analysis reveals how research interests have shifted over time. After an initial emphasis on foundational technologies like machine learning and IoT, there is a noticeable shift towards more specific and integrated themes like Quality 4.0, Total Quality Management (TQM) 4.0, and sustainability over subsequent years. This evolution suggests a maturation of research interests from exploring technologies in isolation to understanding their impact on organisational practices and outcomes.

The theoretical implications extend beyond academic discourse to practical applications in industry. Concepts like TQM 4.0 and digital transformation underscore how theoretical advancements in Quality 4.0 can inform and shape organisational practices, fostering innovation, efficiency, and sustainability in manufacturing and beyond.

Finally, the study's findings suggest that I 4.0 transforms quality management by integrating advanced technologies and fostering global collaboration. The implications underscore opportunities and challenges in adopting Quality 4.0 frameworks across industries, emphasising the need for continued research and strategic implementation to harness its full potential by analysing thematic trends, technological integrations, and the evolving focus on sustainability within the context of I 4.0. These implications advance scholarly understanding and offer practical insights for implementing transformative technologies in organisational settings. The evolution of Quality 4.0 research within I 4.0 has progressed from early integrations of IoT, machine learning, and robotics with quality management systems to a growing focus on diverse applications, human-centric approaches, and sustainability, culminating in recent efforts emphasising systematic literature reviews and advanced quality management practices integration.

In conclusion, I 4.0 transforms quality management by deeply focusing on integrating advanced technologies for competitive advantage. Continued research and strategic implementation are essential to harness the full potential of such a transformation, enhance industrial processes, improve productivity, and achieve sustainability. Future research should continue exploring how advanced technologies like AI, Big Data, and cyber-physical systems can be integrated into quality management for business excellence. A research trend should be focused on education and training initiatives for

developing new skills and a supportive I 4.0 culture, including the focus on customers for value creation and quality enhancements to align with the principles of Quality 4.0. Finally, new directions about how integrating sustainability into I 4.0 frameworks ensure that technological advancements address environmental and social issues, share best practices, standardise approaches, and overcome common challenges in I 4.0 adoption

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