Journal of Production, Operations and Systems Management

revista GEPROS

e-ISSN: 1984-2430

Open Access

A BIBLIOMETRIC ANALYSIS OF QUALITY 4.0: CHARACTERISTICS, STATUS AND TRENDS

UMA ANÁLISE BIBLIOMÉTRICA DA QUALIDADE 4.0: CARACTERÍSTICAS, STATUS E TENDÊNCIAS

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How to reference this paper:

Torres Junior, N., Dias, A. N. de M., Costa, B. O., & Bernardes Filho, O. R. (2025). A bibliometric analysis of quality 4.0: Characteristics, status and trends. *Revista GEPROS*, *Revista GEPROS*, *20*, e025012. DOI: 10.15675/gepros.3054

| **Submitted**: 10/07/2025
| **Approved:** 15/11/2025
| **Published:** 05/12/2025

Editor: Prof. Dr. Paula de Camargo Fiorini

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ABSTRACT

Objective: this study investigates Quality 4.0 (Q4.0), analyzing publication trends, prominent authors and articles, and the characteristics of research on this topic. **Theoretical Framework:** the evolution of quality management, the impact on quality principles, and the role of emerging technologies are discussed. The benefits and challenges of its implementation are explored. **Methodology/Approach:** the study combines a systematic review and bibliometric analysis, with data collected in January 2025 from the Web of Science and Scopus databases. The final sample of 98 articles was analyzed in RStudio, following the PRISMA protocol. **Results:** there has been a continuous increase in publications on the topic. Key trends, authors, and gaps for future investigations were identified. **Contributions, Practical and Social Implications:** the study systematizes knowledge about Q4.0, highlighting the need for workforce training and the role of leadership. Socially, it points to the transformation of the role of quality professionals and their adaptation to Industry 4.0. **Originality/Value:** it uses a combined approach of systematic review and bibliometric analysis, filling a research gap in Portuguese on this topic and offering a comprehensive understanding of this theme.

Keywords: Quality management. Industry 4.0. Technological innovation. Quality 4.0.

RESUMO

Objetivo: Este estudo investiga o tema Qualidade 4.0 (Q4.0), analisando tendências de publicação, autores e artigos proeminentes, e as características da pesquisa sobre este tema. **Referencial Teórico:** Discute-se a evolução do gerenciamento da qualidade, impacto nos princípios da qualidade e o papel de tecnologias emergentes. Exploram-se os benefícios e desafios de sua implementação. **Metodologia/Abordagem:** O estudo combinou revisão sistemática e análise bibliométrica, com dados coletados em janeiro de 2025 nas bases Web of Science e Scopus. A amostra final de 98 artigos foi analisada no RStudio, seguindo o protocolo PRISMA. **Resultados:** Houve um aumento contínuo de publicações sobre o tema. Identificou-se as principais tendências, autores e lacunas para futuras investigações. **Contribuições, implicações práticas e sociais:** O estudo sistematiza o conhecimento sobre Q4.0, destacando a necessidade de capacitação dos trabalhadores e o papel da liderança. Socialmente, aponta para a transformação do papel dos profissionais de qualidade e a adaptação à Indústria 4.0. **Originalidade/Valor:** Utiliza uma abordagem combinada de revisão sistemática e análise bibliométrica, preenchendo uma lacuna de pesquisa em português sobre este tema, oferecendo uma compreensão abrangente deste tema.

Palavras-chave*:* Gerenciamento da qualidade. Indústria 4.0. Inovação tecnológica. Qualidade 4.0.

Introduction

Industry 4.0 (I4.0), initiated by the German government in 2011, has promoted significant transformations in engineering and manufacturing practices, profoundly impacting the way production systems are managed and operated (Lu, 2017). This technological revolution, characterized by the integration of digital technologies such as the Internet of Things (IoT), artificial intelligence (AI), and Big Data, has influenced various sectors, from agriculture to healthcare and logistics. However, although the term "4.0" has been widely adopted in various fields, the concept of "Quality 4.0" (Q4.0) still lacks a more robust and consolidated academic discussion. Q4.0 emerges as an intersection between the principles of I4.0 and traditional quality management practices, but its definition and theoretical foundation remain underexplored in the scientific literature (Alsadi et al., 2024; Kushwaha & Talib, 2024).

The concept of Q4.0, coined by Dan Jacob, emphasizes quality as a corporate strategy driven by digital technologies, aiming to optimize organizational performance. This approach places quality at the center of executive decisions, integrating digital tools for continuous monitoring and process improvement. However, Q4.0 is still in a consolidation phase, presenting two main interpretations. The first understands it as an extension of I4.0 technologies, focusing on the digitization of quality management tools and real-time monitoring. The second approach, in turn, sees Q4.0 as an autonomous evolution of quality management practices, occurring in parallel with I4.0 innovations but with a focus on adapting and modernizing traditional Quality Management methods (Sader et al., 2022).

The distinction between these views is important, as it can directly impact the implementation strategy. A technology-focused approach threatens to subordinate the initiative to technical leadership, while the evolutionary perspective elevates it to a corporate strategy. The latter requires the involvement of top management to ensure the balance among technology, processes, and people.

Despite the transformative potential of Q4.0, academic research on the topic is still incipient, especially when compared to other fields influenced by I4.0. Despite the disruptive potential of Q4.0, its implementation still faces significant challenges, and there are disagreements among scholars regarding the factors that determine its success (Chiarini, 2020; Chiarini & Kumar, 2022; Komkowski et al., 2022; Maganga & Taifa, 2023a; Oliveira et al., 2024; Sader et al., 2022). It can be affirmed that Q4.0 is still a developing field, requiring more in-depth conceptual systematization. Furthermore, bibliometric studies in Portuguese on this topic are scarce, making it difficult to achieve a comprehensive understanding of its literature and applications in the Brazilian context. Given this picture, this study seeks to answer the following research questions:

RQ_1: what is the current status and the publication trends in the Quality 4.0 research domain?

RQ_2: which/who are the most prominent authors, articles, and affiliated countries in Quality 4.0 research?

RQ_3: what are the main elements and characteristics of Q4.0 research?

To answer the proposed research questions, a bibliometric analysis and a Systematic Literature Review (SLR) will be conducted, allowing for the identification of the main elements and applications, research trends, key topics, most frequent keywords, as well as the most relevant authors and academic journals on the topic.

Upon analyzing the main studies on Quality 4.0 (Ali & Johl, 2022; Alsadi et al., 2024; Bousdekis et al., 2023; Broday, 2022; Chiarini, 2020; Condé et al., 2022; Kushwaha & Talib, 2024; Oliveira et al., 2024; Page & Moher, 2017; Tewary & Jadon, 2023), it is observed that the greatest differentiation of this work lies in its comprehensive scope and depth of analysis to consolidate the knowledge of Quality 4.0 (Q4.0), which combines a Systematic Literature Review (SLR) and Bibliometric Analysis. This methodological approach is considered a more complete way to analyze this field (Alsadi et al., 2024). Furthermore, this work incorporated several advanced analyses (Sections 4.4 to 4.8) that go beyond simple descriptive summaries, such as co-citation analysis to examine the theoretical foundations of the research and the PageRank algorithm to identify the most influential and prestigious articles. These advanced analyses allow researchers to investigate and visualize the intellectual structure of knowledge and establish the theoretical foundations of the specific research domain. By integrating detailed metrics—such as trends in scientific production, the identification of the most productive authors, affiliations, and countries, and the creation of Thematic Maps—the work summarized the state of the discipline and highlighted the main themes and areas of interest.

This article is structured in five main sections, including this introduction. The next section presents the research methodology used, detailing the main steps carried out. Following that, the main elements and applications of Q4.0 are presented. The fourth section details the bibliometric analysis performed and its results, highlighting the research trends in Q4.0. Finally, the last section presents the conclusions, as well as the study's limitations and recommendations for future research.

Research methodology

This work adopted a Systematic Literature Review (SLR) in conjunction with bibliometric analysis. SLR is a methodology that rigorously collects and systematically analyzes multiple studies. Its importance lies in the ability to generate reliable knowledge and improve practice by developing theoretical syntheses from the available literature in various fields. Through a proven, qualitative, and replicable approach, SLR ensures that the literature review is comprehensive, impartial, and provides high-quality evidence (Tranfield et al., 2003).

When combined with bibliometric analysis, SLR becomes a powerful tool for understanding the state of the art of a topic and for providing valuable insights for researchers and professionals (Alsadi et al., 2024).

The information collected for this study was retrieved in the last week of January 2025 from the two most prominent databases: Web of Science, owned by Clarivate Analytics, and Scopus, owned by Elsevier. Both possess features for bibliometric analysis.

The data for analysis were searched and collected in February 2025, covering the period from 2014 to January 2025, and include only journal and review articles. Although the selected starting period was 2014, no relevant articles for this research were found before 2016.

The exclusion criterion adopted was the limitation to articles published only in English. The search focused mainly on mapping the existing literature on Quality 4.0 across engineering, management, and interdisciplinary engineering.

Based on this scope, a keyword combination was developed with alternative and related terms—“QUALITY 4.0,” “QUALITY 4,” “Q4.0”—which was used for the search in both databases, Scopus and WoS. Table 1 details the inclusion and exclusion criteria.

Table 1

Inclusion and exclusion criteria

Criteria	Inclusion	Exclusion	Observation
Language	English	Other languages	Only articles in English were considered.
Database	WoS and Scopus	Other databases	Both have bibliometric features.

Publication type	Articles and reviews	Conference papers, books	Focus on publications with greater impact.
Source	Journals	Conference proceedings	Focus on more reliable sources.

The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol was adopted to ensure the transparency and reproducibility of the review (Page & Moher, 2017). The selection process began with the identification of studies in databases such as Scopus and Web of Science. Next, in the screening phase, duplicate records were removed, and the remaining articles were evaluated by title and abstract to exclude irrelevant ones. Subsequently, the full texts were analyzed in the eligibility stage, based on the inclusion and exclusion criteria. In the end, the process resulted in the inclusion of the final set of studies. Table 2 demonstrates the data retrieval process, step by step.

Table 2

Phases of the protocol

Phase	**Description**	**No. of Articles**
Identification	Articles identified in the databases (Scopus=154, WoS=91) Articles after duplicate removal (Scopus=76, WoS=49)	245 125
Screening	Articles screened based on title and abstract (Scopus=66, WoS=32) Articles excluded in the screening phase	98 0
Eligibility	Full-text articles assessed for eligibility	98
Inclusion	Studies included in the bibliometric analysis	98

The 98 remaining articles were examined using bibliometric analysis. For this, the BIBLIOMETRIX package in RStudio was used. BIBLIOMETRIX is a free, open-source tool for conducting scientific mapping of publications. It is written in R, which makes it flexible and easily integrable with other statistical and graphing packages (Derviş, 2019; Radha & Arumugam, 2021).

Literature review

The theoretical framework presented here was structured based on the results of the Systematic Literature Review, which was also conducted to answer research question RQ3: “what are the main elements and characteristics of Q4.0 research?”. Based on the findings, this section explores the intersection of Q4.0 and advancements in quality management, analyzing its evolution, its impact on fundamental quality principles, and the role of emerging technologies. The benefits of adopting Q4.0 and the challenges inherent in its organizational implementation are also discussed to offer a comprehensive and up-to-date perspective on the field.

Quality 4.0 and the evolution of quality management

One way to define Q4.0 is to understand it as the integration of traditional quality management practices with new technologies originating from I4.0, creating a collaborative environment that enhances connectivity throughout the value chain (Antony, McDermott, et al., 2022; Chiarini & Kumar, 2022; Kushwaha & Talib, 2024). It allows manufacturers to achieve highly effective quality management, resulting in greater market share, innovation, and brand recognition. Q4.0 transforms traditional Quality Control into real-time monitoring and focuses on the application of digital technologies in quality management (Jacob, 2017). This concept closely aligns with Industry 4.0, reflecting a trend that shifts quality responsibilities from a single team to all employees. Q4.0 shifts the focus from traditional quality practices, which were predominantly reactive (detection and diagnosis), to an approach that actively anticipates problems (proactive or predictive). Furthermore, greater integration and new communication technologies are revolutionizing the role of the customer, transforming them from a receiver of goods and services into an active participant and co-creator in the value chain by engaging in quality activities during the development and production stages (Sader et al., 2022).

Another way to define Q4.0 is to understand it as an evolution in quality management, integrating fully automated processes with real-time data analysis and control. Unlike traditional approaches, this new phase emphasizes predictive quality management, enabling the identification and resolution of problems before they occur, thereby improving product quality and reducing costs (Jacob, 2017). While Industry 4.0 (I4.0) focuses more on information technology, Q4.0 requires highly skilled quality professionals to interpret and apply these new technological tools (Sader et al., 2022; Santos et al., 2021a; Watson, 2019).

Q4.0 broadens the focus of quality, moving away from a local approach focused on excluding defective products or monitoring manufacturing processes toward a holistic perspective. This holistic perspective is achieved through integration, as Q4.0 is conceptualized as the "digitization of quality management to encompass technology, processes, and people"

(Jacob, 2017), requiring a symbiotic relationship between humans and technology. This new paradigm involves intensive monitoring of all elements of the production value chain and treats quality as the responsibility of the entire organization, including suppliers, sales, marketing, and operational management (Johnson, 2019; Sader et al., 2022). Among its main features are the automation of inspection activities, the digitization of results, and the integration of these results with the entire manufacturing system, closing the quality loop (Antony, McDermott, et al., 2022; Sader et al., 2022).

Q4.0 does not replace traditional quality methods but rather builds upon and improves them (Nenadál et al., 2022). Traditional principles and tools remain essential for achieving greater organizational performance and sustainability. The holistic approach of Q4.0, therefore, is based on integrating these recent technologies with traditional quality practices (Kushwaha & Talib, 2024).

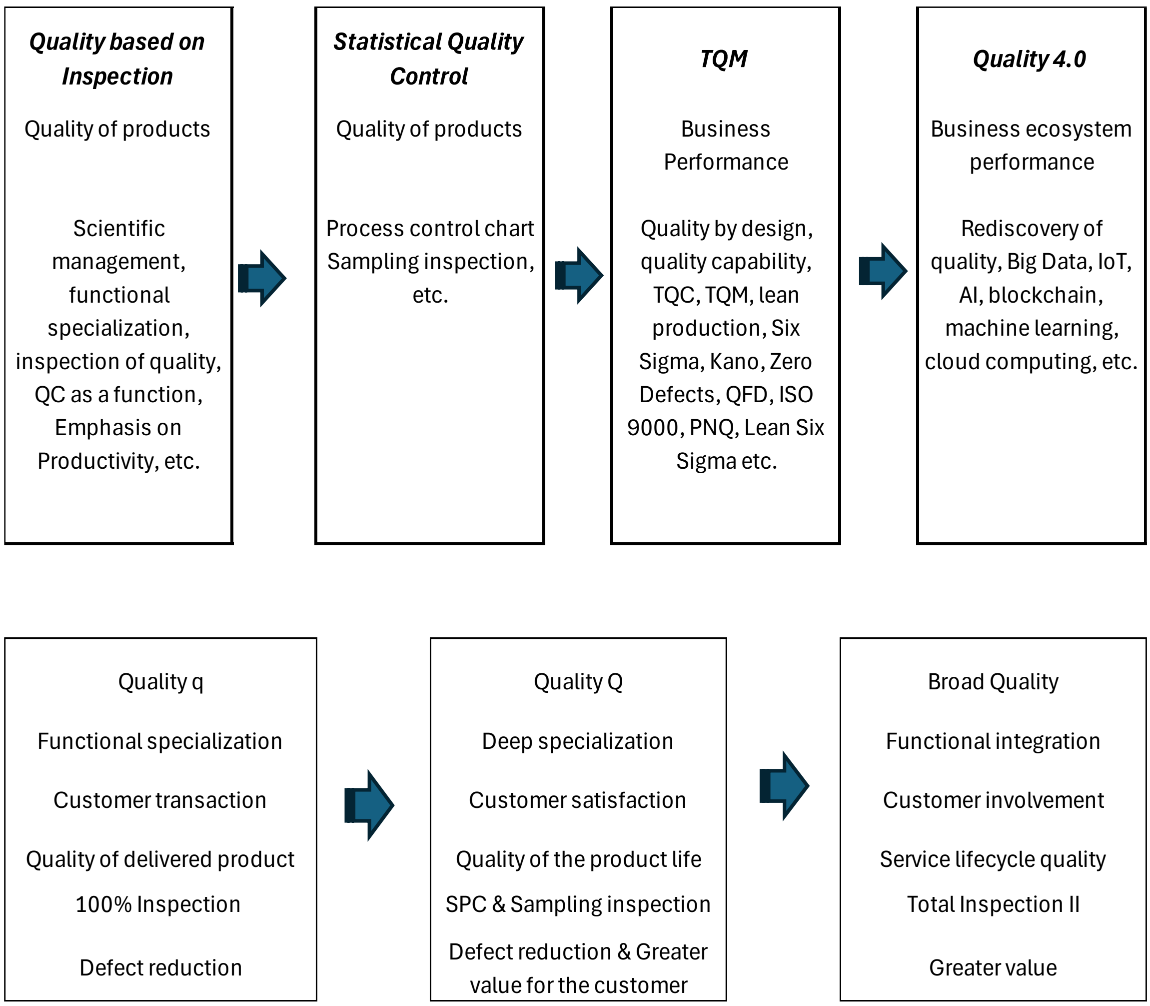
The automation of inspection enables the use of advanced technologies, such as X-rays, digital cameras, laser scanning, and Computed Tomography (CT scan), reducing the time between defect detection and process correction (Antony et al., 2023; Scislo, 2021). Furthermore, sensors and IoT devices control quality steps to prevent defective elements from advancing in production, providing precise information to operators and supervisors (Kubat, 2018). The analysis of results, in turn, becomes more complex due to the increasing customization of products and processes, requiring predictive methods based on Big Data to anticipate problems and prevent failures. Finally, integrating data collected across the entire production chain using Cyber-Physical Systems (CPS) enables real-time adjustments and promotes a smart manufacturing environment with zero-defect production. This approach enables information sharing between factories, standardizes quality practices, and optimizes operational performance (Ganjavi & Fazlollahtabar, 2023; Sader et al., 2022; Sony et al., 2020; Zonnenshain & Kenett, 2020).

The authors Decheng Wen, Xiaojing Sun, and Dongwei Yan (2022) posit that quality management has historically evolved through three main stages: Inspection, Statistical Quality Control (SQC), and Total Quality Management (TQM). However, a new phase, termed “Quality X.0,” is emerging, broadening the focus of quality from products and processes to overall business and ecosystem performance. This transformation will require re-evaluating traditional performance measurement and management models. It will shift attention from product lifecycles to service lifecycles, with a strategic focus on customer engagement as a competitive differentiator. This new era will bring significant innovations in quality methods, driven by greater customer participation in product and service development. The traditional quality management structure may dissolve, with substantial changes in professionals' roles, while smart devices will replace operators.

Furthermore, sampling inspection will be replaced by "total inspection II" or "zero manual inspection," generating large volumes of data. Technologies such as Big Data and machine learning will be fundamental to enhancing quality control methods, prioritizing value creation over mere error reduction. Quality design will increasingly depend on active customer participation (Figure 1).

Figure 1

Evolution of Quality over time



Note. Based on Figure 11 of Wen et al.(2022).

Quality 4.0 and the Principles of Quality

Several authors have addressed the positive impact of Q4.0 on the principles of quality.

Customer Focus

Quality management aims to meet and exceed customer expectations (Kushwaha & Talib, 2024), and Q4.0 enhances this approach by enabling more personalized design and manufacturing processes (Balouei Jamkhaneh et al., 2022). Technologies such as Big Data, IoT, Machine Learning, and AI enable a deeper understanding of customer needs and facilitate access to customised products and services. Furthermore, enhanced quality control and assurance practices in this new era contribute to higher customer satisfaction. Greater connectivity enables customer participation in the production process, promoting greater engagement and personalisation. Q4.0 strengthens customer loyalty throughout their lifecycle by anticipating and responding to evolving needs. In addition, advanced digital technologies enable detailed analysis of customer requirements and evaluation of product performance after purchase, thereby enhancing the experience at all stages of the consumer journey (Ali & Johl, 2022; Canbay & Akman, 2023; Sader et al., 2019).

Leadership

Leadership plays a fundamental role in quality management, establishing a unified purpose and engaging people in the pursuit of organizational objectives. There is an increase in production transparency and support for efficient resource allocation, allowing teams and employees to take on more strategic roles in decision-making. However, research on leadership in the context of Q4.0 is still limited. The decentralization of leadership will be essential at all organizational levels, aligning strategies, processes, and resources to achieve quality objectives. Furthermore, greater connectivity fosters coordination and collaboration across leadership levels, optimising the integration of business processes and manufacturing management (Ali & Johl, 2022; Canbay & Akman, 2023; Sader et al., 2019).

However, implementing Q4.0 requires the support of top leadership to enable significant structural and operational changes, with one of the main challenges being aligning various stakeholders with this new model. The acceptance of new technologies by all interested parties is fundamental to Q4.0's success, and strong leadership commitment helps minimise resistance and increase the perceived usefulness of adopted innovations (Ali & Johl, 2022; Canbay & Akman, 2023; Sader et al., 2019).

People engagement

People's engagement is essential to strengthening the organisation's capacity to generate and deliver value. With Q4.0, manufacturing processes become more efficient through advanced technologies and real-time data, reducing the need for manual intervention. This transformation demands new competencies from workers, who now act in the specification, monitoring, and maintenance of productive strategies in cyber-physical systems. Furthermore, Q4.0 promotes greater transparency, integration, and collaboration among employees, allowing them to share knowledge and make more informed decisions. The managerial hierarchy tends to become more diffuse, encouraging a more collective and agile decision-making process.

On the other hand, Q4.0 will depend on workers' training in using digital tools and interpreting data for decision-making. Instead of machine operators, employees will take on the role of supervisors and problem-solvers, requiring analytical and adaptive skills. Technologies such as Big Data, AI, and IoT enable greater autonomy and creativity, thereby promoting organisational innovation. Q4.0 does not completely replace human work but redefines its functions, shifting the focus from execution to coordination and solving unexpected problems (Ali & Johl, 2022; Canbay & Akman, 2023; Sader et al., 2019).

In this context, training and learning are critical factors for the success of Q4.0. Technologies such as AI, Augmented Reality, and Virtual Reality are being employed to enhance worker training. The growing complexity of industrial processes requires interdisciplinary knowledge, combining technical, organizational, and social competencies. Tools like Learning Management Systems (LMS) and immersive virtual training help adapt the workforce to new demands. Therefore, investing in employees' continuous development is fundamental to ensuring the successful implementation of Q4.0 (Ali & Johl, 2022).

Process approach

The process approach is fundamental to achieving consistent and predictable results, as it allows activities to be understood as interconnected parts of a cohesive system. Technologies such as IoT and Cyber-Physical Systems (CPS) enhance flexibility in process management and planning by providing access to real-time data. This integration promotes greater transparency and optimization of productive and business processes, resulting in increased efficiency and better resource allocation. Furthermore, these technologies facilitate the identification of production bottlenecks, reducing costs and increasing the responsiveness of the supply chain (Ali & Johl, 2022; Canbay & Akman, 2023; Sader et al., 2019).

Q4.0 enhances process transparency, enabling companies to identify inefficiencies and minimise production costs. The use of advanced technologies such as IoT, CPS, and AI enables the simulation and modification of processes before implementation, ensuring greater efficiency. In addition, machine learning and AI facilitate continuous process improvement, enabling proactive problem identification (Ali & Johl, 2022; Canbay & Akman, 2023; Sader et al., 2019).

Continuous Improvement

Successful organisations prioritise continuous improvement in all their operations, ensuring innovation and efficiency. I4.0 drives constant advancements in products, processes, and business models through the integration of emerging technologies (Dalenogare et al., 2018; Radziwill, 2020). In this context, Quality Management Systems need to evolve to keep pace with these changes, emphasising root-cause analysis and preventive actions to enhance customer satisfaction. Smart devices and AI enable real-time data collection and analysis, enabling early failure detection and improved operational performance. Q4.0 facilitates this approach by connecting products to manufacturers after production, permitting continuous data analysis for future optimizations. Furthermore, high connectivity within the organizational ecosystem enables the proactive identification and response to risks and opportunities. Technologies such as AI and machine learning enhance the ability to predict failures and optimise processes, thereby strengthening continuous improvement (Ali & Johl, 2022; Canbay & Akman, 2023; Sader et al., 2019).

Factual approach to decision-making

Evidence-based decision-making is essential for achieving better organisational results, and I4.0 enhances this process by leveraging sensors, automation, and advanced data analysis. With digitisation, autonomous factories use cloud computing and CPS to transform and analyse data in real time. Smart environments emerge as machines and devices interact, sharing information to optimise processes and increase operational efficiency. In quality management, precise data collection and continuous data evaluation are fundamental for more informed decision-making (Ali & Johl, 2022; Canbay & Akman, 2023; Sader et al., 2019).

Relationship management

Effective relationship management with stakeholders, such as suppliers, is essential for organizational success, and I4.0 enhances this dynamic through modern systems that promote greater integration between business units. The use of IoT enables direct, automated communication among people, machines, and objects, facilitating the identification and sharing of information. This connectivity enables agile interactions between technicians, intelligent systems, and customers/suppliers, reducing delivery times and increasing focus on customer needs (Canbay & Akman, 2023; Sader et al., 2019).

A sustainable Quality Management System depends on cooperation and shared interests among all parties involved. Strategic partnerships strengthen the supply chain, enabling more efficient, optimised deliveries. Furthermore, horizontal, vertical, and end-to-end integration enhances the ability to respond to market demands, resulting in greater customer satisfaction and more efficient organizational performance (Canbay & Akman, 2023; Sader et al., 2019).

Role of Technologies

Emerging technologies, such as IoT, AI, Machine Learning (ML), Deep Learning (DL), and Big Data analytics, play a fundamental role in enhancing quality control and continuous improvement. The integration of traditional quality management with these innovations creates a collaborative environment along the value chain, enabling the massive generation and analysis of data to optimize evidence-based management practices. Real-time data collection enables the identification of hidden patterns that affect quality, going beyond traditional analysis approaches (Kushwaha & Talib, 2024; Maganga & Taifa, 2023a; Radziwill, 2020; Sader et al., 2022).

Connectivity among people, devices, and processes strengthens information sharing and root-cause analysis of problems, promoting more effective management. Collaborative technologies, such as social networks and blockchain, facilitate product traceability and enhance interaction between agents in the production chain. Furthermore, effective data presentation on smart devices and through augmented reality improves the user experience and decision-making. The enhanced visibility of manufacturing, provided by sensors and digital tools, contributes to cost reduction and increased product quality (Kushwaha & Talib, 2024; Maganga & Taifa, 2023a; Radziwill, 2020; Sader et al., 2022).

Blockchain technology has been widely adopted across industries to track product history, especially in complex supply chains. This technology offers real-time transparency, reduces costs, and enables the traceability of components throughout the production chain by creating immutable records of quality inspections and production processes. Moreover, blockchain facilitates data transfer, increases transaction transparency, and enhances the auditing and monitoring of operational conditions to ensure compliance with quality standards. In Q4.0, blockchain technology can be combined with additive manufacturing (3D printing) to optimize production processes and enable new manufacturing models (Antony et al., 2023; Carvalho et al., 2021; Maganga & Taifa, 2023a).

Additive manufacturing, also known as 3D printing, enables the rapid and cost-effective creation of prototypes using diverse materials, including polylactic acid filaments, metallic powders, concrete, and even nanomaterials. This technology expands the range of possible products, enables local production of on-demand parts, and reduces delays in obtaining replacement components. Furthermore, autonomous robots play a fundamental role in industrial automation, replacing human tasks in hard-to-reach places and reducing accident risks. These technological innovations drive operational efficiency and contribute to the evolution of quality management in Industry 4.0 (Kushwaha & Talib, 2024; Maganga & Taifa, 2023a; Radziwill, 2020).

Benefits of Quality 4.0

Digitisation and automation driven by I4.0 enable the mass customisation of products and services, making manufacturing systems more agile and responsive. Customising service quality enables organisations to meet growing customer demands better, thereby increasing revenue opportunities (Hyun Park et al., 2017). Furthermore, production automation improves compliance with quality standards and enables comprehensive monitoring of products throughout the production process. The application of Big Data analytics and AI contributes to a better understanding of customer needs, enhancing quality management, innovation, and regulatory compliance, which strengthens companies' competitive advantage (Antony, Sony, et al., 2022).

Q4.0 also enhances after-sales service, ensuring agile, courteous, and effective complaint handling. Sensors embedded in products collect field performance data, enabling manufacturers to understand operational conditions better and make design improvements. As a result, customers receive more efficient operating instructions and technical support, increasing their satisfaction and contributing to a continuous improvement in product quality. Moreover, automation and continuous monitoring enable early failure detection, reducing waste and ensuring that quality is incorporated from the earliest stages of production (Kushwaha & Talib, 2024; Tewary & Jadon, 2023).

Advances in data analysis and digitisation enable significant improvements in industrial processes, such as real-time planning and more accurate forecasts, optimising supplier management and quality metrics. Reducing operational costs, including inspections, rework, complaints, and warranties, lowers product prices for consumers. Furthermore, improvements in operational indicators, such as First Pass Yield (FPY), on-time deliveries, and customer satisfaction, lead to a reduction in internal and external failures. Continuous interaction with consumers enables a deeper understanding of their expectations, while analysing product usage data helps eliminate non-value-adding activities and increase productive efficiency (Antony et al., 2023; Antony, Sony, et al., 2022).

The financial impacts of Q4.0 include increased total revenue and sustainable company growth, combined with improvements in gross and net profit margins. The adoption of digital technologies favours higher inventory turnover and a significant reduction in operational and marginal production costs. Furthermore, mitigating internal and external failures helps minimise losses and waste. In the long run, these transformations drive revenue growth and organisational productivity (Antony, Sony, et al., 2022).

Challenges for implementing Quality 4.0

The Q4.0 implementation faces significant challenges, including the scarcity of qualified workers and the inadequacy of training and education programs. The lack of professionals trained to operate in a data-driven environment is a critical barrier, aggravated by employees' cultural fears of misuse of Q4.0 practices. Resistance to change, especially among more experienced workers, limits the adoption of new technologies and hinders the transition to more digitised processes (Antony, Sony, et al., 2022; Escobar et al., 2021; Tewary & Jadon, 2023).

To overcome these barriers, it is fundamental to promote collaboration between companies and educational institutions, enabling the development of educational programs aligned with new market demands. Furthermore, the successful Q4.0 implementation requires robust internal capabilities, a culture of innovation, and effective leadership. Managerial problems and a lack of persistence can compromise strategic decision-making, making it difficult to integrate digital quality into organisations (Antony, Sony, et al., 2022).

The development of the future workforce must prioritise technical skills, such as data science, combined with behavioural competencies, such as creativity and emotional intelligence. The evolution of the quality profession in the context of Q4.0 requires adaptation to uncertainty and greater recognition of the importance of high-quality data (Antony, Sony, et al., 2022; Sader et al., 2022).

Bibliometric analysis and results discussion

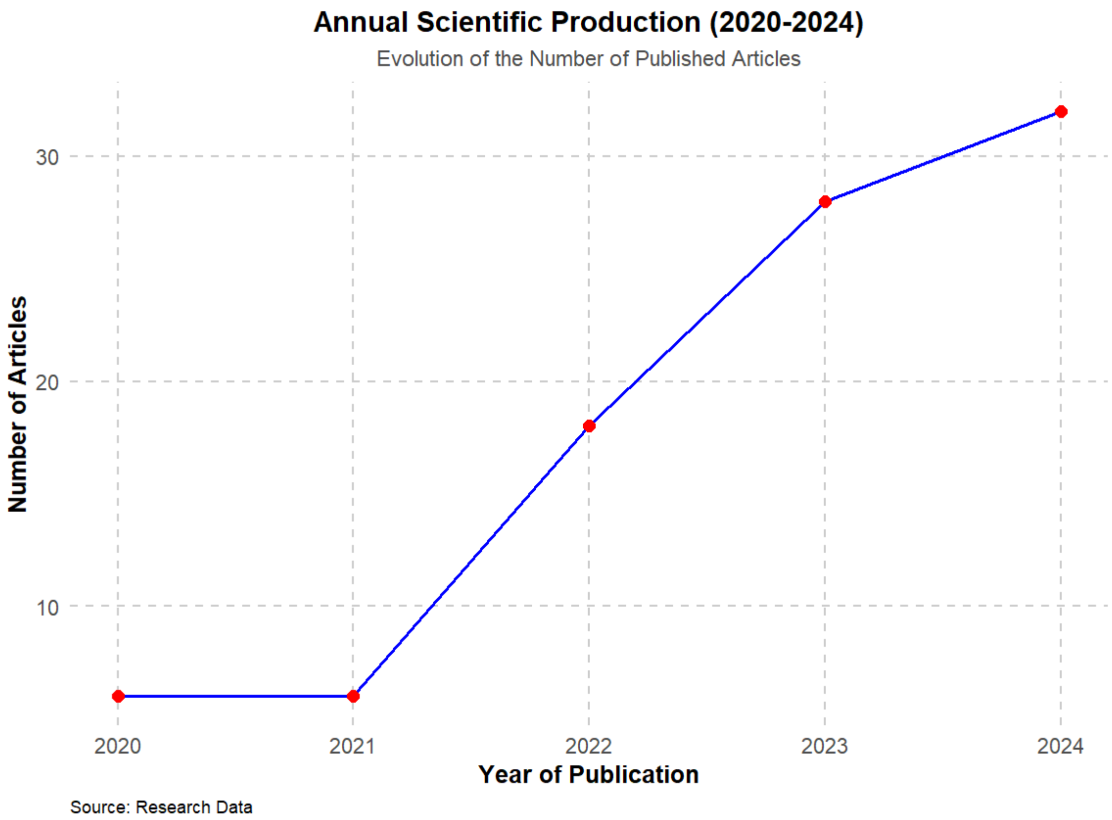
This section presents the bibliometric analysis and discusses the obtained results. Using indicators, the temporal trends in academic production, the most relevant publications, the most productive authors and institutions, and the geographical distribution of the research are explored. Additionally, citations, keywords used by authors, co-citation networks, and historiography are analysed, culminating in the construction of a thematic map that organises the works by types of themes.

Trend of scientific production

Publications began with more than five articles in 2020 and grew to 32 in 2024. Figure 1 illustrates the annual publication trend of articles on Q4.0 from 2020 to 2024. Although the total number of articles remains limited, researchers' interest in this area is steadily increasing.

Graph 1

Annual Scientific Production



The most relevant publications

There are 42 journals available for these 98 articles. Table 3 presents the 10 most relevant journals on Q4.0. These top 10 journals published 65 of the 98 analysed articles, representing 65.66%. The TQM Journal is the most productive, with 24 articles published, followed by the *International Journal of Quality and Reliability Management*.

Table 3

10 Most Relevant Journals on Q4.0

Publication	Quantity	Percentage
TQM JOURNAL	24	24.49
INTERNATIONAL JOURNAL OF QUALITY & RELIABILITY MANAGEMENT	9	9.18
TOTAL QUALITY MANAGEMENT & BUSINESS EXCELLENCE	7	7.14
PROCEEDINGS ON ENGINEERING SCIENCES	5	5.10
QUALITY ENGINEERING	5	5.10
SUSTAINABILITY	5	5.10
QUALITY INNOVATION PROSPERITY-KVALITA INOVACIA PROSPERITA	4	4.08
INTERNATIONAL JOURNAL OF COMPUTER INTEGRATED MANUFACTURING	2	2.04
JOURNAL OF MANUFACTURING TECHNOLOGY MANAGEMENT	2	2.04
QUALITY INNOVATION PROSPERITY	2	2.04
Others	33	33.66

The most productive authors, affiliations, and countries

The five most productive authors in this area are Antony J., McDermott O., Sony M., Barravecchia F., Garza-Reyes, Jose Arturo, and Escobar, Carlos A. (Figure 2). Figure 3 shows the main affiliated institutions with publications on Q4.0. Finally, Figure 4 presents the top 10 countries with the highest number of articles on Q4.0.

Figure 2

Five most productive authors

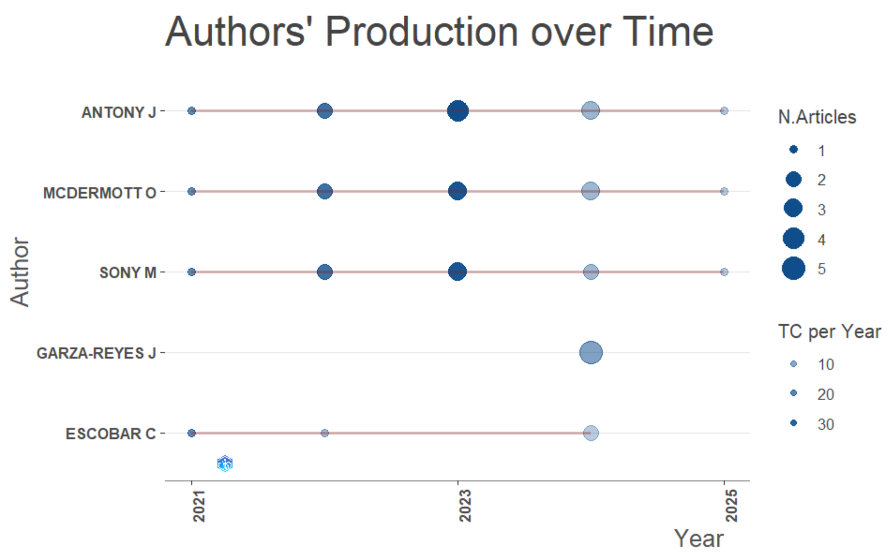


Figure 3

Top affiliations and countries

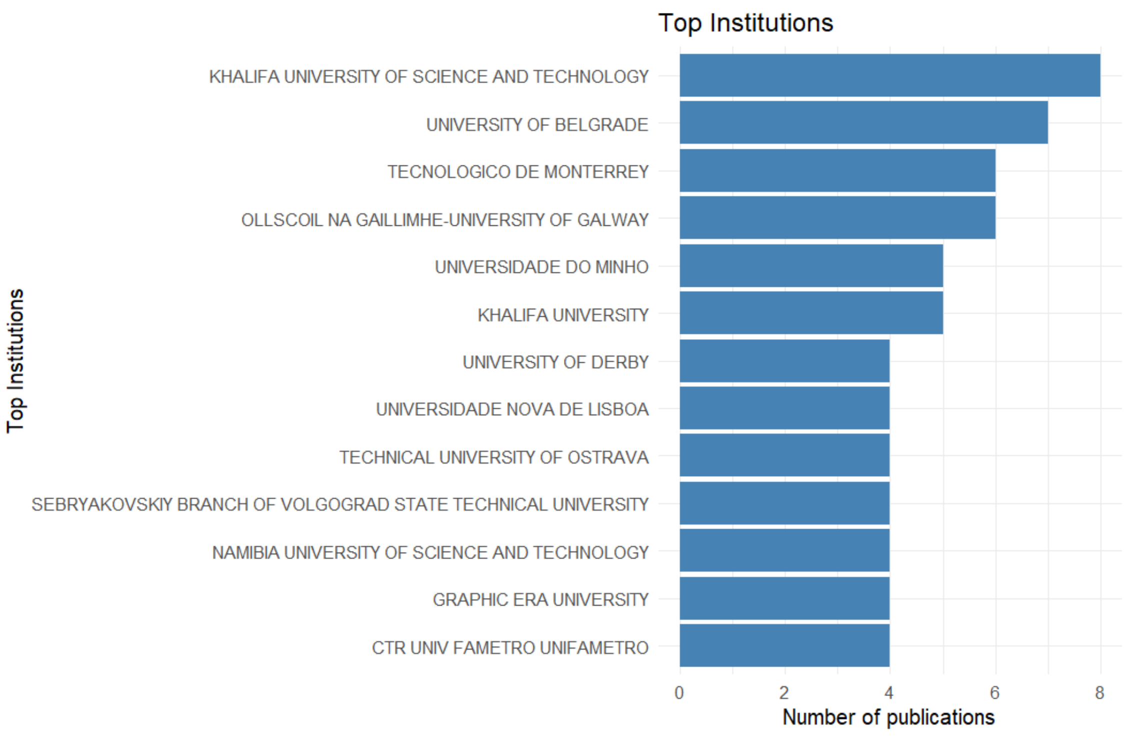
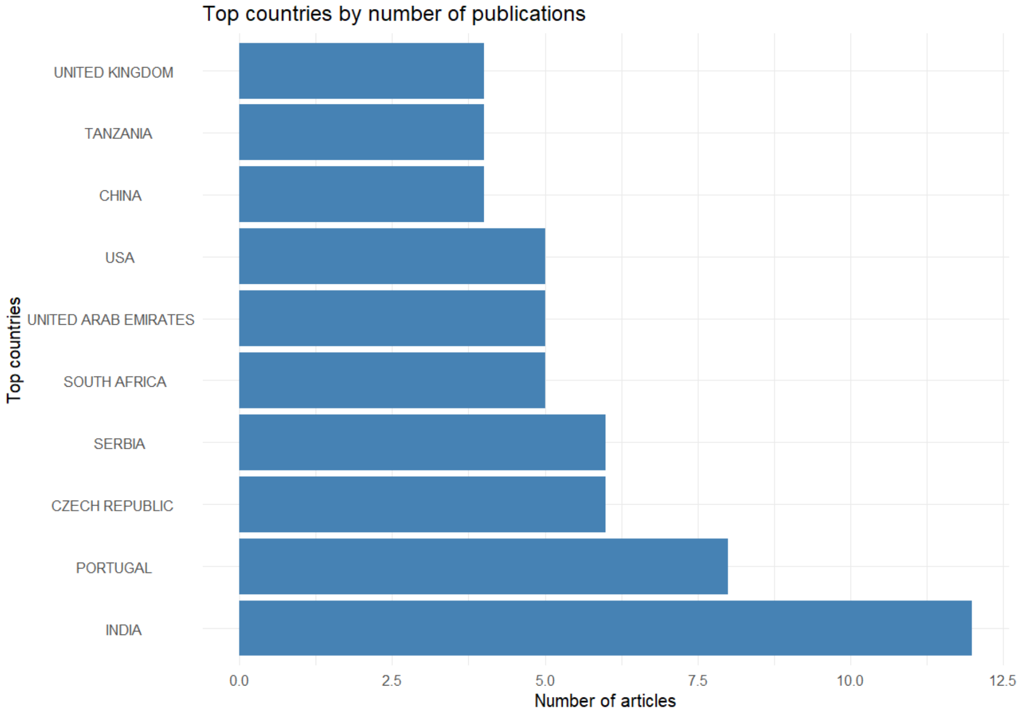


Figure 4

Top countries



Citation Analysis

Citation analysis is an effective method for identifying influential articles on the Q4.0 topic, measuring the frequency with which research articles are cited. An article's citation count reflects its popularity and importance in the field, with more citations indicating greater influence. The 98 documents were analyzed to determine the 10 most globally cited works. Global citations encompass all references made to a document across various databases and fields. Table 4 shows these works.

Table 4

10 most cited works globally

Title	Year/ Quotes	Description
QUALITY 4.0-THE CHALLENGING FUTURE OF QUALITY ENGINEERING (Zonnenshain & Kenett, 2020)	2020 148	The study addresses the concept of Quality 4.0 and a framework for the discipline of quality in the Fourth Industrial Revolution, highlighting future directions for quality engineering and reliability.
INDUSTRY 4.0, QUALITY MANAGEMENT, AND	2020 126	The study analyses the current literature on the relationships among Industry 4.0, Quality Management, and TQM, seeking

Title	Year/ Quotes	Description
TQM WORLD. A SYSTEMATIC LITERATURE REVIEW AND A PROPOSED AGENDA FOR FURTHER RESEARCH (Chiarini, 2020)		to identify the most relevant topics in Quality 4.0 and gaps for future research.
QUALITY 4.0: THE EFQM 2020 MODEL AND INDUSTRY 4.0 RELATIONSHIPS AND IMPLICATIONS (Fonseca et al., 2021)	2021 115	The research analyses the innovations of the EFQM 2020 model and their relations with Industry 4.0, contributing to the understanding of Quality 4.0. The model offers a strategic, technology-neutral perspective that integrates business excellence. With empirical support, future research is recommended to deepen the topic.
QUALITY 4.0: A REVIEW OF BIG DATA CHALLENGES IN MANUFACTURING (Escobar et al., 2021)	2021 92	It reviews the process monitoring initiative for Quality 4.0, identifying four critical issues: paradigm, project selection, process redesign, and relearning. Based on the study, a new seven-step problem-solving strategy is presented to increase the chances of successful implementation of Quality 4.0.
MOTIVATIONS, BARRIERS, AND READINESS FACTORS FOR QUALITY 4.0 IMPLEMENTATION: AN EXPLORATORY STUDY (Sony et al., 2021)	2021 91	This study investigates the motivations, barriers, and readiness factors for implementing Quality 4.0. The survey was conducted online among senior quality professionals at leading companies in Europe and America.
NEW NEEDED QUALITY MANAGEMENT SKILLS FOR QUALITY MANAGERS 4.0 (Santos et al., 2021b)	2021 76	This study was conducted with quality management professionals in Portugal to analyse their perception of the impact of Industry 4.0. In addition, it seeks to review and analyse the main themes under development in quality management in the Fourth Industrial Revolution and how quality is transformed in this context.
THE NEW EFQM MODEL: WHAT IS REALLY NEW AND COULD BE CONSIDERED AS A SUITABLE TOOL WITH RESPECT TO QUALITY 4.0 CONCEPT? (Nenadál, 2020)	2020 72	The article presents a critical analysis of the last two versions of EFQM's excellence models, highlighting original information. The main objective is to identify the advantages and weaknesses of the latest version of the model, particularly from a practical perspective, in the context of Quality 4.0.
QUALITY 4.0 CONCEPTUALISATION AND THEORETICAL UNDERSTANDING: A GLOBAL EXPLORATORY QUALITATIVE STUDY (Antony, McDermott, et al., 2022)	2022 69	The study examines Quality 4.0, its benefits, motivating factors, critical success factors, and the skills needed by quality professionals. In addition, it explores the aspects of organisational readiness and the challenges to be overcome before adopting Quality 4.0, and evaluates their importance.
CRITICAL SUCCESS FACTORS FOR LEAN SIX SIGMA IN QUALITY 4.0 (Yadav et al., 2021)	2021 57	The study also validates critical success factors of Lean Six Sigma (LSS) in the context of Quality 4.0 with conventional technologies. Twenty factors for LSS success were evaluated: seven related to Quality 4.0 technologies and thirteen to the

Title	Year/ Quotes	Description
		conventional model. All seven factors of Quality 4.0 were considered critical.
WHAT IS QUALITY 4.0? AN EXPLORATORY SEQUENTIAL MIXED METHODS STUDY OF ITALIAN MANUFACTURING COMPANIES (Chiarini & Kumar, 2022)	2022 54	The study explores the main themes that underlie the Quality 4.0 model and its development. Based on two samples of Italian manufacturing companies, eleven themes were identified and tested. A theoretical model of Quality 4.0 is proposed, structured in three categories: people, processes, and technology.

Analysis of the authors' keywords

The fundamental premise of word co-occurrence analysis is that authors' keywords accurately reflect the central idea of their articles and the connections between the topics addressed in those works (Strozzi et al., 2017). In total, 286 relevant keywords were identified in the 98 selected articles.

In the Bibliometrix package, it is not possible to automatically integrate synonyms for a given term. Therefore, the authors removed similar or alternative terms before visualizing the network in RStudio.

Figure 5 presents a treemap of the keywords that appear three or more times. Since Quality 4.0 is an emerging field, with publications starting in 2020, we set a minimum threshold of three occurrences for keywords, given our current understanding of the topic and the adopted approach.

The analysis of keyword frequency reveals that "Quality 4.0" (89) and "Industry 4.0" (58) are the most recurrent themes. "Quality Management" (21) and "TQM" (8) also stand out, while concepts like "Artificial Intelligence" (6), "Digital Transformation" (6), and "Six Sigma" (5) appear shortly after. Emerging terms such as "Quality 5.0" and "Sustainability" still have few mentions. The number of times a keyword appears in the articles determines the size of each quadrilateral; the larger the quadrilateral, the more frequent the keyword.

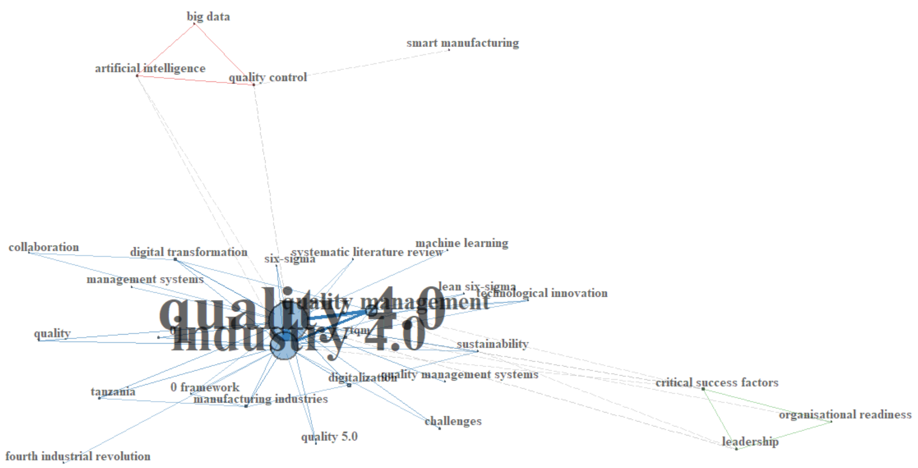
Figure 5

Treemap of keywords that appear three or more times

Figure 6 depicts the keyword co-occurrence network. The number of times a keyword (or set of keywords) appears in the articles determines the size of each circle; the larger the circle, the more frequent the keyword. Furthermore, the weight of each link indicates the relative strength of a keyword in relation to others; the thicker the line, the stronger the connection. The domain presents a single cluster, represented by two shades of blue. Figure 6 shows that Quality 4.0 is widely connected to Industry 4.0 and Quality Management.

Figure 6

Keyword co-occurrence network in Quality 4.0



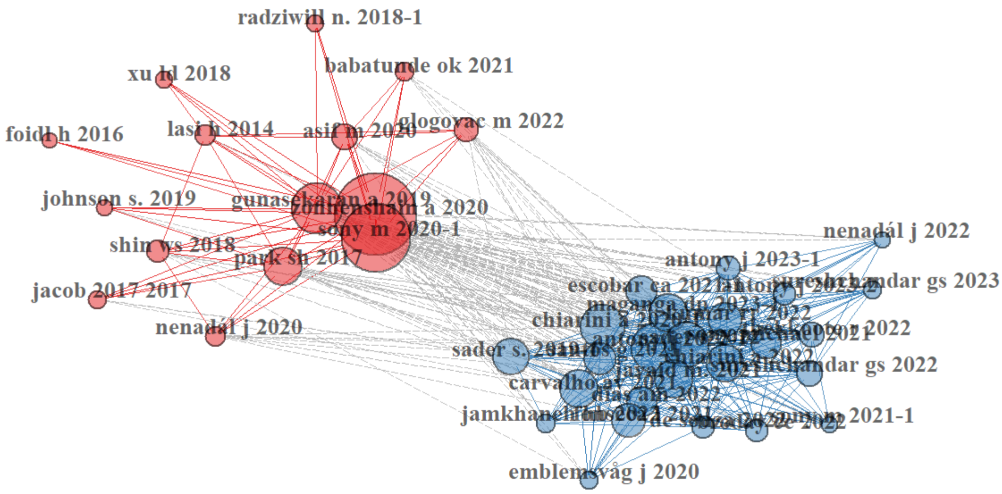
Co-citation analysis

Co-citation analysis identifies the frequency with which two articles are cited together in a third document. When this occurs, it is presumed that they share a common theme, even without citing each other directly. The greater the number of articles that co-cite two documents, the stronger their thematic relationship. This analysis is a powerful technique for examining the theoretical foundations of research and for identifying thematic similarities between documents based on cited references (Caputo et al., 2023). This process establishes intellectual connections between scientific disciplines and serves as a tool for knowledge mapping, enabling the classification of documents and the identification of thematic clusters. Co-citation networks reveal three main components of a scientific domain: the most referenced documents, the most cited authors, and the most cited journals, forming a weighted graph. In this structure, the nodes represent documents, authors, or journals, while the connections (edges) reflect the co-citation frequencies.

In this study, the co-citation analysis was performed using the Bibliometrix package in R (Figure 7), which is used to visualise document co-citation networks (Aria & Cuccurullo, 2017).

Figure 7

Co-citation network for cited reference groups



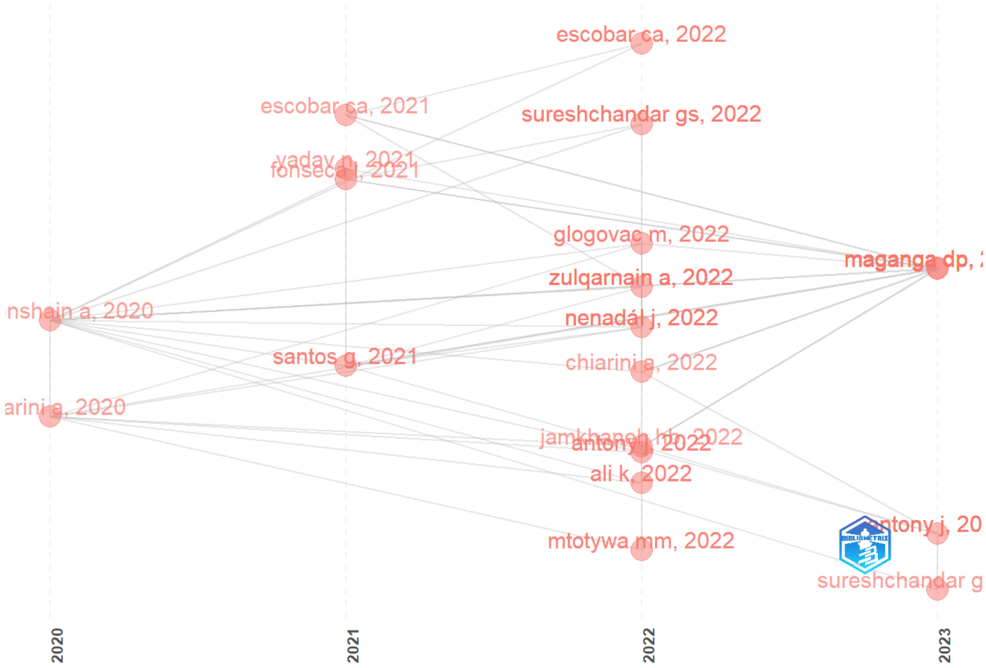
Historiography

Historiography is built based on direct citations, establishing intellectual connections in chronological order. The works cited by various authors in a collection of published scientific articles are sufficient to reconstruct the historiographical structure of a field, highlighting its fundamental works (Aria & Cuccurullo, 2017).

The historiographical analysis of the selected articles reveals part of the evolution of the Q4.0 field, evidencing its intersection with I4.0 and traditional quality management (Figure 8). The early studies, such as those by Chiarini (2020) and Zonnenshain & Kenett (2020), established the conceptual foundations of Q4.0 by emphasising the integration of digital technologies, including IoT, AI, and Big Data, into quality management systems.

Figure 8

Historiography of the selected articles



Subsequent research, such as that by Santos et al. (2021) and Fonseca et al. (2021), explored sustainability and business excellence in the context of Q4.0, while Escobar et al. (2021) and Yadav et al. (2021) investigated practical applications, such as smart quality control and success in Lean Six Sigma implementation.

Starting in 2022, studies like those by Ali & Johl (2022) and Sureshchandar (2022) deepened the analysis of critical dimensions and success factors, using methods such as the Analytic Hierarchy Process (AHP). In 2023, research such as that by Maganga & Taifa (2023) and Antony et al. (2023) focused on transition frameworks, organisational maturity, and implementation challenges, highlighting the importance of leadership, organisational culture, and digital capability.

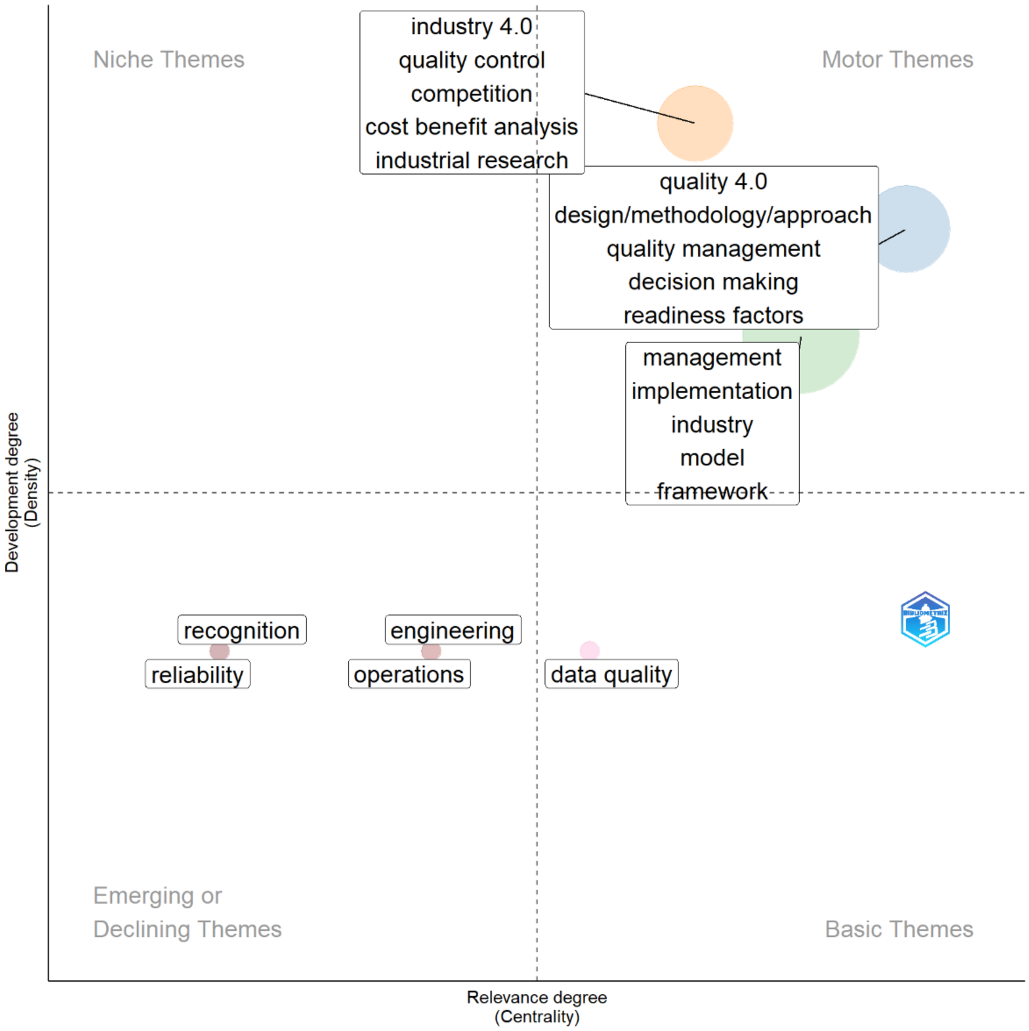
Thematic Map

The co-occurrence analysis of keywords (co-word analysis) groups terms into clusters that represent specific themes, whose density and centrality allow them to be classified and mapped in a two-dimensional diagram. The thematic map, an intuitive visual tool, organizes these themes into four quadrants, each with distinct characteristics: (1) the upper-right quadrant houses the "motor themes," consolidated and highly connected themes; (2) the lower-right quadrant contains the "basic themes," central themes but still in development; (3) the lower-left quadrant includes emerging or declining themes, with low density and centrality; and (4) the upper-left quadrant represents specialized or niche themes, well-developed but poorly connected to the general field.

The interpretation of the thematic map is based on two main dimensions: centrality (X-axis), which indicates the degree of connection of a theme with others, and density (Y-axis), which reflects the level of development and structuring of the theme. Themes with high centrality are fundamental to the field, while those with high density represent well-established areas. On the other hand, themes with low centrality and density are emerging or underexplored topics, suggesting opportunities for future research. This approach enables a strategic analysis of the field of study, identifying both the established pillars and the innovative frontiers of research (Aria et al., 2020). Figure 9 presents the thematic map constructed with the Bibliometrix package.

Figure 9

Thematic Map



The thematic map highlights emerging and underexplored topics in the context of Quality 4.0, pointing to promising areas for future research. Two clusters of works were identified in this quadrant (Recognition & Engineering). The study by Carvalho & Lima (2022) proposes an integrated framework that combines quality management practices with I4.0 technologies and cognitive engineering, aiming to optimise quality management systems and reduce specialists' workload. The work by Glogovac et al. (2023) investigates the influence of leadership on Quality 4.0 outcomes and analyzes relationships among variables such as process management, innovation, and learning. The work by Shivam & Gupta (2023) focuses on the reengineering of quality control processes, proposing a method that incorporates Industry 4.0 technologies, such as sensors, autonomous robotics, and virtual reality, to replace traditional methods. The article by Akhmedova et al. (2023) develops a cyclical model of Industry 4.0

development, highlighting the central role of Quality 4.0 in the advanced stage of high-tech companies. These studies, together, point to the need for integrated frameworks, strategic leadership, and process reengineering as fundamental pillars for consolidating Quality 4.0, paving the way for future research exploring the synergy among technology, management, and innovation.

The Thematic Map points to the Data Quality cluster, whose studies highlight the importance of Q4.0 in Industry 4.0, emphasising the role of data-driven quality (Data Quality) in digital transformation and the improvement of production processes. Zonnenshain and Kenett (2020) highlight the need for innovation in quality engineering, emphasizing the integration of data science and modelling to improve the efficiency of quality monitoring. Escobar et al. (2021, 2022, 2025) deepen the discussion by exploring the challenges of Big Data in manufacturing and the evolution of traditional statistical quality control methods toward approaches based on machine learning and artificial intelligence, enabling real-time monitoring and defect detection. Karbekova et al. (2023), in turn, discuss automation based on artificial intelligence applied to corporate accounting and sustainability reporting, emphasizing the relationship between product quality and the effectiveness of information management systems.

The Thematic Map points to the Management, Quality 4.0, and Industry 4.0 clusters as “motor-themes,” whose works represent the majority of articles exploring the intersection of Quality Management and Industry 4.0, highlighting challenges, opportunities, and strategies for implementing the Quality 4.0 concept. Q4.0 faces significant challenges, notably the high initial implementation cost and the uncertainty about the Return on Investment (ROI) (Antony, Sony, et al., 2022; Sony et al., 2021). The lack of implementation success is frequently attributed to non-technological factors, such as the absence of knowledge and skills in Q4.0 and insufficient support from top management (Maganga & Taifa, 2023b; Tewary & Jadon, 2023). Strategies for a successful transition involve aligning Q4.0 with corporate strategy and focusing on Critical Success Factors (CSFs), such as top management commitment and organizational culture (Sony et al., 2021; Thekkoote, 2022). Research examines the integration of traditional quality management practices (TQM, Six Sigma) with emerging technologies, such as artificial intelligence and the Internet of Things, to assess their impact on operational efficiency and sustainability in manufacturing.

Furthermore, they discuss readiness factors, necessary competencies for quality managers, and frameworks for assessing organizational maturity in adopting these practices. The works point to the transformation of the quality function from reactive to predictive, using advanced real-time data analysis to anticipate failures and enhance organisational performance, innovation, and customer service (Broday, 2022). Q4.0 offers significant benefits, such as improved customer satisfaction, increased productivity, and long-term cost and time savings.

Conclusion, limitations, and direction of future research

This study conducted a systematic literature review and a bibliometric analysis on Quality 4.0. The analysis identified significant patterns in the knowledge domain, including emerging trends, influential authors, and highly cited works, highlighting “The TQM Journal” as a key vehicle for publications on the topic. The results suggest that Quality 4.0 transforms quality management practices, both theoretically and practically, especially with the integration of advanced technologies into Quality Planning, Control, and Improvement processes.

The current literature on Quality 4.0 (Q4.0) presents significant gaps and limitations that must be highlighted. The main one is the insufficiency of empirical studies to investigate performance implications or implementation practices, a consequence of the topic’s novelty, which means most academic production is theoretical or conceptual. Other methodological limitations include the restricted scope of data collection, generally limited to English-language sources and databases such as Scopus and Web of Science, which may lead to the omission of relevant studies. Finally, a sectoral bias is also evident, with a predominance of research in the manufacturing sector, limiting the generalizability of results to other industries.

It is recommended that future studies focus on strengthening the theoretical foundations of Quality 4.0 by proposing frameworks and conceptual models to guide its implementation. Empirical research is essential to validate the proposed practices and understand the real impacts of Quality 4.0 on organizations. Furthermore, investigations into the integration of emerging technologies can broaden the understanding of how these tools can optimize quality management. Finally, comparative studies between sectors and countries can offer valuable insights into best practices and critical success factors for Quality 4.0.

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