



Bibliometric Exploration of Lean Manufacturing in the Era of Industry 4.0

Exploración Bibliométrica del Lean Manufacturing en la Era de la Industria 4.0

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Received: 26 Aug 2025 / **Revised:** 7 Oct 2025 / **Accepted:** 19 Oct 2025 / **Published:** 8 Dec 2025

Abstract. The accelerating digitalization of industrial systems has reshaped traditional management frameworks, including Lean Manufacturing, and has promoted their convergence with the technologies characteristic of Industry 4.0. This intersection has given rise to what is often termed Lean Digital or Lean 4.0, a perspective that aims to merge process optimization with data-driven and connected environments. Despite the growing interest, the academic landscape surrounding this topic shows a dispersed thematic focus, heterogeneous methodological approaches, and limited consolidation of collaborative and bibliographic patterns. As a result, clarifying research trajectories, influential contributors, and strategic areas of development has become increasingly necessary to strengthen conceptual coherence and support future scientific advances. This paper presents a bibliometric assessment of the literature addressing the digital evolution of Lean Manufacturing, using a corpus of 187 documents gathered from the Scopus database. Through VOSviewer, networks for keyword co-occurrence, co-authorship, co-citation, and institutional collaboration were generated, along with productivity and citation indicators. The results show sustained growth in publications from 2019 onward, with a notable rise in 2024. The terminology most frequently appears in the literature illustrates the close alignment between lean methodologies, Industry 4.0, IoT, big data, and digital transformation. Overall, findings indicate an expanding and interdisciplinary research domain with substantial opportunities for further development. The study offers an updated overview for scholars seeking to understand the theoretical and applied progression of Lean systems in digitally enabled environments.

Keywords. Industrial engineering, digital transformation, smart manufacturing, industry 4.0.

Resumen. La acelerada digitalización de los sistemas industriales ha transformado los marcos tradicionales de gestión, incluido el Lean Manufacturing, y ha impulsado su convergencia con las tecnologías características de la Industria 4.0. Esta intersección ha dado lugar a lo que se conoce como Lean Digital o Lean 4.0, una perspectiva que busca integrar la optimización de procesos con entornos conectados y basados en datos. A pesar del creciente interés, el panorama académico en torno a este tema presenta una dispersión temática, enfoques metodológicos heterogéneos y una limitada consolidación de patrones colaborativos y bibliográficos. Como consecuencia, se vuelve necesario clarificar las trayectorias de investigación, los autores influyentes y las áreas estratégicas de desarrollo para fortalecer la coherencia conceptual y apoyar futuros avances científicos. Este artículo presenta una evaluación bibliométrica de la literatura relacionada con la evolución digital del Lean Manufacturing, utilizando un corpus de 187 documentos obtenidos de la base de datos Scopus. Mediante el uso de VOSviewer, se generaron redes de

coocurrencia de palabras clave, coautoría, cocitación y colaboración institucional, complementadas con indicadores de productividad y citación. Los resultados evidencian un crecimiento sostenido en las publicaciones desde 2019, con un incremento notable en 2024. La terminología más frecuente en la literatura refleja la estrecha relación entre las metodologías lean, la Industria 4.0, el IoT, el big data y la transformación digital. En conjunto, los hallazgos muestran un campo de investigación en expansión e interdisciplinario, con amplias oportunidades para su desarrollo futuro. Este estudio ofrece una visión actualizada para investigadores interesados en comprender la evolución teórica y aplicada de los sistemas Lean en entornos digitalmente habilitados.

Palabras clave. Ingeniería industrial, transformación digital, manufactura inteligente, industria 4.0.

1. Introduction

The accelerated incorporation of digital systems into industrial settings has reshaped the foundations of production and organizational management, giving rise to new forms of automation, interconnection, and data-driven control (Villi & Matikainen, 2016). Within this evolving landscape, Industry 4.0 has positioned technologies such as the Internet of Things (IoT), big data, artificial intelligence (AI), collaborative robotics, and real-time analytics as catalysts for redesigning, coordinating, and optimizing manufacturing operations (Stelmach, 2024)(Solano García et al., 2025).

At the same time, the Lean Manufacturing approach, focused on waste elimination and continuous improvement, has maintained its relevance as an operational management model (Chayan, 2018)(de Carvalho et al., 2025). However, its interaction with emerging digital systems has sparked growing academic and business interest, as the integration of both trends promises smarter, more flexible, and more sustainable production (Salvadorinho & Teixeira, 2021).

Although significant progress has been made through the application of lean tools in digitized environments, significant challenges remain (Arcidiacono & Pieroni, 2018). These include the lack of standardized integrated models, barriers to technology adoption, difficulties in the cultural transformation of organizations, and conceptual dispersion around the terms and applications that define the synergy between Lean and Industry 4.0 (Rana & Jani, 2025).

At the same time, the rapid growth of scientific production in this area has generated a large but fragmented body of literature, in which diverse approaches to implementation, impact, and conceptual evolution coexist (Tripathi et al., 2021). This situation makes it difficult to obtain a clear and structured view of the current state of knowledge (Tripathi et al., 2021).

In this scenario, bibliometric studies are essential for understanding how research on the digital transformation of Lean Manufacturing has been shaped, which topics dominate the scientific agenda, which gaps remain, and which actors are most influential in its development. This analysis seeks to provide that panoramic and up-to-date view, with the aim of guiding future lines of research and supporting evidence-based strategic decision-making.

2. Materials and Methods

2.1 Study design

This study adopted a descriptive bibliometric approach, with the aim of quantitatively analyzing the evolution of scientific production related to the integration of traditional Lean Manufacturing tools and emerging Industry 4.0 technologies. The research focused on examining publication patterns, influential authors, relevant sources, institutional collaboration, and thematic networks through the analysis of keyword co-occurrence.

2.2 Data source and search strategy

For this study, only articles published in English between 2014 and 2025 were considered. The data were obtained from the Scopus database, due to its international recognition and its extensive coverage of scientific literature in the field of industrial engineering and technological innovation.

The search strategy was designed with the aim of identifying publications related to the digitization of Lean Manufacturing, focusing specifically on studies that integrated traditional continuous improvement tools with emerging technologies associated with Industry 4.0. To this end, key terms representative of both approaches (e.g., “lean manufacturing,” “industry 4.0,” “digital transformation,” “smart manufacturing,” among others) were selected and searched for in the title, abstract, and keyword fields of the articles.

The criteria applied during the search were as follows: (i) inclusion of documents classified as articles and reviews; (ii) restriction of language to publications in English; (iii) exclusion of meta-analysis reviews, letters to the editor, errata, and duplicate documents.

Articles containing terms unrelated to the industrial field in their metadata, such as “health,” “education,” “biomedical,” “covid,” among others, were also eliminated. During the selection process, thematic relevance was determined by reviewing titles, abstracts, and keywords, retaining only those works that explicitly addressed the relationship between Lean Manufacturing and digital technologies applied in industrial contexts.

2.3 Data processing and analysis

The retrieved records were exported in CSV format for further analysis. Duplicates were removed by checking for matches in the author, title, year of publication, and source fields.

The analysis was carried out in two stages:

- Descriptive analysis: annual publication trends, the most relevant journals, the most productive authors, collaborating institutions, and the countries with the highest participation in the topics of Lean Manufacturing and Industry 4.0 were identified.
- Network analysis: keyword co-occurrence techniques were applied using VOSviewer software (v1.6.19), which allowed the main lines of research and thematic interrelationships within the field studied to be visualized.

2.4 Research questions

This study was designed to explore how scientific literature on the digitization of Lean Manufacturing has evolved. To this end, the following research questions were formulated:

- RQ1: How has scientific output on the digitization of Lean Manufacturing evolved over time?
- RQ2: What are the most relevant sources of publication in this area?
- RQ3: Which authors, institutions, and countries lead this line of research?
- RQ4: Which documents have had the greatest impact in terms of citations?
- RQ5: Which topics emerge most frequently, and how are lines of research structured according to the co-occurrence of keywords?

3. Results

3.1 Evolution of Scientific Production

The annual evolution of the publications identified through the defined search strategy (see Section 2.1) is presented in Figure 1. The analyzed period spans from 2014 to May 2025, focusing the study on recent production related to Lean Manufacturing and its integration with digital technologies associated with Industry 4.0.

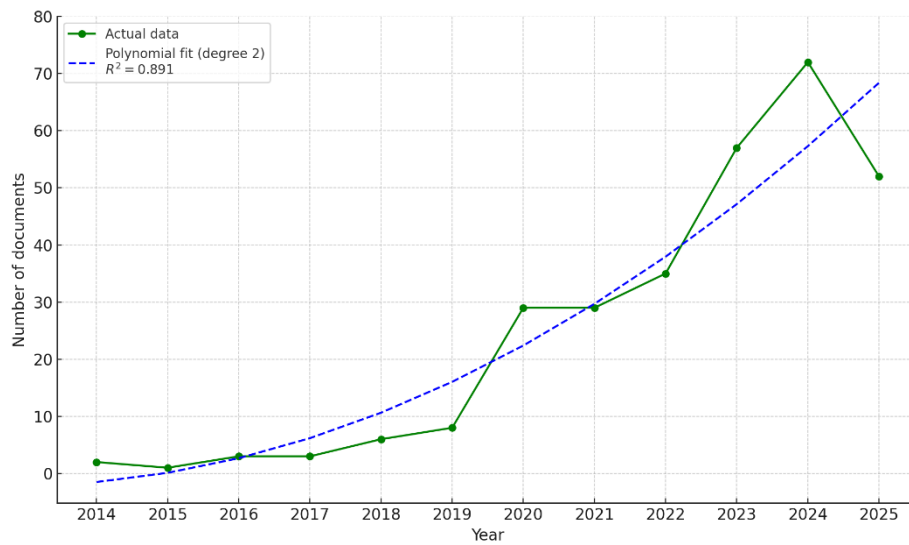


Fig. 1. Annual distribution of documents published by year.

As can be seen in the graph, during the first years of the period (2014–2018), scientific production was in its infancy, with fewer than 10 documents per year. This phase can be interpreted as an exploratory stage, in which the traditional Lean approach began to be linked to the possibilities offered by digitization. From 2019 onwards, there was progressive growth, which intensified significantly in 2020, when the number of publications reached 29 documents. This point marks a significant change in the trend and coincides with the beginning of a stage of academic consolidation of the subject. Production remained constant in 2021 and increased again in 2022 (35 documents), reaching an all-time high in 2024 with 72 indexed publications. In 2025, there was a slight decrease (52 documents), although this figure should be interpreted with caution, given that the year had not yet ended at the time of analysis. In general terms, the observed trajectory is in line with Price's Law, which posits exponential growth in scientific production in emerging fields during their early stages of development.

The second-degree polynomial fit applied to the time series offers a coefficient determination of ($R^2=0,891$), indicating a high correspondence between the model and the observed trend. This evolution reflects the scientific community's growing interest in studying the digital transformation of Lean Manufacturing, driven by the rise of technologies such as the Internet of Things (IoT), Big Data, artificial intelligence, and cyber-physical systems. The dynamism of this line of research is associated with the interdisciplinary nature of the phenomenon, which links engineering, automation, data analysis, and continuous improvement strategies. All of this has contributed to the consolidation of Lean Manufacturing digitization as a rapidly expanding emerging field within academia and industry.

3.2 Distribution of Publication Sources

Table 1 shows the main publication channels through a co-citation analysis of sources, while Table 1 summarizes the 10 most relevant journals in terms of publication volume and number of citations received. There is a notable concentration of articles in journals specializing in production management, continuous improvement, and industrial sustainability, reflecting the interdisciplinary nature of the subject.

Among the sources with the highest number of publications, the International Journal of Production Research (Taylor & Francis) stands out, with 15 indexed articles and a total of 2,015 citations, representing an average of 134.3 citations per article. This figure positions it as the source with the greatest impact in study. It is followed by Production Planning and Control and TQM Journal, both also published by highly

prestigious publishers, with 14 publications each and average citations per article of 52.36 and 20.29, respectively.

Table 1. The 10 most relevant journals/conferences based on the number of citations.

Publisher	Journal / Conference	Publications	Citations	ACPA
Taylor and Francis Ltd.	<i>International Journal of Production Research</i>	15	2015	134.33
Taylor and Francis Ltd.	<i>Production Planning and Control</i>	14	733	52.36
Emerald Publishing	<i>TQM Journal</i>	14	284	3.33
MDPI	<i>Sustainability (Switzerland)</i>	8	203	54.60
Emerald Publishing	<i>International Journal of Lean Six Sigma</i>	8	170	9.40
Emerald Publishing	<i>Journal of Manufacturing Technology Management</i>	7	86	3.20
Elsevier B.V.	<i>International Journal of Production Economics</i>	7	167	6.75
Springer Science and Business Media Deutschland GmbH	<i>International Journal of Advanced Manufacturing Technology</i>	6	94	0.00
Elsevier Ltd.	<i>Journal of Cleaner Production</i>	6	450	28.67
Inderscience Publishers	<i>International Journal of Services and Operations Management</i>	5	18	25.00

ACPA: average citations per article.

Other relevant journals include Sustainability (Switzerland) (MDPI), which has 8 publications and an average of 25.4 citations per article, as well as the International Journal of Lean Six Sigma, with the same number of documents and an average of 21.25 citations. Editorial diversity, which includes Taylor & Francis, Emerald Publishing, and MDPI, confirms the breadth of research interest in the digitization of Lean Manufacturing, both from a technical and organizational perspective.

3.3 Most Prolific Co-Authors

The co-authorship analysis identified researchers with at least three published papers on the topic of digital Lean Manufacturing. Figure 2 shows the collaboration network generated using VOSviewer software, where the nodes represent the authors and their size is related to the number of publications, while the links indicate co-authorship relationships.

The author Antony, Jiju, stands out in the network, with multiple connections linking him to researchers such as Sony, Michael, Swarankar, Vikas, and Komkowski, Tim, which highlights his central role in the thematic development of the area. There is also a cohesive group led by Garza-Reyes, Jose Arturo, who collaborates closely with Shokri, Alireza, Skalli, Ounia, and Charkaoui, Abdelkadir, forming a cluster of high productivity and international cooperation.

Another relevant cluster is formed by Tortorella, Guilherme Luz, Rossini, Matteo, Costa, Federica, and Portioli-Staudacher, Alberto, who have worked together on studies applied to advanced production environments, consolidating a line of research focused on the digital transformation of industrial operations.

This mapping of co-authorships reflects an active scientific community, with interrelated nuclei that drive the advancement of knowledge through stable and multidisciplinary collaborations. The existence of diverse clusters suggests a thematic and geographical expansion of interest in the digitization of the Lean approach.

3.4 Most Cited Documents

Figure 3 shows the bibliographic coupling of the most cited documents in the dataset, considering a minimum threshold of 10 citations. Each node represents an individual publication, with its size proportional to the number of

citations it has received. The links between nodes reflect co-citation relationships, revealing the intellectual structure and shared references across the literature.

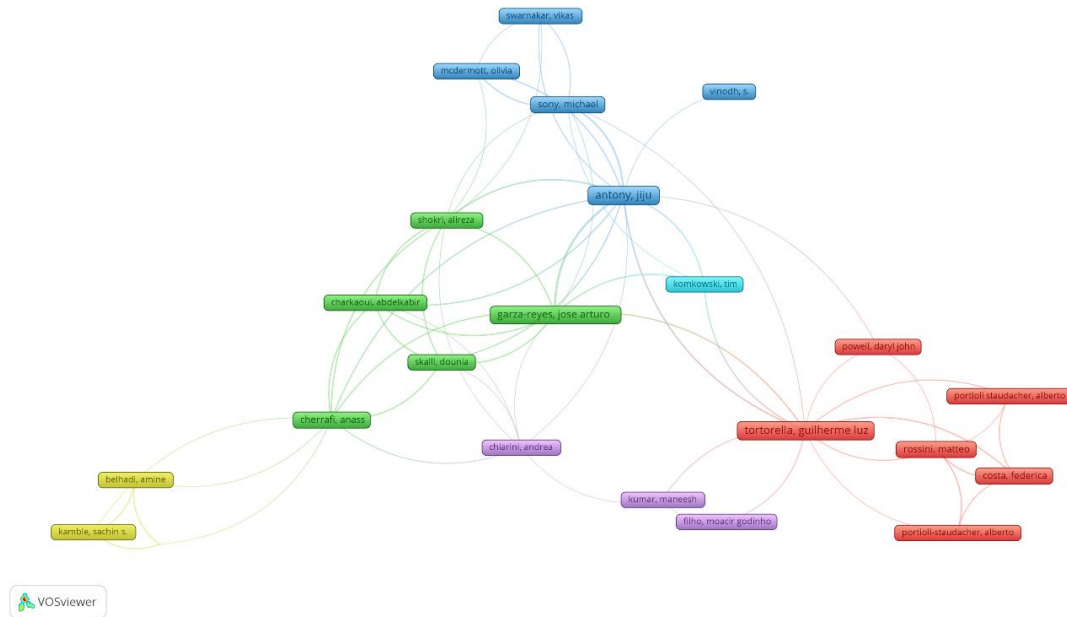


Fig. 2. Co-authorship network of researchers with at least three publications in the field of digitalization and Lean Manufacturing.

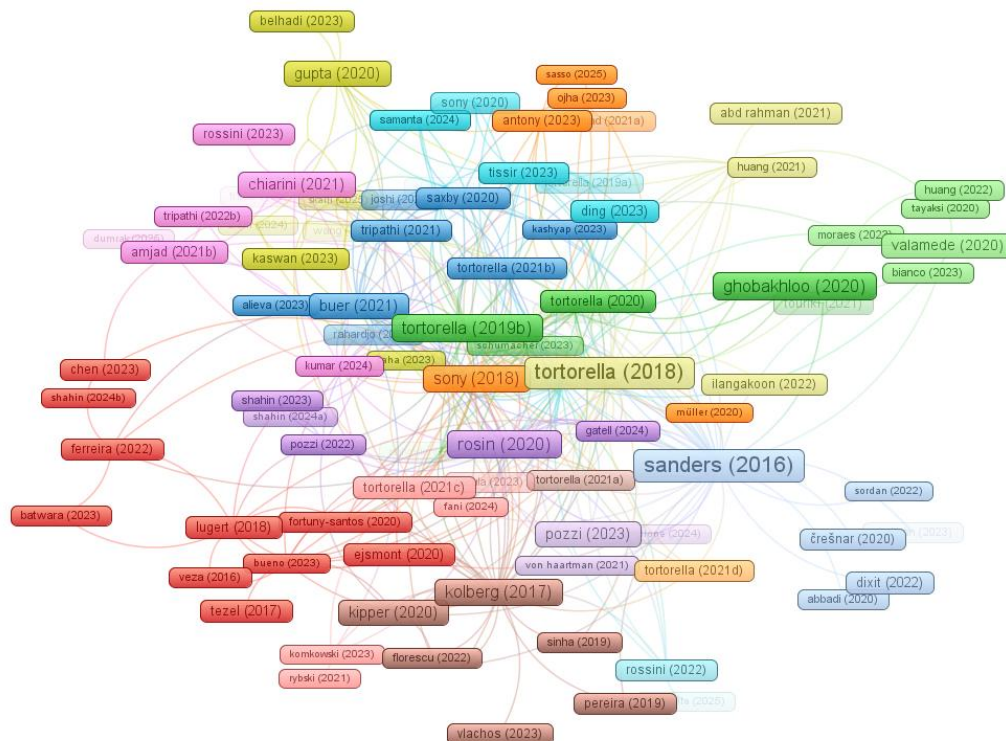


Fig. 3. Co-citation map of documents with a minimum of ten citations in the field of study.

Among the most influential documents, (Sanders et al., 2016) stands out with a central role in the network. This work laid foundational concepts on Industry 4.0, which have served as a reference point for the digital

transformation of lean systems. Similarly, the prolific contributions of (Tortorella & Fettermann, 2018)—especially his 2018 and 2019 publications—form a dense cluster of citations, indicating their strong impact and thematic continuity in exploring Lean 4.0 maturity models, implementation barriers, and enablers.

The papers by (Ghobakhloo, 2020) and (Gupta et al., 2020) are also highly cited, frequently referenced for their integrative frameworks on digitalization strategies and operational excellence. (Sony, 2018) and (Buer et al., 2021) contribute to this core body of literature by offering empirical evidence and theoretical insights on the interplay between lean practices and emerging digital technologies.

Overall, the citation network suggests that a select group of publications is shaping the academic dialogue on digital lean transformation. These works provide conceptual grounding, methodological approaches, and practical case studies that inform ongoing research and industrial applications, reinforcing their status as seminal contributions within this emerging interdisciplinary field.

3.5 Keyword Co-occurrence Analysis

Figure 4 shows the co-occurrence network of keywords extracted from the analyzed corpus, using a minimum threshold of six occurrences per term. The most central nodes are “industry 4.0” and “lean manufacturing”, which articulate the main thematic axis of the research field. These terms are strongly connected with keywords such as *digitalization*, *cyber-physical systems*, *integration*, *automation*, and *operational performance*, reflecting a convergence between traditional lean practices and emerging digital technologies. This suggests a clear research trend focused on how lean philosophies are being redefined in the context of technological transformation.

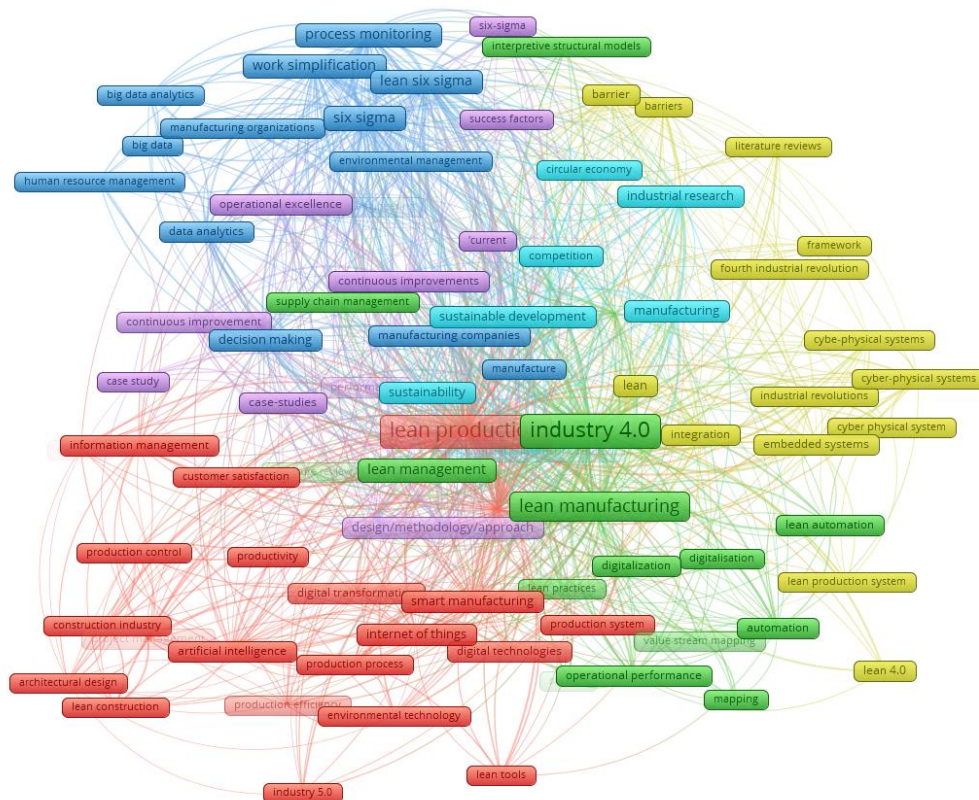


Fig. 4. Co-occurrence map of keywords.

In addition, other keyword clusters reinforce the multidimensional nature of the field. Concepts such as big data analytics, six sigma, operational excellence, and data analytics point to a growing interest in data-driven

strategies and quality management. Meanwhile, terms like sustainability, circular economy, and environmental management highlight the integration of lean with ecological and social responsibility frameworks. Finally, the presence of topics like smart manufacturing, lean construction, and industry 5.0 illustrates the expansion of lean digital principles into various sectors and future-forward paradigms. Together, these trends underscore a dynamic, interdisciplinary research space where lean is evolving toward broader digital and sustainable frontiers.

4. Discussion

The bibliometric analysis carried out provides several relevant insights into the current development of research on the digital transformation of Lean Manufacturing in the context of Industry 4.0. First, the observed growth in scientific production, particularly since 2019 reveals an accelerating interest in understanding how traditional lean principles are being redefined through emerging technologies. However, the temporal distribution of publications also suggests that the field is still undergoing consolidation, with fluctuations that point to exploratory and stabilization phases. This highlights the importance of fostering continuity and methodological robustness in future research efforts.

Secondly, the distribution of publication sources and co-authorship networks reflects a research community that is active but moderately fragmented. Although several prominent authors and journals have emerged, there is no clear concentration of academic leadership, which may limit the formation of cohesive and influential schools of thought. Moreover, the diversity of publication venues and moderate interconnectivity among researchers suggest the need to strengthen international collaboration and promote more structured dissemination channels to unify dispersed findings.

The co-occurrence of keywords reveals a field characterized by strong interdisciplinarity, where Lean Manufacturing intersects with concepts such as Internet of Things, Big Data, cyber-physical systems, and sustainability. This convergence reflects not only the technological dimension of Lean 4.0 but also its socio-environmental implications. Nevertheless, the coexistence of diverse thematic clusters—ranging from quality management and operational efficiency to sustainability and digital transformation—underscores the absence of unified conceptual frameworks capable of integrating these perspectives under consistent models of smart manufacturing (Sony, 2020).

Finally, while the bibliometric indicators demonstrate a positive trend in the visibility and interest surrounding Lean 4.0, its long-term scientific and industrial impact will depend on overcoming several pending challenges. These include the empirical validation of proposed frameworks, the standardization of integration methodologies between lean and digital systems, and the articulation of sustainable innovation strategies. Future research must move beyond descriptive mappings and toward the development of replicable, scalable, and sector-adaptable models that respond to the complexity and variability of modern industrial environments (Oliveira-Dias et al., 2023).

5. Conclusions

The conducted bibliometric analysis provides a comprehensive overview of the scientific landscape surrounding the digital transformation of Lean Manufacturing. The steady growth in publications, especially from 2019 onward, confirms a growing academic interest in exploring how lean principles are being redefined within the framework of Industry 4.0. The co-authorship networks and distribution of publication sources reveal an active but dispersed research community, with a few influential authors and journals beginning to shape the field. However, the lack of strong academic hubs highlights the need to foster collaborative structures that enhance visibility, integration, and leadership within the domain.

Thematic analysis through keyword co-occurrence reveals the convergence of lean practices with enabling technologies such as the Internet of Things, artificial intelligence, and cyber-physical systems. This confirms the interdisciplinary nature of the field and the complexity of implementing Lean 4.0 in diverse

industrial contexts. Despite the maturity of lean as a management philosophy, its digitalization is still an evolving research area that requires further conceptual integration and empirical validation. Future studies should focus on bridging methodological gaps, consolidating international collaboration, and developing robust frameworks that support sustainable, efficient, and technologically enhanced production systems.

Ethics Statement. Because this article is a bibliometric review, it did not involve human participants, experimental procedures, or the collection of personal data. According to institutional policies, ethical approval was not required for this type of research.

Author Contributions. E.X.C.: Conceptualization; Methodology; Formal Analysis; Investigation; Data Curation; Writing – Original Draft; Writing – Review & Editing; Visualization; Project Administration.

The author has read and approved the final manuscript.

Funding. This research did not receive any external funding.

Conflict of Interest. The author declares the absence of financial or commercial conflicts of interest.

Generative AI Statement. Generative AI tools (GPT-4) were used solely for linguistic refinement and grammar editing. All conceptual decisions, methodological processes, analyses, and interpretations were conducted independently by the author.

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