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A bibliometric analysis: exploring the intersection of IA and decarbonisation

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Abstract. The integration of Artificial Intelligence (AI) and Industry 4.0 technologies into decarbonisation strategies has attracted increasing scholarly attention. To capture the dynamics of this emerging field, a bibliometric analysis was conducted using the Scopus database for the period 2014–2024. After data cleaning, a corpus of about 700 documents was analysed through descriptive statistics and network visualisation with VOSviewer.The results show a sharp increase in publications after 2018, with a peak in 2024, confirming the growing centrality of AI and Industry 4.0 in sustainable industrial transitions. Geographically, the United Kingdom, India, China, and Italy emerge as leading contributors, while countries such as Morocco remain peripheral but show growing participation. In terms of document types, journal articles (56.5%) dominate over conference papers (43.5%), with Sustainability (Switzerland) and the Journal of Cleaner Production among the most prolific outlets. Collaboration networks reveal a concentration of influential scholars in sustainable supply chain and digital transformation research. Keyword co-occurrence mapping highlights major clusters around artificial intelligence, *Industry 4.0*, *machine learning*, *sustainability*, and digitalisation, complemented by emerging themes such as circular economy and energy efficiency. This study provides an updated overview of the field, offering insights into research trends, collaboration patterns, and thematic evolution to guide future investigations.

Keywords: Artificial Intelligence, Industry 4.0, Decarbonisation, Bibliometric Analysis

1 Introduction

According to Sustainable Development Goal number 13, which is the fight against climate change established by the member states of the United Nations to protect the planet to the current and future generation, it can be deduced that the subject of climate is among the most important topics at the national and global level. According to the United Nations Development Program (UNDP) [1], all countries in the world are witnessing the serious effects of climate change.

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Industry accounts for a substantial share of global CO_2 emissions, which underscores the crucial importance of transitioning toward less polluting practices. The objective of decarbonisation requires profound transformations across the value chain, particularly within industrial processes, through the adoption of advanced digital technologies.
Industry 4.0 embodies the convergence of physical and digital technologies, including the Internet of Things (IoT), cyber-physical systems (CPS), artificial intelligence (AI), advanced robotics, and big data analytics, to create smart factories that redefine production methods.[2] It contributes to environmental sustainability through real-time energy monitoring, predictive maintenance, and resource optimization [3] [4].
Recent reviews confirm that AI lies at the core of this industrial revolution, offering advanced capabilities in modeling, prediction, and automation.[5] [6]
Despite their potential, AI and Industry 4.0 technologies face concrete barriers in certain industrial sectors. For example, in the steel industry, obstacles include insufficient infrastructure, lengthy learning curves, and organizational resistance [7] .
More broadly, studies highlight technical and human challenges in integrating AI systems into industrial environments, such as system interoperability, data quality, trust, and workforce skill adaptation. While traditional literature reviews have explored the technological applications of Industry 4.0 and AI particularly in sustainability and optimization, a bibliometric approach proves essential. Such an approach enables the systematic mapping of trends, international collaborations, emerging themes, and research gaps[4].
The main objective of our paper is to provide a bibliometric analysis of scientific publications between 2014 and 2024 on the joint use of AI and Industry 4.0 in industrial decarbonisation strategies. Specifically, the study aims to:

- Analyze the temporal evolution of publications.
- Identify the geographical distribution of contributions and their density by country.
- Examine the typology of documents and the main sources of publication.
- Study the most influential authors and collaboration networks.
- Explore key and emerging themes through keyword co-occurrence analysis.

2 Methodology

Before presenting the methodology in detail, Table 1 summarizes the key methodological choices, including the search strategy, selection criteria, and analytical tools, prior to the detailed presentation of the methodology.

Table 1. Methodological Framework Overview.

Component	Description
Source	Scopus, search with AI × Industry 4.0 × Decarbonisation keywords (2014–2024)
Cleaning	Deduplication, keyword normalization, country extraction, date filtering
Network analysis tool	VOSviewer (co-occurrence, co-authorship, citation maps)
Visualizations	Network, density
Descriptive analysis	Publications per year, document type, top journals
Literature grounding	Based on recent bibliometric studies in AI, Industry 4.0, sustainability

2.1. Data Sources and Search Strategy

The bibliographic data were collected from the Scopus database, selected for its extensive coverage of peer-reviewed journals and conference proceedings. The search was structured around three main thematic pillars: artificial intelligence, Industry 4.0, and decarbonisation. The bibliographic query was configured to target the title, abstract, and keyword fields of documents indexed in Scopus, and was restricted to the period 2014–2024 to exclude incomplete records dated beyond 2024. This strategy yielded an initial corpus of more than 1,000 documents, in line with recent bibliometric mapping studies[8- 9] on AI and Industry 4.0.

2.2. Data Cleaning and Preparation

The data were exported in CSV format, including the following fields: citation information, authors, affiliations, abstracts & keywords, document type, and cited references. A cleaning process was then applied:

- Removal of duplicates (based on DOI and title normalization).
- Standardization of keywords (lowercasing, removal of special characters, and grouping of synonyms).
- Extraction of countries from author affiliations.
- Exclusion of articles dated beyond 2024.

The final corpus comprised approximately 700 unique documents, which is both representative and consistent with the standards of bibliometric studies.

2.3. Bibliometric Analysis and Tools

Network analysis was conducted using the VOSviewer software, which is widely employed in the scientific literature [10]. Three types of maps were generated:

1. Keyword co-occurrence (author keywords) → to identify thematic clusters and research trends.
2. Co-authorship (authors and countries) → to visualize scientific collaborations.
3. Citation analysis (sources and documents) → to highlight the most influential journals and articles.

Two visualization modes were employed:

- Network visualization (clusters and relationships).
- Density visualization (areas of high activity).

2.4. Complementary Descriptive Analyses

Additional quantitative analyses were carried out, including:

- The evolution of publications by year.
- The distribution by document type.
- The ranking of the top 10 journals by number of publications.

These descriptive indicators provide additional context to the VOSviewer maps, offering both a quantitative and structural perspective of the research landscape.

3. Results and discussion

3.1. Temporal and Geographical Distribution of Publications

Figure 1 illustrates the annual growth of publications between 2014 and 2024. The results highlight a marginal activity until 2018, followed by a progressive increase from 2019 onwards, and a sharp acceleration after 2020. The number of publications reached a peak of more than 300 documents in 2024, confirming that research on the integration of Artificial Intelligence (AI) and Industry 4.0 into decarbonisation strategies has become a mainstream topic. This dynamic is consistent with previous bibliometric analyses showing a surge of interest in AI-driven sustainability solutions after the Paris Agreement and the global diffusion of Industry 4.0 technologies.[10] The temporal distribution of publications reveals a significant increase only after 2019, despite the Paris Agreement having been adopted in 2015. This temporal lag can be explained by the causal dynamics of research cycles and policy translation into academic output. Following the Agreement, industrial sectors and governments began integrating decarbonisation requirements into strategic roadmaps, which subsequently influenced funding priorities and research agendas. However, the impact of such policy instruments typically manifests with a delay due to the time required for policy adoption, implementation mechanisms, data availability, and the publication process itself.

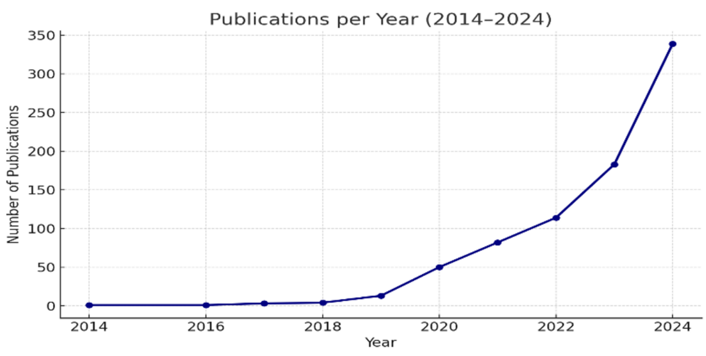

Fig. 1. Annual Growth of Publications (2014–2024)

Figure 2 presents the density visualization of scientific production by country. The map reveals that the United Kingdom, India, China, and Italy are the leading contributors, represented by yellow clusters indicating high publication density. Other countries such as Germany, France, and Spain appear in green, showing a significant but secondary level of activity. Peripheral countries like Morocco as highlighted by the red circle, Lithuania, or Serbia are represented in blue, reflecting emerging but still limited contributions. These findings are in line with global research dynamics reported by recent bibliometric studies, which emphasize the leadership of China, the USA, and European countries in Industry 4.0 and sustainability research, while also highlighting the increasing participation of emerging economies.[11 -12].

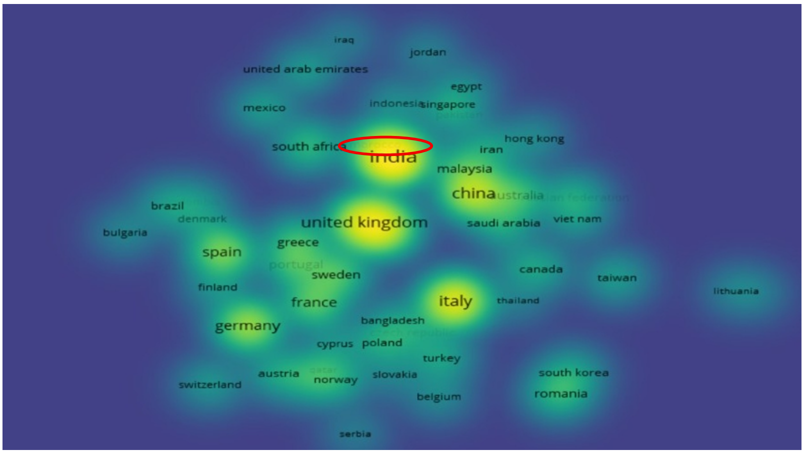

Fig. 2. Country Density Visualization

Overall, this dual analysis confirms both the temporal acceleration of publications and the geographical polarization of research, with a concentration around a few leading nations and a gradual opening towards emerging contributors.

3.2. Document Types and sources of Publication

Figure 3 presents the distribution of documents by type. The results show that journal articles account for 56.5% of the corpus, while conference papers represent 43.5%. This balance highlights that the research field is not only consolidated in peer-reviewed journals but also remains highly active in conference proceedings. Such a pattern is consistent with the evolving nature of Industry 4.0 and AI-related research, where conferences often serve as primary venues for the dissemination of emerging work, later refined into journal publications.[8]

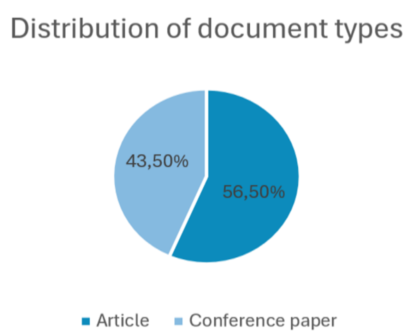

Fig. 3. Distribution of Document Types (Articles vs. Conference Papers)

Figure 4 shows the top 10 journals by number of publications. The results reveal a strong dominance of Sustainability (Switzerland), which alone accounts for more than 60 documents. Other leading outlets include the Journal of Cleaner Production, IEEE Access, Sensors, and Technological Forecasting and Social Change. This distribution suggests that research on AI, Industry 4.0, and decarbonisation is anchored both in sustainability-oriented journals and technology-driven outlets, reflecting the multidisciplinary nature of the topic. Previous bibliometric studies have also reported Sustainability and Journal of Cleaner

Production as major publication hubs for Industry 4.0 and sustainable manufacturing research [11-8].
Overall, these findings confirm the dual structure of the field: on one side, journals dedicated to sustainability and environmental management, and on the other, outlets focusing on technological advances in manufacturing and digital transformation.

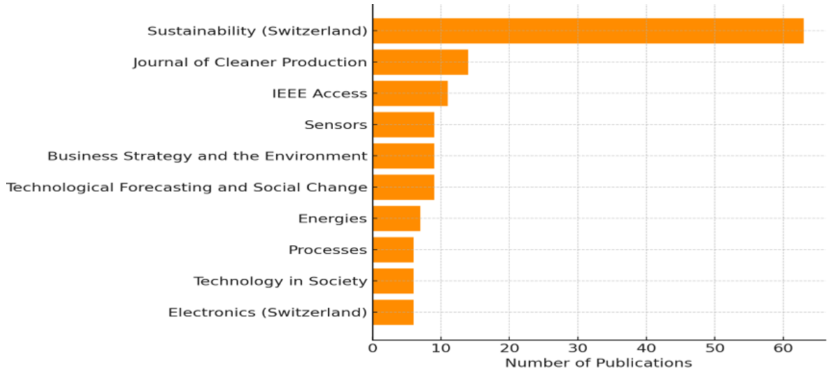

Fig. 4. Top 10 Scientific Journals by Number of Publications

3.3. Author Collaboration and Thematic Clusters

Figure 5 illustrates the author collaboration network. The analysis identified a limited set of connected researchers, with Jose Arturo Garza-Reyes, Anil Kumar, Vikas Kumar, and Sunil Luthra forming the most central cluster. Other clusters, such as those including Monica Sharma, Rajeev Agrawal, and Anbesh Jamwal, show strong regional collaboration, particularly in India. In contrast, researchers from emerging countries such as Anass Cherrafi and Abla Chaouni (Morocco) appear more isolated, suggesting that while the field is global in scope, international collaborations remain concentrated around a few research hubs. This pattern of fragmentation has also been reported in similar bibliometric reviews of Industry 4.0 and sustainability research[13].
The co-authors' analysis revealed 52 researchers active in the field, but only 11 of them form a significant collaborative network. Most authors appear in isolation, suggesting that the field remains fragmented and that international collaborations are still limited.

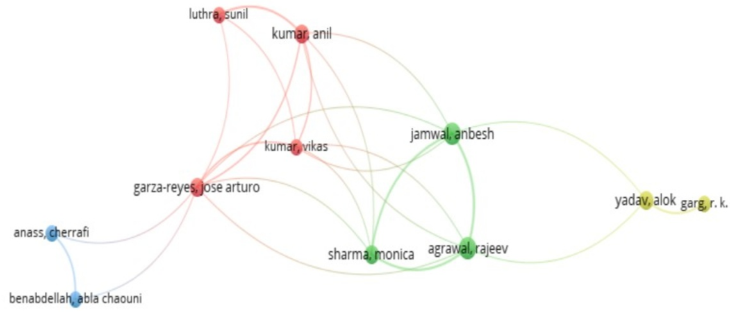

Fig. 5. Author Collaboration Network

Figure 6 presents the keyword co-occurrence map. Of the 775 keywords identified, the 100 most frequent and best related were retained for the co-occurrence analysis, to ensure a clear and readable map.

The analysis shows that the field is dominated by major clusters around artificial intelligence, industry 4.0, machine learning, sustainability, and digitalization. Secondary clusters include internet of things, data analytics, energy efficiency, circular economy, and supply chains. The coexistence of technological terms (AI, IoT, big data) with environmental and managerial ones (sustainability, circular economy, decision making) confirms the multidisciplinary nature of this research domain. Similar findings were reported by Liao et al [14], who emphasized the convergence of digital technologies and sustainable manufacturing, and by Tavares-Lehmann & Varum [12], who underlined the integration of Industry 4.0 technologies into green innovation strategies.
Overall, this section demonstrates that research on AI, Industry 4.0, and decarbonisation is structured around a few leading research groups and multidisciplinary thematic clusters, highlighting both the concentration of expertise and the emerging global diversity of contributions.

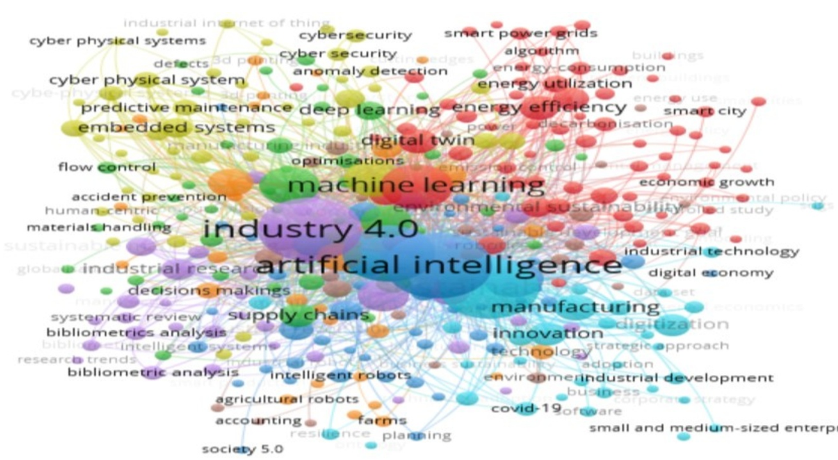

Fig. 6. Keyword Co-occurrence Network (Author Keywords)

4. Conclusion

This bibliometric analysis provides a comprehensive overview of the intersection between artificial intelligence, Industry 4.0, and decarbonisation strategies over the period 2014–2024. The results highlight a sharp increase in scientific production after 2018, reflecting the growing global emphasis on digital technologies to support the energy transition and climate neutrality objectives.

The network visualizations revealed four major research clusters: artificial intelligence and machine learning applications, Industry 4.0 and smart manufacturing, sustainability and carbon neutrality, and data analytics and decision-making. Collaboration analysis showed that scientific output is geographically concentrated in a limited number of countries (China, UK, India, Italy), while emerging countries, including Morocco, contribute more modestly but exhibit potential for future development.

In addition, the journal distribution confirms that leading outlets such as Sustainability (Switzerland), Journal of Cleaner Production, and Technological Forecasting and Social Change play a central role in disseminating research on digital transformation and low-carbon transitions. The strong presence of both journal articles and conference proceedings also underlines the dynamism and multidisciplinary nature of this research area.

Overall, this study contributes to the literature by mapping the current state of research and identifying future directions. It suggests that integrating artificial intelligence and Industry 4.0 tools into decarbonisation strategies is not only a technological challenge, but also a socio-technical transition requiring international collaboration, interdisciplinary approaches, and alignment with global climate targets.

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