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Integrating Industry 5.0 Transitions With Sustainable Development Goal-9 and Circular Economy Models: A Bibliometric Analysis Utilizing Web of Science Database

Ashima Varghese [1] , Baldeo Kakde [2] , Shriya Gokhale [3]

1. Post Graduate Diploma in Business Management, National Academy of Defence Production, Nagpur, IND 2. Department of Commerce, Manoharbhai Patel College of Arts, Commerce and Science, Sakoli, Bhandara, IND 3. Department of Management Studies, Sandip Institute of Technology & Research Centre, Nashik, IND

Corresponding author: Ashima Varghese, ash12varghese@gmail.com

Abstract

The study focuses on the concept of a circular economy based on industrial ecology. Industry 5.0 has the potential to advance Sustainable Development Goal-9 (SDG-9), fostering innovation, encouraging inclusive and sustainable industry, and building resilient infrastructure by going beyond profit-centered productivity.

The research utilized bibliometric analysis to examine the transitions of Industry 5.0 with SDG-9 and circular economy models. The three crucial phrases “sustainable development goals 9,” “circular economy,” or “industry 5.0” were employed to collect data from the Web of Science database during the period 2005-2025. The researchers examined 1,165 papers on performance analysis indicators, viz., most prolific authors, disciplines, universities, etc. We performed scientific mapping on citation analysis, bibliographic coupling of authors and countries, and co-occurrence of keywords using VOSviewer, which displayed network and density visualizations.

The results revealed that most papers, 495, were published in the year 2024. The most prolific author among the 4,004 authors leading the analysis is Leng JW, with 19 publications. SDG-9, Industry, Innovation, and Infrastructure, accounted for the highest number of articles published among the 17 SDGs, with 552. Among the documents, 959 were articles published in the English language. The highest affiliation out of 1,732 is Hong Kong Polytechnic University, leading with 34 publications. Premier publishers were Elsevier with 317 publications, MDPI with 295, and IEEE with 198. China led with 276 publications, followed by Italy with 178, India with 155, and England with 123 out of a total of 91 countries. The keyword that appeared most frequently was "industry 5.0," occurring 507 times.

The principal findings indicate that Industry 5.0's human-centric approach establishes the social foundation, SDG-9 gives the strategic direction, and the Circular Economy offers the operational model for a sustainable industrial system. Key contributions encompass: (1) a comprehensive theoretical framework integrating these three domains, (2) the identification of specific technological enablers (e.g., artificial intelligence for resource optimization, collaborative robots for remanufacturing) that facilitate this integration, and (3) a precise delineation of the novel findings and their substantial policy and practical implications for businesses, governments, and researchers.

The amalgamation creates new opportunities for interdisciplinary study and innovation for scholars. Policymakers and educational institutions may impart the new skills and abilities needed for the shift to Industry 5.0. This integration ensures that technological innovations benefit all facets of society by placing a strong emphasis on human-centric approaches in agriculture and healthcare. Future research should explore the role of renewable energy in achieving sustainable industrialization.

Categories: Social systems (economies, governments, industry), Sustainable Economic Development, Sustainable manufacturing
Keywords: industry 5.0, sustainable development goals (sdgs), circular economy, bibliometric analysis, web of science, sdg-9

Introduction And Background

The global economy is undergoing a transformative shift as industries transition from Industry 4.0 to Industry 5.0. Anang et al. emphasize that this development is distinguished by the incorporation of cutting-edge technologies like robotics and artificial intelligence (AI), the Internet of Things (IoT), and human-centric approaches (Anang et al., 2024). At the same time, the United Nations' Sustainable Development Goals (SDGs), particularly SDG-9 (Industry, Innovation, and Infrastructure), provide a

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framework for building resilient infrastructure, promoting inclusive and sustainable industrialization, and fostering innovation. The integration of Industry 5.0 with SDG-9 is further enhanced by the principles of a circular economy, which emphasize resource efficiency, waste reduction, and sustainable production and consumption patterns (Sustainable Development Goals, 2022). This paper investigates how Industry 5.0 transitions can harmonize with SDG-9 and circular economy models, thereby fostering a sustainable, innovative, and resilient industrial ecosystem.

Understanding Industry 5.0

According to Adams, building on the principles of Industry 4.0, Industry 5.0 is the next phase of industrial evolution (Kenneson, 2024). Beyond the profit-driven productivity of Industry 4.0, Industry 5.0 has the potential to advance sustainable development objectives like resilience, socioenvironmental sustainability, and human-centricity. Industry 5.0 is a human-centric strategy, stressing cooperation between humans and machines, whereas Industry 4.0 concentrated on automation, data interchange, and smart production. Adel and Alani emphasize on Human-Machine Collaboration, means that rather than replacing human capabilities, Industry 5.0 uses AI and cobots (collaborative robots) to augment them (Adel and Alani, 2024). The article by Nahavandi presented the concept of Industry 5.0, in which robots function as collaborators rather than rivals because they are integrated with the human brain (Nahavandi, 2019). Given their awareness of human presence, these collaborative robots will attend to safety and risk factors. Germany's "Industrie 4.0" initiative has evolved into Industry 5.0, integrating human-centric approaches with advanced technologies. German manufacturers are using AI and IoT to optimize production processes, reduce waste, and enhance energy efficiency (Androniceanu et al., 2021). Advanced technologies like personalization and customization enable mass production tailored to individual consumer needs while maintaining efficiency. Sustainability Focus: Industry 5.0 prioritizes environmental sustainability, aligning with global efforts to combat climate change and resource depletion. Vinuesa et al. emphasize that resilience and adaptability, indicated by the integration of AI and IoT, allow industries to respond dynamically to disruptions, such as pandemics or supply chain challenges (Vinuesa et al., 2020).

Sustainable Development Goal 9: Industry, Innovation, and Infrastructure (Adel and Alani, 2024) To support economic progress, it aims to enhance the productivity and association of industries in developing nations and construct robust infrastructure systems. Industries in developing nations may lack the innovation possibilities and infrastructure needed to achieve long-term economic success. The outcome is stagnated production levels, a lack of innovation, and a growing gap between rural and urban areas. Infrastructure systems that are robust and of high quality will boost a nation's economy and improve its citizens' quality of living. Industrial and labor productivity can be increased in emerging nations by increasing public and private infrastructure investment and offering technical support (Ortiz-de-Montellano et al., 2023) (Xu et al., 2024). Construct robust infrastructure, encourage sustainable equitable industrialization, and stimulate inventiveness. UN emphasizes encouraging sustainable and inclusive industrialization and, by 2030, doubling the industry's share in least developed nations and dramatically increasing its employment and GDP share in accordance with national conditions. Expand small-scale industrial and other businesses' access to financial services, such as reasonably priced financing, and facilitate their inclusion into markets and value chains, especially in emerging nations (United Nations, 2015) (Mahmood et al., 2023).

Models of the circular economy

According to Nandi et al., the premise of a circular economy (CE) has developed considerably throughout time, shaped by variables such as resource scarcity, environmental deterioration, and the necessity for sustainable growth. Research demonstrates that the CE models promote environmental sustainability while providing economic benefits, including cost reductions, innovation, and job development (Nandi et al., 2020).

de Melo et al. emphasizes that, due to resource scarcity, material circulation, and the promotion of the reuse and recycling paradigm, the CE is regarded as an entirely novel form of sustainability and continues to rise in popularity (de Melo et al., 2022).

According to the Hivenet report, by placing a strong emphasis on sustainability, waste minimization, and resource optimization, the CE model of economics opposes the conventional linear economy (take-make-dispose) (Hivenet, 2024). Circular practices aim to restore and regenerate natural ecosystems. Research by (Geissdoerfer et al., 2017) concluded that the CE is a regenerative system that slows, closes, and narrows material and energy loops to minimize resource input, waste, emissions, and energy leakage. Long-lasting design, upkeep, repair, reuse, remanufacturing, refurbishment, and recycling can all help achieve this. (de Melo et al, 2022) discovered that when it came to advancing CE through tangible measures, Germany and Japan were leaders.

According to the report by Hivenet, by integrating CE models into Industry 5.0 transitions, industries can achieve sustainable production and consumption patterns, reduce environmental impact, and contribute to SDG-9 (Hivenet, 2024).

Integrating Industry 5.0, SDG-9, and CE models

The integration of Industry 5.0, SDG-9, and CE models creates a synergistic framework for sustainable industrial development. Industry 5.0 drives innovation by combining advanced technologies with human creativity. This aligns with SDG-9's focus on fostering innovation and upgrading technological capabilities. The principles of circularity (Cradle-to-Cradle and Performance Economy) give the analysis a framework for how to work, transforming it from a linear "take-make-dispose" model to a circular one that focuses on getting rid of trash, moving materials around, and restoring nature. Industry 5.0 technologies make this feasible.

Androniceanu et al. emphasized, the Dutch fashion industry is adopting CE models by designing clothes for durability and recyclability. Industry 5.0 technologies, such as 3D printing and AI-driven supply chains, enable personalized, sustainable fashion production (Androniceanu et al., 2021).

As per Geissdoerfer et al., AI and IoT enable predictive maintenance, reducing downtime and resource waste (Geissdoerfer et al., 2017). Vinuesa specified artificial intelligence (AI) as any software technology that possesses at least one of the following: logical reasoning (e.g., theory development from premises), automatic knowledge extraction and pattern recognition from data (e.g., discovery of fake news circles in social media), perception (including audio, visual, textual, and tactile (e.g., face recognition)), and decision-making (e.g., medical diagnosis systems). Machine learning is one of the many subfields covered by this perspective (Vinuesa et al., 2020).

According to Ford and Despeisse, additive manufacturing (3D printing) supports on-demand production, minimizing overproduction and material waste. The phrase "additive manufacturing" refers to a wide range of production technologies that create goods layer by layer, making it possible to "print" three-dimensional objects whenever demanded (Ford and Despeisse, 2016).

Cammarano et al. mentioned how blockchain technology enhances supply chain transparency, ensuring sustainable sourcing and ethical practices. This review examines how blockchain can enhance transparency and sustainability in supply chains (Cammarano et al., 2022).

Munir et al. emphasized blockchain as a transformative technology that has the potential to completely restructure the supply chain to incorporate sustainable practices. A distributed ledger called blockchain offers a digital database for logging every supply chain transaction (Munir et al., 2022).

Sustainable infrastructure development

Industry 5.0 promotes the development of smart, sustainable infrastructure, which is a core target of SDG-9. Androniceanu et al. emphasized that advocacy for sustainable production and consumption behaviors is essential for achieving social, economic, and environmental advantages (Androniceanu et al., 2021).

Androniceanu et al. (Androniceanu et al., 2021) and Vitale (Vitale, 2021) focused on the urban agriculture's rise as an example of how local food systems may be incorporated into urban planning to encourage sustainability and lessen adverse environmental impacts.

Equipped with IoT sensors and AI, smart factories optimize energy use and reduce emissions. Adel and Alani found that to promote an inclusive, sustainable future, this study has carefully outlined how a variety of Industry 5.0 technologies - from blockchain and IoT to smart health and robotics - can significantly improve. The study highlights their implementation in smart cities and communities (Adel and Alani, 2024).

As per Adel and Alani, the strong structure of the “Integrative Technology for Sustainable Development” (ITSD) framework, which combines human-centered design, technology breakthroughs, and a strong sustainability focus, offers a solid basis for addressing today's pressing global issues. It provides a flexible strategy that predicts future demands and changes in societal needs in addition to directly addressing the demands of today's technological environment. In addition to maximizing resource management and efficiency, the convergence of various technologies within the ITSD framework aims to improve quality of life and encourage fair access to the advantages of technology (Adel and Alani, 2024). Incorporating renewable energy sources and energy-efficient systems, green buildings align with CE principles. As per Androniceanu et al., Denmark is a leader in renewable energy infrastructure, leveraging Industry 5.0 technologies to optimize wind turbine production and maintenance. This aligns with SDG-9's focus on sustainable infrastructure and innovation (Androniceanu et al., 2021).

Collaboration and partnership

Achieving SDG-9 requires collaboration between governments, industries, and communities. Industry 5.0

fosters such partnerships by leveraging government support and private sector innovation. As per Nahavandi (Nahavandi, 2019), Industry 5.0 will decrease production time cycles, reduce labor injuries, improve environmental sustainability, and boost productivity and operational efficiency. Contrary to popular belief, Industry 5.0 will actually increase employment rather than decrease it. Numerous jobs will be generated in the fields of robotics, AI, and intelligent systems, including programming, maintenance, training, scheduling, repurposing, and the development of new types of manufacturing robots. Thus, sharing best practices and technologies across sectors by involving local communities in sustainable industrial projects will boost the global economy (Nahavandi, 2019).

We offer a novel viewpoint indicating that human personnel are not only operators but are vital for value-driven circular processes like as repair, remanufacturing, and quality control, which are challenging to fully automate. This makes human ingenuity and talent a key part of the circular transformation.

The current study offers a thorough mapping of scholarly publications about the SDG-9, Industry 5.0, and the CE with the following research questions (RQs):

RQ 1: Which year has the most cumulative publications between 2005 and 2025?

RQ 2: Who are the most prominent authors?

RQ 3 Which articles received the most citations in the prevalent years?

RQ 4: Which affiliations are the most prominent for publishing relevant papers?

RQ 5: Which top publishing houses have published the greatest number of articles?

RQ 6: Which countries have published the most articles?

RQ 7: On which SDG were the most articles published?

RQ 8: Which are the top funding agencies?

RQ 9: Which are the top Web of Science (WoS) subject categories?

RQ 10: Which are the co-citations of the most cited references?

RQ 11: Which are the highest document-wise citations?

RQ12: Which of the top sources has the highest bibliographic coupling?

RQ13: Which countries have the highest number of bibliographic coupling networks?

RQ14: What are the most occurring keywords while publishing articles?

It assesses scientific outputs by looking at the quantity of publications, recognizing authors who write a lot, and emphasizing the best universities that are involved in the subject of study. To find recurring themes and subjects in sustainable business operations, the study also incorporates keyword analysis. looks at the bibliographic coupling of nations, exposing international partnerships and sustainability research patterns. Additionally, the mapping identifies highly cited publications that provide insights into significant and influential works in the field. It provides insightful information about the changing academic landscape of sustainable firms, cutting-edge green practices, and their role in furthering the SDGs by integrating these various analytical methodologies. By pushing beyond profit-centered productivity, Industry 5.0 has the potential to accomplish SDG-9, creating innovation, promoting inclusive and sustainable industry, and developing resilient infrastructure. This thorough review helps to clarify the findings of the study.

Literature review

Cradle-to-cradle design principles and industrial ecology form the foundation of the CE concept (Bakker et al., 2021). Research on the CE focuses far more intently on several aspects of user and consumer participation than earlier concepts like "Cradle-to-Cradle" did.

Sustainability can be characterized as the harmonious combination of environmental resilience, social inclusion, and economic performance (Geissdoerfer et al., 2017). In the landmark review, Geissdoerfer et al. designates the CE as an innovative sustainability paradigm.

The authors Hassan and Faggian suggested that thorough evaluations of organizations, which equally focus on social, environmental, and economic factors, should guide the implementation of CE (Hassan and Faggian, 2023). Liu et al. design products to be long-lasting, reusable, and recyclable (Liu et al., 2024).

Recycling, remanufacturing, and refurbishment ensure that materials are used for as long as possible. Remanufacturing sectors encourage extended product usage, foster community development, use less energy, and provide plenty of opportunities (Ortiz-de-Montellano et al., 2023). Literature demonstrates its evolution from waste management methods to a cohesive economic model that emphasizes resource circulation, product longevity, and systemic change. A recent study has expanded to include business strategies, supply chain reconfiguration, and digital technologies as enablers.

Belaud et al. noted that industrial ecology leverages energy and material exchange, derived from waste stocks and by-products, to optimize industry networking. It seeks to enhance integrated clusters known as eco-industrial parks' (EIPs) environmental potential (Belaud et al., 2019). According to the findings by Androniceanu et al., the CE is a tactical tool that may be used to gain a competitive edge and encourage long-term economic expansion (Androniceanu et al., 2021).

Liu et al. emphasized, in accordance with the CE's "3R" approach, the equation for resource circulation efficiency has been simplified down into three parts: input, circulation, and output. The productivity of the resource input aligns with CE's "reduction" premise, and the value-added rate of the output is related to the "recycling" idea. Additionally, environmental efficiency supports the "reuse" goal of the CE. These sections help businesses make the best CE decisions by forming a visual decision-making tool (Liu et al., 2024).

According to the findings by Palm et al., gender inequality in CE needs to be addressed to promote inclusive, innovative, and sustainable development and avoid reproducing the drawbacks of the linear economy (Palm et al., 2024).

According to de Melo et al., surveys frequently include Sweden, Germany, and Japan as nations that have campaigned for laws pertaining to recycling and trash reduction initiatives. Till 2015, China was the only nation to enact the CE into law, establishing it as a large-scale industrial ecology from a distinctive "harmonious society" perspective (de Melo et al., 2022).

This paper discusses the transition from Industry 4.0 to Industry 5.0, emphasizing human-machine collaboration and sustainability. As per Liu et al., the value flow analysis's resource value distribution theory serves as the basis for the resource circulation efficiency equation. It suggests that the value of waste includes both resource loss and potential environmental harm. The equation for resource circulation efficiency developed using this method takes into account social benefits (economic added value), environmental benefits (external environmental damage value), and economic gains (resource recycling value) (Liu et al., 2024).

According to the study by Munir et al., blockchain may completely transform the supply chain from a perspective of sustainable growth. Blockchain will help achieve environmental and social sustainability through resource efficiency, accountability, smart contracts, trust building, and fraud prevention. It will also improve the economic sustainability of the supply chain through effective traceability, enhanced visibility through information sharing, transparency in processes, and decentralization of the entire structure (Munir et al., 2022).

The initial findings from Adel and Alani showed that new ideas in industry can lead to improvements in environmental sustainability, health, and education, emphasizing how SDG-9 can help expand sustainability goals even further (Adel and Alani, 2024). According to UN-SDGs, by 2030, all countries should take action that is consistent with their respective capacities to upgrade infrastructure and retrofit industries to become sustainable, with greater resource-use efficiency and increased adoption of clean and environmentally sound technologies and industrial processes. Encourage scientific research and strengthen the technological prowess of industrial sectors worldwide, particularly in developing countries. The goal includes, by 2030, promoting innovation, significantly raising the number of R&D employees per million population, and increasing both public and private R&D spending (United Nations, 2015) (Munir et al., 2022).

By focusing on human-machine collaboration, Industry 5.0 creates opportunities for training workers in advanced technologies and sustainable practices. Industry 5.0 opens up new roles in AI, robotics, and sustainability management. It is vital to guarantee that technological advancements yield benefits for all segments of society. Industry 5.0 transitions may play a pivotal role in achieving these targets by driving innovation, enhancing infrastructure, and promoting sustainable industrial practices.

Review

According to a study by Donthu et al., bibliometric analysis is a systematic and rigorous method for scrutinizing and assessing extensive scientific data, allowing researchers to elucidate the intricacies of a specific field's development and highlight its emerging frontiers (Donthu et al., 2021). Bibliometric analysis has gained traction and is widely employed across various industries due to its major advantage of providing thorough scientific mapping over a certain time frame that identifies unique patterns for practitioners and decision-makers.

Bibliometric analysis is the "application of mathematics and statistical methods to books and other media of communication, according to Alan Pritchard," who first used the phrase. It serves as the "metrology" for managing and evaluating the information transfer process. Citation analysis is the statistical or quantitative examination of the references or citations that are appended at the end of every article. Numerous significant details regarding the composition and identification of current and developing knowledge in a field are revealed through the analysis of both referenced and citing articles. It is a quantitative evaluation of several aspects of the literature on a topic and aims to identify trends in authorship, publishing, and secondary journal coverage to shed light on the dynamics of knowledge expansion in the fields of study, according to Kannan and Thanuskodi (Kannan and Thanuskodi, 2019). Using bibliometric research methods like citation and co-citation analysis helps to study, organize, and share information about work done in a specific field.

Source of data and search strategy

The researchers used the WoS database for data mining. “Sustainable development goals 9” and “circular economy” or “industry 5.0” were the search terms used. We used these three noteworthy expressions from 2005 to 2025. WoS served as the main source of data for the "VOSviewer program (version 1.6.20)." The first search yielded 1,300 articles. We reduced the total number of documents to 1,165 after applying the time period filter and the "All field" search criterion (Figure *1*). The papers were further refined with the aid of subject categories. Below, we provide an overview of science mapping indicators and performance measurements.

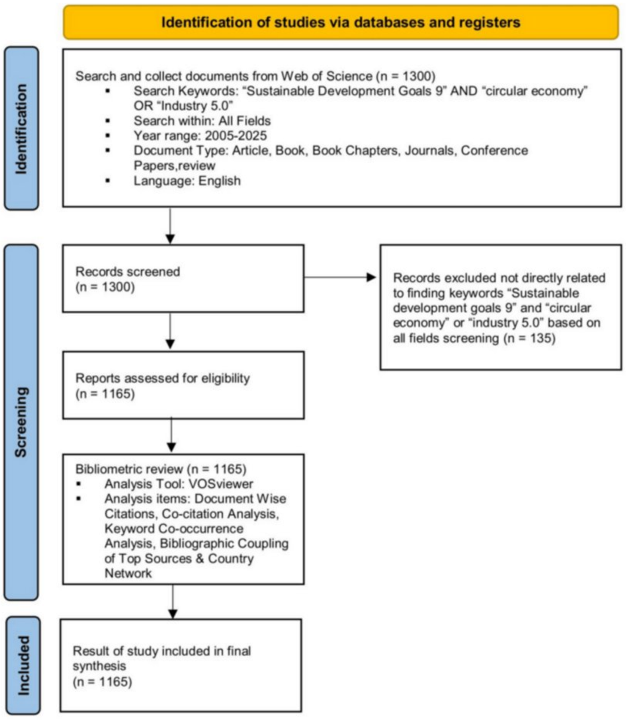

FIGURE 1: A flowchart detailing the selection criteria for articles used in the study

Analyzing performance metrics provides important information about the scholarly environment of a specific field of study. We examined the contributions of prominent journals to identify those that consistently publish high-impact articles. With an emphasis on the rise of pertinent articles year after year, the cumulative publications by year display trends throughout time, highlighting times of heightened research effort. The quantity of works produced by the most prolific writers identifies the important academics advancing the area and highlights their impact. Furthermore, the breakdown of the most pertinent papers by document simplified the identification of foundational works that have influenced the field. Lastly, we examine the contributions of important nations, highlighting the global distribution of research endeavors and identifying the top countries contributing to the area. This multifaceted approach provides a thorough grasp of research trends, important contributions, and the intellectual dynamics within the academic community.

Science mapping indicators use a range of analytical techniques to examine the trends and organization of a field of study. We can trace the influence of important publications by identifying notable scholars and their most cited works through document-wise citation analysis of top authors. We highlight the most referenced journals to demonstrate which ones have significantly contributed to the field's scholarly conversation. Co-citation analysis reveals links between researchers' ideas by identifying trends in the frequency of mentioning the most cited authors' works together. The bibliographic coupling of universities and sources reveals collaboration between institutions based on shared references, demonstrating the strength of their research networks. Similarly, by mapping common references across nations, bibliographic coupling of countries demonstrates international research partnerships. Last but not least, keyword co-occurrence analysis reveals the primary study themes and their relationships, illuminating changing patterns and new key terms. Collectively, these metrics offer a comprehensive insight into the research environment via network and density visualizations.

Research gaps

Geissdoerfer et al. identified gaps in circular economy research, including the need for sector-specific studies and long-term impact assessments (Geissdoerfer et al., 2017). Vinuesa et al. mentioned gaps in AI research for sustainability, such as ethical concerns and the need for interdisciplinary collaboration (Vinuesa et al., 2020). Ford and Despeisse focused on gaps in additive manufacturing research, such as energy consumption and material limitations (Ford and Despeisse, 2016). Yu and Nielsen's study highlighted gaps in human-centric approaches, such as the need for inclusive policies and workforce training (Yu and Nielsen, 2020).

Results

Performance Analysis

Cumulative Publications by Year

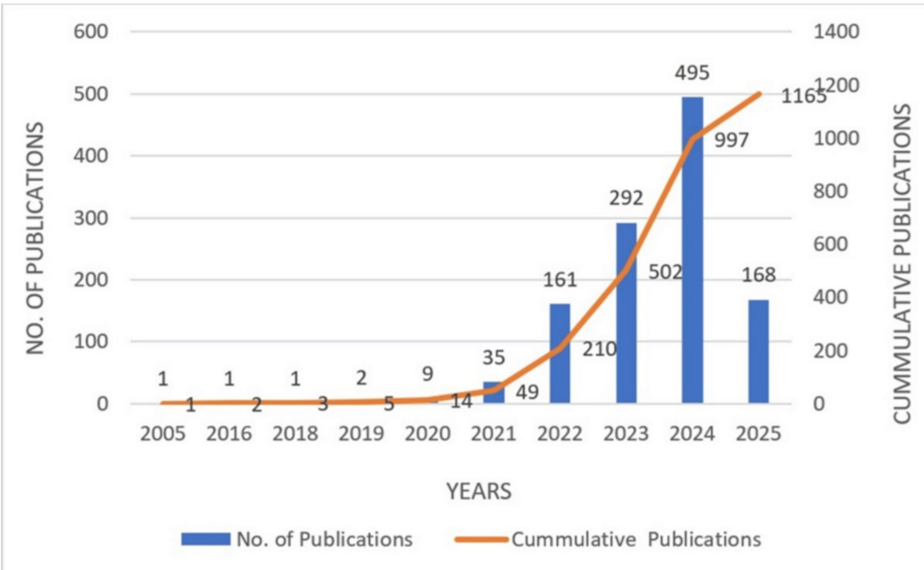

FIGURE 2: Cumulative publications by year

Source: WoS database. WoS, Web of Science.

Overall, 1,165 publications were examined; Figure *2* shows the cumulative number of publications from 2005 to 2025 in a combination chart. The graphic shows annual publication trends by combining line and bar graphs with cumulative publications on the secondary axis. With a peak of 495 articles focused on "Industry 5.0," "Sustainable Development," and "Circular Economy," 2024 stands out as the year with the most publications.

Top Prominent Authors

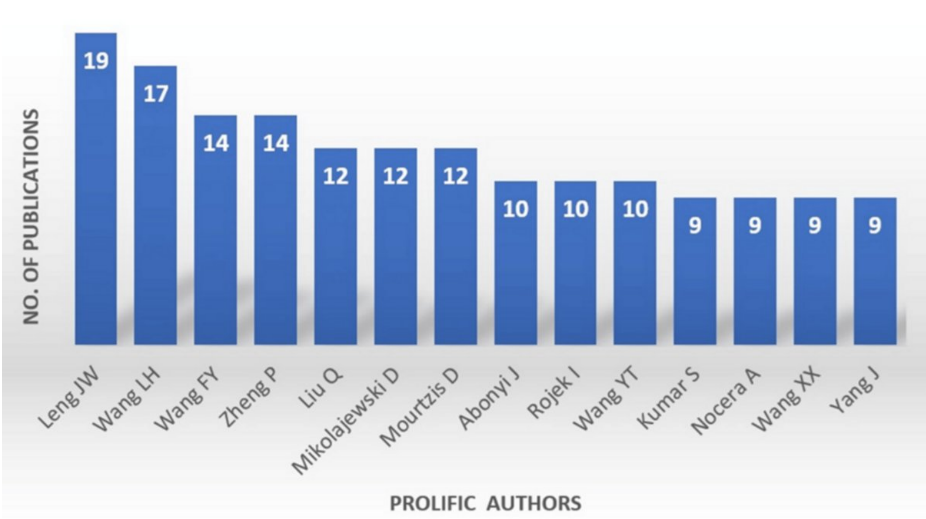

FIGURE 3: Top prominent authors

Source: WoS database. WoS, Web of Science.

Figure 3 illustrates the top 15 authors. Among 4004 authors, leading the analysis is Leng JW with 19 publications, indicating a highly influential body of work that is often cited in connection with other authors. Wang LH and Wang FY follow closely with 17 and 14 publications, respectively. Zheng P with 14 and Liu Q with 12 publications, followed by others. These authors, along with others in the top 15, are key contributors in the field that highlight their significant impact on the research community.

Publications and Citations

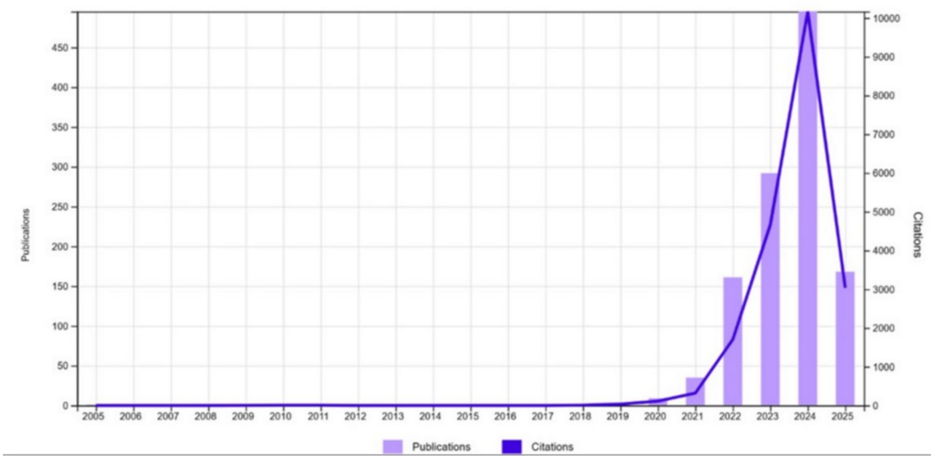

FIGURE 4: Publications and citations

Source: WoS database. WoS, Web of Science.

Total publications displayed in Figure 4 are 1,165, as per the citation report. Citing articles have cited one or more of the items in the citation report. The total number of citing articles is 11,636. The total number of citations to all items in the results set is 20,052. The average per item is 17.21. This is the average number of citing articles for all items in the results set. It is the sum of the count of times cited divided by the number of results in the set. The h-index value of 65 is based on a list of publications ranked in descending order by the Times Cited count. Academic communication in this area predominantly utilizes English as its primary medium. Given that English is frequently the dominant language for academic papers, the data emphasizes the accessibility and global reach of research.

Top Affiliations

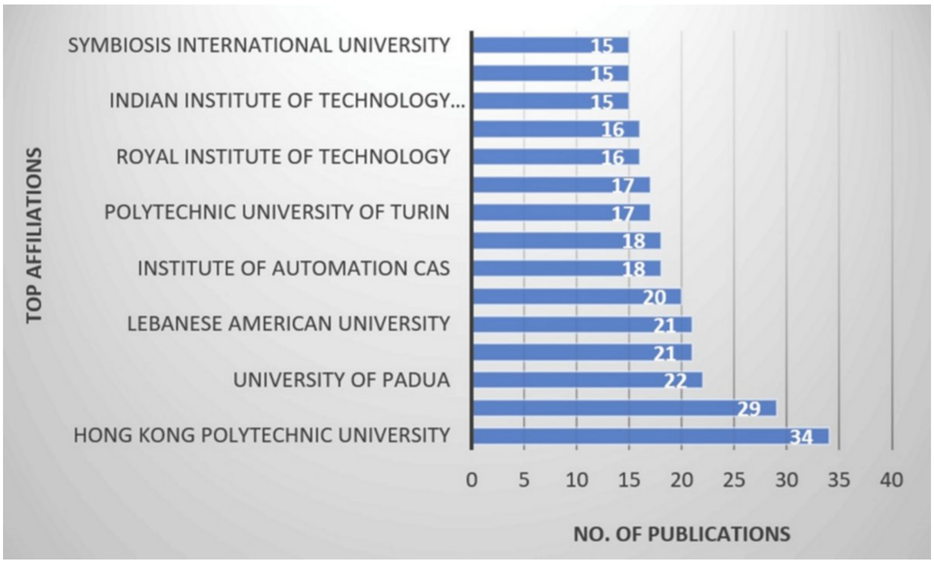

FIGURE 5: Top affiliations

Source: WoS database. WoS, Web of Science.

Figure 5 demonstrates top universities among 1,732 affiliations. Hong Kong Polytechnic University leads with most of the publications. Despite having fewer articles, other top 15 universities are also acknowledged for their noteworthy contributions.

Top 10 Publishing Houses

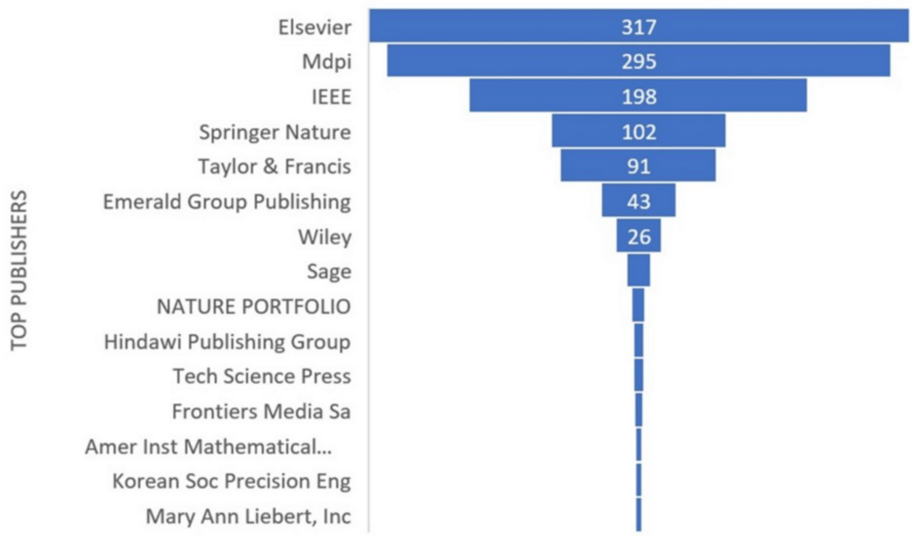

FIGURE 6: Top 10 publishing houses

Source: WoS database. WoS, Web of Science.

Figure 6 represents the top 15 publishing houses. Based on the quantity of papers published, this graph shows the top publishers out of 56. Elsevier has the most publications. The other publishers at the top of the list also made significant contributions to the topic, despite the fact that their publications were smaller. The ranking identifies the major academic publications advancing research on industry 5.0, sustainability, and CE domains, demonstrating their significant contribution to the dissemination of significant discoveries in the field.

Top 20 Nations with Highest Published Articles

#	Country	Documents	Citations	Total link strength	#	Country	Documents	Citations	Total link strength
1	Peoples R China	276	5,597	201,609	11	Pakistan	55	1,105	40,043
2	Italy	178	2,338	154,957	12	Canada	54	1,141	43,476
3	India	155	3,154	157,941	13	Poland	52	822	39,182
4	England	123	1,920	165,704	14	Sweden	51	2,880	85,579
5	USA	99	3,575	106,211	15	Portugal	44	749	43,316
6	Saudi Arabia	67	1,002	49,496	16	Taiwan	41	939	33,320
7	Spain	67	809	71,556	17	South Korea	37	1,555	32,619
8	Australia	60	1,962	79,097	18	Greece	32	1,577	49,902
9	France	55	995	67,582	19	Malaysia	31	683	49,566
10	Germany	55	2027	60,493	20	Brazil	26	200	24,281

TABLE 1: Top 20 nations with the most published articles

A more prominent position in the research community is usually indicated by nations with greater citation counts and link strengths, indicating their substantial contribution to the advancement of knowledge in the field. In Table *1*, visualization makes it possible to identify the top nations and their impact on worldwide research trends, as well as the collaborative networks that propel scientific advancement, by examining these indicators. Table *1* illustrated the number of documents representing the amount of research produced in that nation. This table emphasized the top countries contributing in terms of research productivity while showcasing the global distribution of academic publications.

Publications on SDG

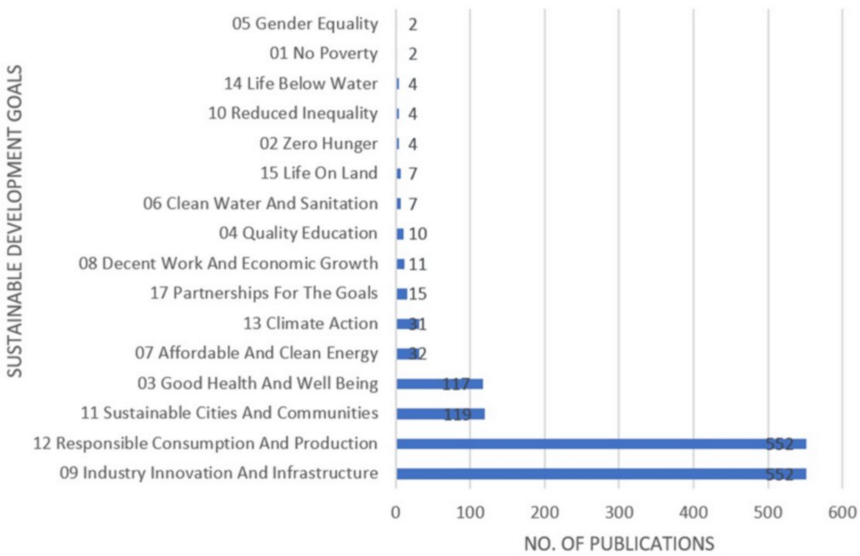

FIGURE 7: The number of articles published on SDGs

SDS, Sustainable Development Goals.

Figure *7* displays the number of articles published on SDGs. Among 17 United Nations SDGs, the highest number of articles, 552, were published on SDG-9, i.e., Industry, Innovation, and Infrastructure.

Top Funding Agencies

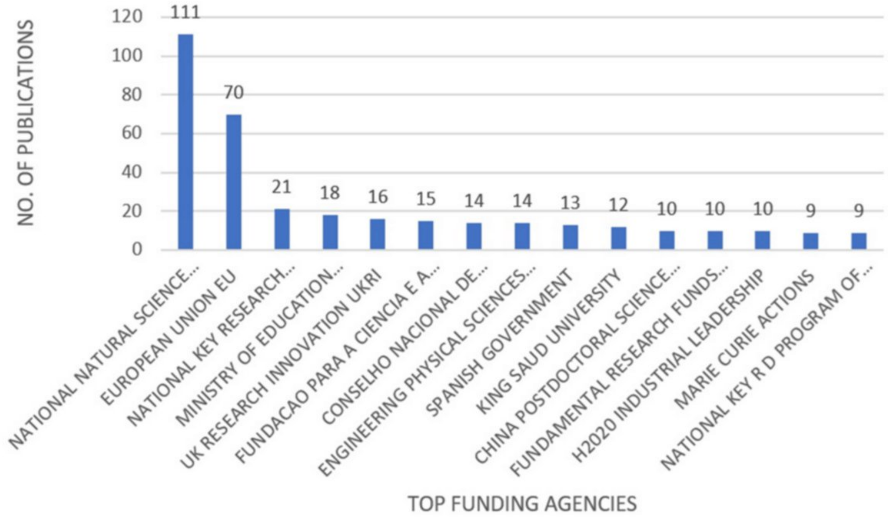

FIGURE 8: Top funding agencies

Figure 8 focuses on the top fifteen to highlight the organizations that support research in the particular field the most. These organizations are essential to the advancement of knowledge and innovation because they fund research projects and initiatives, allowing for major contributions to sustainable development and other related fields.

Top WOS Subject Categories

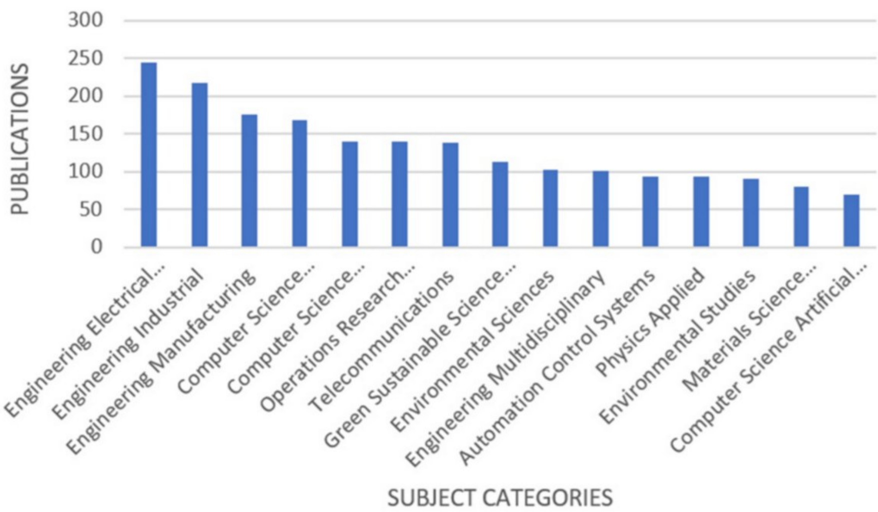

FIGURE 9: Top subject categories

As displayed in Figure 9, the top WOS categories out of 97 are Engineering Industrial at 18.62%, Engineering Manufacturing at 15.10%, Green Sustainable Science Technology at 9.7%, Environmental Sciences at 8.84%, Environmental Studies with 7.81% articles, and so on.

Scientific Mapping

Co-citations of the most cited references

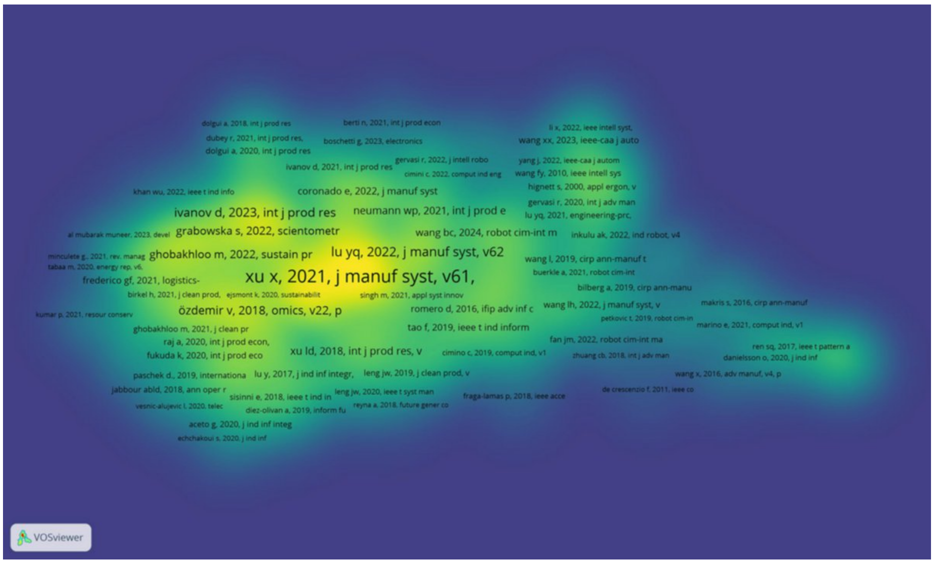

FIGURE 10: Co-citations of the most cited references

Figure *10* presents the co-citations of the most frequently mentioned references, of which 3,477 meet the criteria. The density visualization of co-citation illustrates the connections between the references that are mentioned the most in a dataset, drawing attention to the degrees to which particular works are cited in conjunction with one another. The edges that connect the nodes in this visualization show co-citation, which means that the references are cited together in the same articles. Each node in this visualization represents a reference, which is typically an academic article or paper. The strength of the connection, also known as the edge thickness, is a reflection of the frequency of co-citation. Research frequently mentions the references together, indicating stronger linkages. By highlighting which references are prominent and regularly mentioned alongside others, this form of analysis is helpful in determining which works are considered to be the most important in a particular field.

Document-Wise Citations

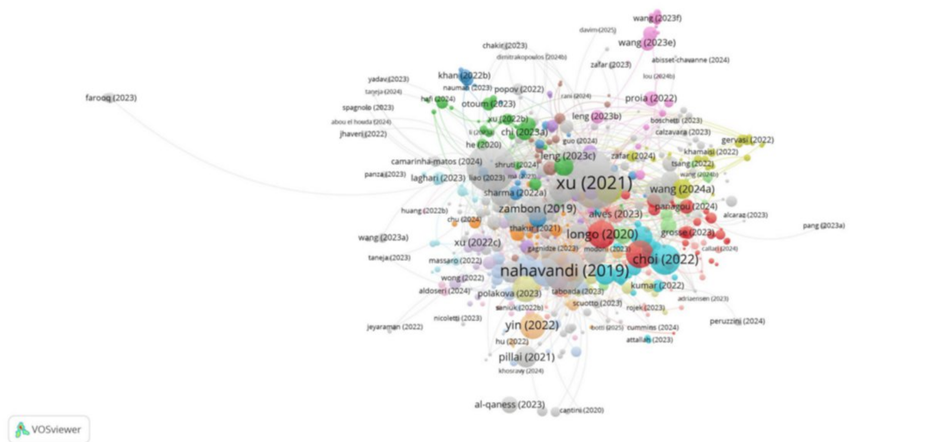

FIGURE 11: Document-wise citations

Source: WoS database. WoS, Web of Science.

Figure *11* illustrates where the document-wise citations are presented in network visualization. It is required that a paper has a minimum of three citations. There are 1,165 documents; however, only 672 of them match the criteria. The total number of citation linkages was determined for each of the 672 documents that were examined. We decided to select the documents with the highest number of links.

Bibliographic Coupling of Top Sources

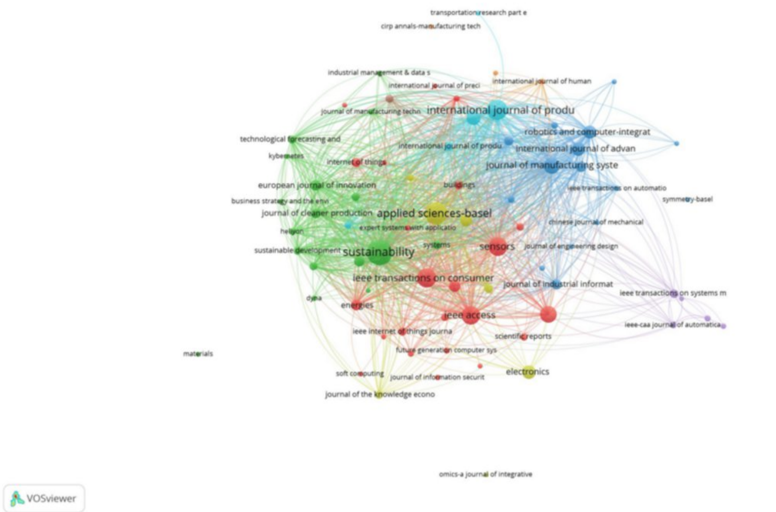

FIGURE 12: Bibliographic coupling of top sources

Source: WoS database. WoS, Web of Science.

Figure 12 illustrates the bibliographic coupling of the most important sources out of 289. There are a total of 76 journal sources, and the top five sources with the number of documents, citations, and total link strength are as follows: sustainability (80 documents, 1,589 citations, and 29,707 link strength), applied sciences - Basel (63, 723, 18,899), international journal of production research (53, 1,149, 20,200), IEEE transactions on consumer electronics (46, 321, 4606), sensors (43, 649, 12,369), and so on.

Highest Number of Bibliographic Coupling of Country Networks

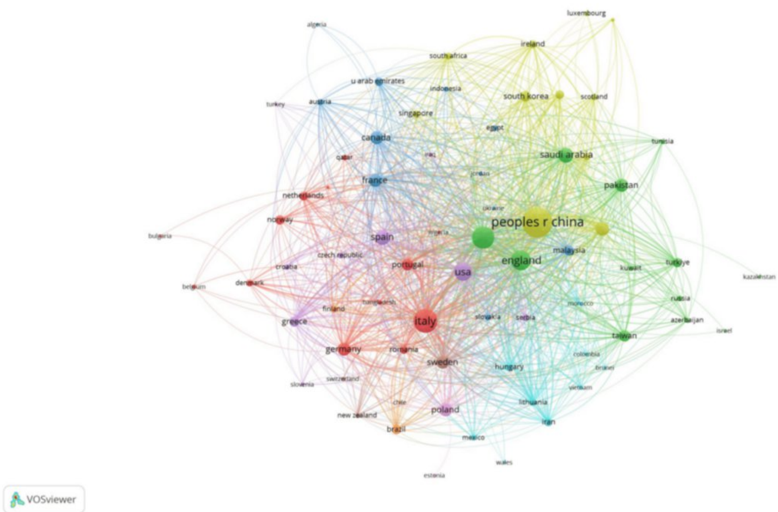

FIGURE 13: Bibliographic coupling of country networks

The bibliographic coupling of nations is shown in VOSviewer's network visualization mode, which highlights their collaborative relationships through common research outputs. In Figure 13, which illustrates the bibliometric coupling of countries, the minimum number of documents required for a country to be included is 3. Out of the 91 countries, 73 attain the threshold. The chosen visualization in this context focuses on China and demonstrates its cooperation with a number of nations, including India, Italy, England, and the USA.

With nodes standing for nations and edges indicating the level of cooperation between them, the network map graphically depicts these connections. Generally speaking, wider lines denote stronger relationships and more regular or important collaboration. Researchers and policymakers can gain insights into international research cooperation trends by using this network visualization mode to comprehend worldwide collaboration patterns and the movement of scientific knowledge across various locations. It is a crucial tool for examining international research networks and locating important nations for collaboration.

Most Occurring Keywords

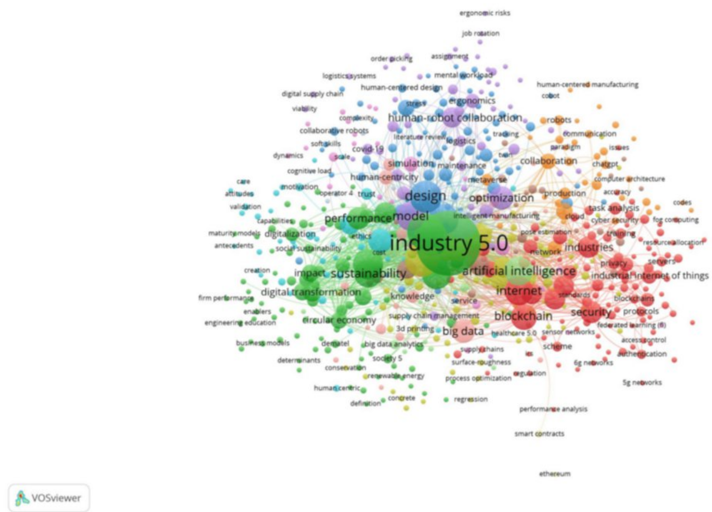

FIGURE 14: Most occurring keywords

Source: WoS database. WoS, Web of Science.

Each keyword's color corresponds to the normal publishing year in which it is most frequently found, and the network visualization shows both the quantity of occurrences and the intensity of connection of keywords. The connecting strength illustrates the degree of connection between keywords based on their co-occurrence in the same texts, while the number of occurrences shows how frequently each term occurs throughout the dataset. Thick margins between terms indicate a higher degree of correlation and a stronger link.

The color coding, which shades each keyword based on the usual publishing year, provides another dimension of understanding. For instance, a keyword that has become more popular recently might be represented with a warmer hue, whereas older, less popular keywords might be represented with a cooler color. Users can see how certain keywords change over time in the literature and spot new trends in study topics with the aid of this visualization.

Within Figure 14, the co-occurrence of each and every keyword is presented. There must be a minimum of three occurrences of a term in order for it to be considered a co-occurrence. Out of the 4,906 keywords, 631 keywords qualified for the threshold. To determine the total link strength of the occurrence links with other terms, the 631 keywords were each given their own unique number. We selected the keywords with the highest total link strength for further consideration.

Co-Occurrence of Top Keywords

No.	Keyword	Occurrences	Total link strength	No.	Keyword	Occurrences	Total link strength
1	Industry 5.0	507	2,962	11	Systems	96	735
2	Industry 4.0	142	1,049	12	Sustainability	95	723
3	Industry 5	133	1,039	13	Digital twin	83	584
4	Design	125	947	14	Blockchain	80	673
5	Management	112	901	15	Future	69	623
6	Framework	109	998	16	System	69	517
7	Artificial intelligence	103	766	17	Big data	66	626
8	Model	102	729	18	Human-robot collaboration	50	295
9	Challenges	101	915	19	Circular economy	35	308
10	Internet	99	938	20	Sustainable development	35	275

TABLE 2: Co-occurrence of top 20 eywords

The tabular visualization displays the co-occurrence of the top 20 most relevant keywords based on their frequency and total link strength, highlighting their interconnectedness in the research domain. These keywords reflect the main ideas of recent studies on Industry 5.0, the circular economy, and sustainability concerns. In addition to displaying the frequency of each term, the visualization also displays the strength of the ties between them; a higher total link strength denotes better associations between keywords across various studies. This analysis identifies key research trends, subject groupings, and the shifting emphasis in areas related to SDG-9 and environmental concerns.

The researchers use performance bibliometric analysis to solve the first seven RQs. This method offers data on publishing patterns, the most pertinent sources, and the main contributors. Figure *2* illustrates the pattern of cumulative publishing over time, generating a total of 1,165 publications. The increase in publications shows that academics are becoming more interested in combining Industry 5.0 with SDG-9 and CE models. This pattern highlights significant growth periods and the recent peak of research activity, demonstrating the increasing scholarly interest in these disciplines over time.

The top 15 prolific authors among 4,004 authors, indicating a highly influential body of work, are demonstrated in Figure *3*. Most of the documents were articles, 959 in the English language, which highlighted the importance for academics from non-English-speaking areas to publish in English or offer translations to make their work available to a larger global audience. Within this field of research, such linguistic patterns can have an impact on the worldwide flow of ideas and the distribution of knowledge.

Figure *4* represented a citation report with 168 publications and 3,064 citations in the year 2025. The year 2024 was leading with 495 publications and 10,165 citations. A total of 292 publications and 4,659 citations in the year 2023 were followed by 161 publications and 1,703 citations in the year 2023, and so on.

Based on the quantity of published articles, Figure *5* showed the top universities from a dataset of 1,732 affiliations. Hong Kong Polytechnic University is leading with 34 publications, Chinese Academy of Sciences 29, University of Padua 22, and Guangdong University of Technology and Lebanese American University 21 each, demonstrating their significant contributions to the research community, followed by others.

Among 56 publishing houses, the top 15 are displayed in Figure *6*. With a total of 317 papers, Elsevier has the most publications. With 295 publications, MDPI comes in second, IEEE has 198 publications, Springer Nature 102, and Taylor & Francis 91, followed by others.

Table *1* illustrated the visualization of published documents by the top 20 nations together with the total link strength and citation count for each nation. This information sheds light on the scholarly contributions made by various countries to this area of study. The total link strength indicates the level of cooperation between nations based on shared references, whereas the number of citations indicates the significance and acknowledgment of the published works. China is in first place with 276 publications, Italy with 178, India with 155, England with 123, and the USA with 99, followed by other countries, which offer a clear picture of the nation’s advancing scientific understanding in the discipline under study.

Out of the 17 UN SDGs, the highest number of articles, 552, were published on SDG-9 - Industry, Innovation, and Infrastructure - followed by SDG 12 - Responsible Consumption and Production - with 552 papers. Figure 6 displays sustainable cities and communities at number 11, with 119 articles, good health and well-being at number 03, with 117 articles, and affordable and clean energy at number 32.

Among 882 funding agencies illustrated in Figure 8, the National Natural Science Foundation of China (NSFC) funded 111 research articles, the European Union (EU) funded 70, the National Key Research Development Program of China funded 21, the Ministry of Education, Universities, and Research (MIUR) funded 18, and UK Research and Innovation (UKRI) funded 16 researches, followed by others.

Figure 9 displays the top WOS subject categories, including Engineering Electrical Electronic with 244 articles, Engineering Industrial with 217 articles, Engineering Manufacturing with 176 articles, Computer Science Information Systems with 169 articles, and Computer Science Interdisciplinary Applications with 140 articles.

The researchers use VOSviewer software to answer the remaining five questions in the study. In scientific mapping, the network visualization has the capability of revealing clusters of connected references, which represent areas of research that have received significant attention from scholars. This sophisticated tool enables us to understand citation trends, monitor the development of ideas, and chart the intellectual landscape.

Figure 10 displays the co-citation analysis of the most cited references among 1000. The top five references with citations and total link strength are as follows: The top five references are Xu X, 2021 (286 citations, 5,696 total link strength); Maddikunta PKR, 2022 (260 citations, 5,534 total link strength); Nahavandi S, 2019 (223 citations, 5,038 total link strength); Leng JW, 2022 (176 citations, 3,806 total link strength); and Longo F, 2020 (119 citations, 3,641 total link strength), followed by additional references.

In Figure 11, the top five documents in terms of citations and overall link strength are illustrated as Xu (2021) has 870 citations and 186 links, Maddikunta (2022) has 786 citations and 178 links, Nahavandi (2019) has 610 citations and 169 links, Leng (2022a) has 402 citations and 129 links, and Choi (2022) has 307 citations and 19 links. Other documents follow in the same order.

Bibliographic Coupling of Top Sources In Figure 12, there are 76 journal sources, and the top five sources based on the number of documents, citations, and total link strength are: sustainability (80 documents, 1,589 citations, and 29,707 link strength), applied sciences-Basel (63 documents, 723 citations, and 18,899 link strength), International Journal of Production Research (53 documents, 1,149 citations, and 20,200 link strength), IEEE transactions on consumer electronics (46 documents, 321 citations, and 4,606 link strength), and sensors (43 documents, 649 citations, and 12,369 link strength).

Bibliographic coupling of top countries, which reflected a collaborative connection in research, happens when two nations use similar references in their published scientific works. The top five countries with the number of documents, citations, and total link strength are the People's Republic of China (276 documents, 5,597 citations), Italy (178, 2,338), India (155, 3,154), England (123, 1,920), and the USA (99, 3,575), followed by others as displayed in Figure 13.

In Figure 14, among all the keywords that appear the most frequently are “industry 5.0” (507 times), “industry 5” (133 times), “sustainability” (95 times), “blockchain” (80 times), “human-robot collaboration” (50 times), “circular economy” (35 times), and “sustainable development” (35 times), followed by other keywords. Table 2 displays the total link strength of top keywords like “industry 5.0,” which has a total link strength of 2962; “sustainability,” which has 723; “blockchain,” which has 673; “human-robot collaboration,” which has 295; “circular economy,” which has 308; “sustainable development,” which has 275; and so on.

Limitations

The analysis was limited to articles that were only indexed in the WoS database. Consequently, it's possible that publications from unidentified databases like Scopus, PubMed, and Dimensions were undetected.

Scope for Future Study

Future research should explore the application of Industry 5.0 and circular economy models in diverse sectors, such as agriculture, construction, and healthcare. Studies should address cybersecurity risks associated with Industry 5.0 technologies and develop strategies for risk management. Research should explore the role of renewable energy in achieving sustainable industrialization and reducing reliance on fossil fuels.

Conclusions

The aim of the present research was to understand how Industry 5.0 SDG-9 and CE models are inter-related. The findings of the study reveal that businesses would wish to think about adopting circular economy models that prioritize the production of goods that are durable, can be repaired, and can be recycled. Industry 5.0 as a human-centric evolution promotes inclusivity and creativity by reorienting the focus from automation to enhancing human capabilities. By encouraging sustainable industrialization, innovation, and resilient infrastructure, Industry 5.0 and circular economy models support SDG-9, as they address issues including socioeconomic injustice, climate change, and resource depletion. This integration bridges the gap between innovation and sustainability by creating possibilities for circular business models that are viable and sustainable, like shared economies, remanufacturing, and product-as-a-service. The study emphasizes the necessity of policies and regulations that encourage innovation and sustainable practices. It is concluded to have specific policy implications for governments, international organizations, and industry groups.

For Policymakers and Governments: Change the policy for industry: Instead of merely distributing funds to basic research and development, give targeted grants and tax breaks to initiatives that show how to combine human-centered AI and robots with circular business models like remanufacturing and product-as-a-service. Update Education and Skills Policy: To get the workforce ready for Industry 5.0, put money into national upskilling and reskilling programs that teach "green digital skills," such AI-aided lifespan assessment, cobot-assisted maintenance, and sustainable supply chain management. Implement Circular Public Procurement: Require that a certain percentage of public sector purchases follow circular principles (durability, repairability, recyclability). The government can use its buying power to establish a market for items that fit this vision. The above incorporation implies that technological innovations benefit all facets of society, particularly underserved groups, by placing a strong emphasis on human-centric approaches.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

Concept and design: Ashima Varghese, Shriya Gokhale

Acquisition, analysis, or interpretation of data: Ashima Varghese, Baldeo Kakde

Drafting of the manuscript: Ashima Varghese, Shriya Gokhale

Critical review of the manuscript for important intellectual content: Ashima Varghese, Baldeo Kakde

Supervision: Ashima Varghese, Baldeo Kakde

Disclosures

Conflicts of interest: In compliance with the ICMJE uniform disclosure form, all authors declare the following: **Payment/services info:** All authors have declared that no financial support was received from any organization for the submitted work. **Financial relationships:** All authors have declared that they have no financial relationships at present or within the previous three years with any organizations that might have an interest in the submitted work. **Other relationships:** All authors have declared that there are no other relationships or activities that could appear to have influenced the submitted work.

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