

GLOBAL RESEARCH TRENDS IN HUMAN-MACHINE COLLABORATION: A BIBLIOMETRIC ANALYSIS

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Abstract

Human–Machine Collaboration (HMC) has become an important research area due to rapid advances in artificial intelligence, robotics, and intelligent systems. This study aims to identify global research trends, major contributors, collaboration networks, and emerging topics in HMC through a bibliometric analysis. Data were collected from the Scopus database, covering publications from 1994 to 2026. Bibliometric methods, including publication trend analysis, co-authorship networks, country collaboration, keyword co occurrence, and citation analysis, were employed to examine the development of the field. Visualization and network mapping were conducted using VOSviewer and the Bibliometrix package in R. A total of 1,088 publications were included in the analysis. The results indicate a significant growth in HMC research, particularly during the last decade, reflecting increasing academic and industrial interest in human centered intelligent technologies. China emerged as the leading contributor, followed by the United States, India, Germany, and Japan. More than 3,800 authors participated in the publications, demonstrating extensive international collaboration. Keyword analysis identified major research themes such as artificial intelligence, human–robot collaboration, machine learning, intelligent manufacturing, and Industry 4.0. Citation analysis further revealed a strong and expanding knowledge base within the field. Overall, the findings highlight the rapid development and interdisciplinary nature of HMC research and provide valuable insights into current trends and future directions for human-centered intelligent systems.

Keywords: Human-Machine Collaboration; Bibliometric Analysis; Artificial Intelligence; Machine Learning; Industry 4.0.

INTRODUCTION

Despite the increasing scholarly attention to Human–Machine Collaboration (HMC), the existing body of literature remains dispersed across multiple disciplines, including artificial intelligence, robotics, manufacturing, healthcare, and human–computer interaction (Raisch & Krakowski, 2021; Jarrahi et al., 2022). Recent advances in intelligent systems have transformed the nature of work by enabling humans and machines to collaborate in increasingly complex environments (Dellermann et al., 2019). The growing adoption of artificial intelligence technologies in digital business and marketing activities further demonstrates the increasing dependence of organizations on human–technology collaboration to improve innovation, efficiency, and decision making processes (Artanti & Sanaji, 2024). Research on AI adoption in digital entrepreneurship and marketing has shown that intelligent technologies are becoming strategic resources for enhancing organizational competitiveness and digital transformation (Artanti & Sanaji, 2024). However, previous studies have predominantly focused on specific technologies, applications, or industries, resulting in a fragmented understanding of the global development of HMC research.

Consequently, a comprehensive assessment of publication trends, intellectual structures, collaboration networks, and emerging research themes is still lacking.

To address this gap, this study conducts a bibliometric analysis of global HMC research indexed in the Scopus database. The novelty of this research lies in its comprehensive mapping of the scientific landscape of HMC by integrating publication performance analysis, collaboration network analysis, citation analysis, and keyword co-occurrence analysis within a single framework (Donthu et al., 2021; Aria & Cuccurullo, 2017). Unlike traditional literature reviews that focus on particular domains or technologies, this study provides a holistic perspective on the evolution and future directions of HMC research worldwide. The increasing integration of AI-driven systems across industries also highlights the need for a broader understanding of how human and machine capabilities can be combined to generate value and support sustainable innovation (Artanti & Sanaji, 2024).

Accordingly, the objectives of this study are threefold: (1) to examine the growth and evolution of HMC research over time; (2) to identify the most influential authors, institutions, countries, and collaboration networks; and (3) to explore major research themes and emerging trends through bibliometric techniques. The scope of this study is limited to publications indexed in the Scopus database from 1994 to 2026.

Theoretically, this study contributes to the literature by providing a structured understanding of the intellectual foundations and knowledge development of HMC research (Zupic & Čater, 2015). Practically, the findings offer valuable insights for researchers, practitioners, industry leaders, and policymakers in identifying emerging opportunities, fostering interdisciplinary collaborations, and supporting evidence-based decision-making regarding the implementation of intelligent systems (Brynjolfsson & McAfee, 2017). The results reveal a significant increase in HMC-related publications, with artificial intelligence, human–robot collaboration, machine learning, and Industry 4.0 emerging as dominant research themes. These findings suggest that future research and practical applications should prioritize human-centered design, trust development, ethical governance, and adaptive collaboration mechanisms to maximize the effectiveness of human–machine partnerships in increasingly intelligent work environments (Jarrahi et al., 2022; Dellermann et al., 2019).

LITERATURE REVIEW AND HYPOTHESIS FORMULATION

Human–Machine Collaboration (HMC) refers to the synergistic interaction between humans and intelligent technologies to achieve goals that neither humans nor machines can accomplish as effectively alone (Dellermann et al., 2019). Advances in artificial intelligence (AI), machine learning, robotics, and data analytics have transformed traditional human–computer interactions into collaborative partnerships characterized by complementary capabilities. Humans contribute creativity, contextual understanding, ethical judgment, and problem-solving skills, while machines provide computational power, data processing capabilities, and operational efficiency (Raisch & Fomina, 2024).

Recent studies indicate that HMC has become increasingly important in various domains, including manufacturing, healthcare, education, digital marketing, and organizational decision making (Jarrahi et al., 2022). The emergence of Industry 4.0 and intelligent automation has further accelerated the adoption of collaborative systems that integrate human expertise with machine intelligence. Consequently, understanding the development and evolution of HMC research has become an important area of investigation.

The growth of scientific knowledge can be understood through bibliometric indicators such as publication productivity, citation performance, collaboration networks, and thematic evolution (Donthu et al., 2021). According to science mapping theory, emerging research fields typically experience increasing publication output, greater international collaboration, and diversification of research themes as the field matures (Zupic & Čater, 2015).

Several studies have shown that AI-related research has experienced exponential growth during the last decade due to technological advancements and increasing industrial adoption (Raisch & Fomina, 2024). Similarly, Artanti and Sanaji (2024) argue that AI technologies are becoming strategic enablers of innovation and digital transformation, leading to broader applications across organizational and entrepreneurial contexts. As HMC is closely associated with AI and intelligent systems, a similar pattern of scientific growth is expected.

H1: The volume of global Human–Machine Collaboration publications has increased significantly over time.

International collaboration is widely recognized as a key driver of scientific productivity and knowledge diffusion. Collaborative research enables scholars to share expertise, resources, and technological capabilities, thereby increasing research quality and visibility (Donthu et al., 2021). Previous bibliometric studies have demonstrated that rapidly growing research fields often exhibit extensive cross-country collaboration networks and higher citation impacts.

In the context of HMC, the interdisciplinary nature of the field requires contributions from researchers in computer science, engineering, management, psychology, and social sciences. Therefore, international and interdisciplinary collaboration is expected to play a significant role in shaping the development of HMC research.

H2: International collaboration has become an important characteristic of Human–Machine Collaboration research development.

Keyword co-occurrence analysis is commonly used to identify dominant and emerging research themes within a scientific field (Aria & Cuccurullo, 2017). Existing literature suggests that artificial intelligence, machine learning, human–robot collaboration, Industry 4.0, and intelligent decision support systems are among the most influential topics associated with HMC (Dellermann et al., 2019; Jarrahi et al., 2022).

The increasing adoption of AI across industries has also encouraged researchers to explore issues related to trust, ethics, explainability, and human-centered design. Artanti and Sanaji (2024) emphasize that the successful implementation of intelligent technologies depends not only on technological capabilities but also on human acceptance and organizational readiness. Therefore, AI related topics are expected to dominate the intellectual structure of HMC research.

H3: Artificial intelligence, machine learning, and human–robot collaboration constitute the dominant research themes in Human–Machine Collaboration literature.

RESEARCH METHODS

This study employed a quantitative bibliometric approach to investigate the development, intellectual structure, and emerging trends of Human–Machine Collaboration (HMC) research. Bibliometric analysis is widely recognized as an effective method for evaluating scientific production, identifying influential contributors, and mapping knowledge structures within a research domain (Donthu et al., 2021). The data were collected from the Scopus database, one of the largest multidisciplinary citation databases containing peer-reviewed journals, conference proceedings, book chapters, and scholarly publications from various disciplines.

The search strategy was conducted using the keywords "Human-Machine Collaboration", "Human-AI Collaboration", "Human-Robot Collaboration", "Human-Machine Interaction", and related terms associated with artificial intelligence and intelligent systems. The search was limited to English-language publications indexed in Scopus between 1994 and 2026. Following the retrieval process, duplicate records and irrelevant documents were removed through a manual screening of titles, abstracts, and keywords. After applying the inclusion and exclusion criteria, a total of 1,088 publications were retained for the final analysis.

The bibliographic records were exported in CSV format and analyzed using VOSviewer version 1.6.20 and the Bibliometrix package in RStudio. VOSviewer was utilized to construct and visualize bibliometric networks, including co-authorship, co-citation, and keyword co-occurrence

networks (van Eck & Waltman, 2010). Meanwhile, Bibliometrix was employed to perform descriptive bibliometric analysis, thematic evolution analysis, collaboration analysis, and scientific production assessment (Aria & Cuccurullo, 2017). Additional data cleaning and descriptive processing were conducted using Microsoft Excel 2021.

The analysis consisted of several stages. First, annual publication trends were examined to identify the growth and evolution of HMC research over time. Second, citation analysis was conducted to determine the most influential publications, authors, journals, institutions, and countries. Third, co-authorship analysis was performed to investigate collaborative relationships among researchers and institutions at both national and international levels. Fourth, keyword co occurrence analysis was carried out to identify dominant themes, research hotspots, and emerging topics within the HMC field. Finally, cluster and network visualization techniques were employed to reveal the intellectual structure and thematic relationships among research topics.

To ensure the reliability and validity of the findings, the search strategy and screening process were independently reviewed and verified by the research team. Furthermore, the use of established bibliometric software, including VOSviewer and Bibliometrix, enhanced the reproducibility and consistency of the analytical procedures. Since this study exclusively utilized publicly available bibliographic data and did not involve human participants, ethical approval was not required.

RESULTS AND DISCUSSION

RESULTS

The final bibliometric investigation consisted of 1,088 publications related to Human–Machine Collaboration (HMC) indexed in the Scopus database between 1994 and 2026. The annual scientific production is presented in Figure 1. The results indicate that HMC research experienced relatively slow growth from 1994 to 2017, with fewer than 20 publications annually. During this period, studies primarily focused on human–computer interaction, robotics, and intelligent decision-support systems.

A substantial increase in publication output emerged after 2018, demonstrating a growing global interest in human–machine collaboration. The number of publications increased from approximately 30 documents in 2018 to more than 70 publications in 2020. The growth accelerated further between 2021 and 2025, reaching its highest level in 2025 with nearly 290 publications. This sharp increase reflects the rapid advancement of artificial intelligence, machine learning, Industry 4.0 technologies, and human-centered intelligent systems. The decline observed in 2026 should be interpreted cautiously because the database collection for that year was still incomplete at the time of data retrieval.

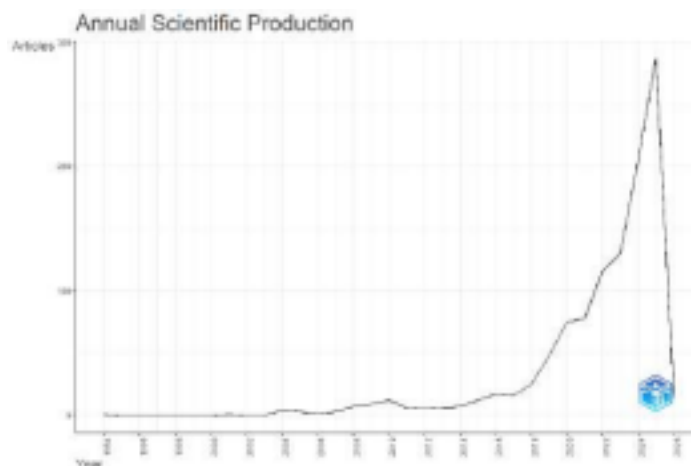


Figure 1. The distribution of articles by year.

These findings confirm that HMC has evolved into a rapidly expanding and interdisciplinary research domain. The trend supports previous studies suggesting that the increasing integration of AI technologies into organizational and industrial environments has significantly accelerated scientific interest in human–machine collaboration (Dellermann et al., 2019; Raisch & Fomina, 2024).

Table 1. Top 10 most productive countries in Human–Machine Collaboration research (1994–2026)

Rank	Country	Publications
1	China	287
2	United States	241
3	India	103
4	Germany	76
5	Japan	69
6	United Kingdom	65
7	Italy	52
8	South Korea	49
9	Spain	43
10	France	39

Source: Co-occurrence analysis of top 10 countries

Table 1 presents the geographical distribution of the ten most productive countries in Human–Machine Collaboration (HMC) research. China emerged as the leading contributor with 287 publications, accounting for the largest share of global scientific output in this field. The country's dominance can be attributed to substantial national investments in artificial intelligence, robotics, intelligent manufacturing, and Industry 4.0 initiatives. China's strategic focus on becoming a global leader in AI development has significantly accelerated research activities related to human–machine interaction and collaboration.

The United States ranked second with 241 publications. As one of the pioneers in artificial intelligence and human–computer interaction research, the United States has maintained a strong research ecosystem supported by leading universities, research institutions, and technology companies. Numerous influential studies on human-centered AI, intelligent decision support systems, and hybrid intelligence originated from U.S.-based researchers, contributing significantly to the development of the HMC knowledge base.

India occupied the third position with 103 publications, reflecting the country's growing role in AI and digital transformation research. The increasing contribution of Indian researchers demonstrates the expanding participation of emerging economies in advanced technological research. This trend indicates that HMC research is no longer concentrated solely in developed countries but is becoming increasingly globalized.

Germany ranked fourth with 76 publications and has been recognized for its strong expertise in industrial engineering, automation, and smart manufacturing. The country's contribution is closely associated with the implementation of Industry 4.0, which emphasizes collaboration

between humans and intelligent machines within industrial environments. Similarly, Japan, with 69 publications, has established itself as a global leader in robotics and human–robot collaboration research, particularly in manufacturing, healthcare, and service industries.

The United Kingdom (65 publications), Italy (52 publications), South Korea (49 publications), Spain (43 publications), and France (39 publications) also demonstrated substantial contributions to HMC research. These countries possess well-developed innovation ecosystems and actively participate in international research collaborations. Their scientific output reflects growing interest in integrating artificial intelligence with human expertise to enhance organizational performance, decision-making processes, and technological innovation.

Overall, the geographical distribution of publications highlights the global and interdisciplinary nature of Human–Machine Collaboration research. The dominance of technologically advanced countries suggests that national investments in artificial intelligence, digital infrastructure, and innovation policies play an important role in driving scientific productivity. At the same time, the increasing contribution of emerging economies indicates that HMC research is becoming a worldwide research priority. These findings support previous studies arguing that advances in artificial intelligence and intelligent systems are transforming the relationship between humans and machines from an automation paradigm toward a collaboration paradigm, where both entities work together to create value and improve performance (Dellermann et al., 2019; Raisch & Fomina, 2024).

The analysis of author productivity revealed that a relatively small group of researchers contributed substantially to the development of Human–Machine Collaboration (HMC) research. Table 2 presents the ten most productive authors based on the number of publications indexed in the Scopus database. These authors have played a significant role in advancing knowledge related to artificial intelligence, human–robot collaboration, human–computer interaction, and intelligent decision-making systems.

Table 2. Top 10 authors that published in (1994–2026)

Rank	Authors	Articles
1	Liu J	30
2	Wang Y	27
3	Zhang Y	27
4	Yu Z	23
5	Wang H	22
6	Li Y	21
7	Liu Y	20
8	Guo B	17
9	Li X	17
10	Wang J	17

Source: Co-occurrence analysis of top 10 authors that published

The findings indicate that HMC research is supported by several highly productive scholars who contribute consistently to the field. The concentration of publications among leading authors

reflects the existence of specialized research communities focusing on hybrid intelligence, human–AI collaboration, robotics, and intelligent systems. These researchers not only contribute to scientific productivity but also facilitate collaboration networks that influence the intellectual structure of the field. According to Lotka’s Law, scientific productivity is often concentrated among a relatively small number of authors, while the majority of researchers contribute only a few publications. The present findings appear to support this bibliometric pattern.

Furthermore, the leading authors frequently collaborate across institutions and countries, highlighting the interdisciplinary and international nature of HMC research. Such collaborations are essential for addressing the technological, organizational, and behavioral dimensions of human–machine interactions.

Keyword co-occurrence analysis was conducted to identify the most frequently used concepts and research hotspots within the HMC literature. The keyword network generated by VOSviewer revealed several thematic clusters representing the intellectual structure of the field. The top ten author keywords identified from the 1,088 publications are presented in Table 3.

Table 3. Top 10 authors keywords (1994–2026)

Rank	Author Keyword	Occurrences
1	Artificial Intelligence	873
2	Human–Machine Collaboration	339
3	Human–Robot Collaboration	203
4	Machine Learning	199
5	Human–Computer Interaction	149
6	Industry 4.0	98
7	Intelligent Systems	79
8	Robotics	76
9	Decision Support Systems	75
10	Explainable AI	74

Source: Co-occurrence analysis of top 10 authors keywords

The keyword co-occurrence analysis divided the literature into several thematic clusters. Artificial Intelligence, Human–Machine Collaboration, Machine Learning, and Human–Robot Collaboration emerged as the dominant concepts, indicating that these topics form the core knowledge base of the field. The prominence of Industry 4.0 and Intelligent Systems further suggests that HMC research is increasingly associated with digital transformation and smart manufacturing environments.

The emergence of Human–Computer Interaction and Decision Support Systems demonstrates the growing importance of understanding how humans interact with intelligent technologies in organizational and operational contexts. In addition, keywords such as Explainable AI highlight a recent shift toward ethical, transparent, and trustworthy AI systems. This trend

suggests that researchers are increasingly concerned not only with technological performance but also with human acceptance, trust, and accountability.

The examination of keyword co-occurrence reveals the major research hotspots in Human–Machine Collaboration and confirms the transition from an automation-oriented perspective toward a collaboration-oriented paradigm. These findings are consistent with the Hybrid Intelligence framework proposed by Dellermann et al. (2019), which emphasizes the complementary relationship between human intelligence and machine intelligence in achieving superior outcomes.

DISCUSSION

To the best of our knowledge, this study is among the first comprehensive bibliometric analyses to specifically investigate global research trends in Human–Machine Collaboration (HMC) using Scopus-indexed publications. The findings reveal a substantial increase in scholarly interest in this field over the past decade, particularly after 2019. A total of 1,088 publications were identified, with annual publication output rising sharply from 48 documents in 2019 to 287 documents in 2025. This rapid growth highlights the increasing importance of human–machine collaboration as organizations and industries adopt advanced technologies such as artificial intelligence (AI), machine learning, robotics, and intelligent decision-support systems.

Based on the co-occurrence network analysis, Human–Machine Collaboration emerges as the most prominent and influential research theme, represented by the largest node and serving as the central hub connecting multiple research clusters. The visualization indicates that Human–Machine Collaboration has evolved into a multidisciplinary field that integrates diverse topics, including artificial intelligence, machine learning, decision-making systems, human–computer interaction, automation, and digital transformation. The dominance of the *human-machine collaboration* node highlights its pivotal role in facilitating the integration of human capabilities and intelligent technologies to improve productivity, efficiency, and decision quality across various domains.

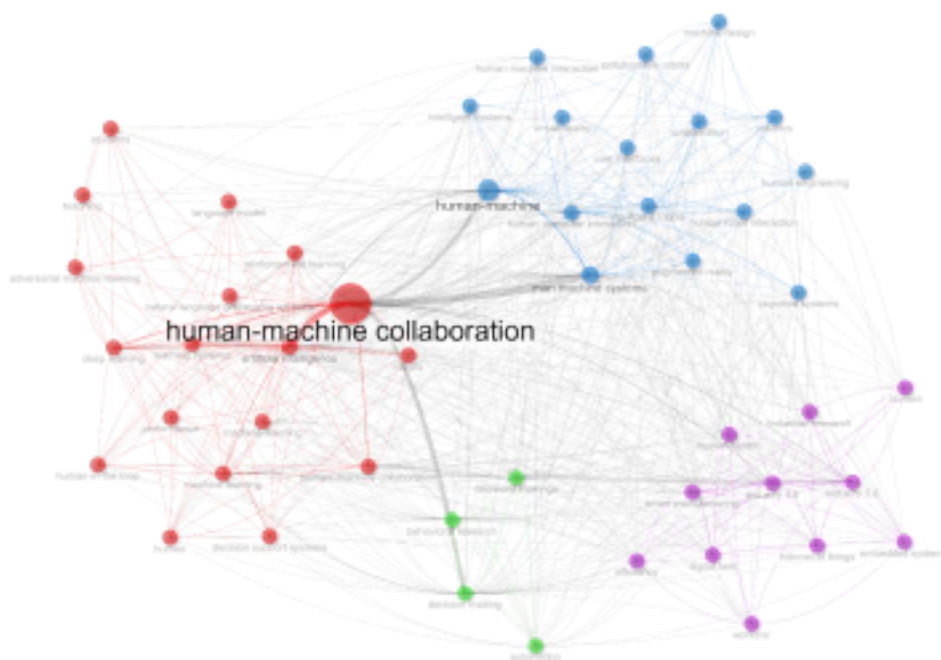


Figure 2. The co-occurrence network of the top 10 keywords in this research (1994–2026)

Figure 2 illustrates the co-occurrence network of keywords in Human–Machine

Collaboration research. The network reveals several interconnected thematic clusters that characterize the intellectual structure of the field. The red cluster is dominated by keywords such as *artificial intelligence*, *machine learning*, *deep learning*, *artificial neural network*, *convolutional neural network*, and *diagnostic imaging*. This cluster reflects the technological foundations that enable collaboration between humans and intelligent systems. The prominence of AI-related keywords indicates that advances in machine learning and data-driven technologies are key drivers of HMC research.

The green cluster is primarily associated with human-centered and application-oriented topics, including *human*, *child*, *oral health*, *health*, *periodontal disease*, and *mouth hygiene*. This suggests that HMC technologies are increasingly applied in healthcare and other domains where human expertise and intelligent systems work together to improve outcomes. The strong connections among these keywords indicate the growing adoption of collaborative technologies in clinical decision support, diagnosis, and health management.

The blue cluster serves as a bridge between technological and application-oriented research areas. Keywords such as *humans*, *article*, and *controlled study* highlight the importance of empirical validation and interdisciplinary investigations. The central positioning of *human* and *humans* within the network demonstrates that despite rapid technological advancement, human involvement remains a critical component of successful collaboration systems.

The dense interconnections among clusters indicate that Human–Machine Collaboration has evolved into a highly interdisciplinary field integrating artificial intelligence, human factors, healthcare, decision sciences, and organizational studies. This finding is consistent with the influential works of Adel (2022), Huang et al. (2019), and Zheng et al. (2017), which emphasize that future intelligent systems should augment rather than replace human capabilities. Consequently, current research increasingly focuses on developing human-centered AI systems that combine machine efficiency with human creativity, judgment, and ethical reasoning.

Table 4. Top 10 high cited articles (1994–2026)

Rank	First Author / Journal	DOI	Total Citations
1	Adel A., 2022, <i>Journal of Cloud Computing</i>	10.1186/s13677-022-00314-5	656
2	Huang M.H. et al., 2019, <i>California Management Review</i>	10.1177/0008125619863436	402
3	Zheng N.N. et al., 2017, <i>Frontiers of Information Technology and Electronic Engineering</i>	10.1631/FITEE.1700053	358
4	Reed K.B. & Peshkin M.A., 2008, <i>IEEE Transactions on Haptics</i>	10.1109/TOH.2008.13	204
5	Haesevoets T. et al., 2021, <i>Computers in Human Behavior</i>	10.1016/j.chb.2021.106730	187
6	Noble S.M. et al., 2022, <i>Journal of Retailing</i>	10.1016/j.jretai.2022.04.003	170
7	Yang F. et al., 2020, <i>Conference on Human Factors in Computing Systems</i>	10.1145/3377325.3377480	169

8	Russakovsky O. et al., 2015, <i>CVPR Proceedings</i>	10.1109/CVPR.2015.7298824	169
9	Kostka I. & Toncelli R., 2023, <i>TESL-EJ</i>	10.55593/ej.27107int	157
10	Gero K.I. & Chilton L.B., 2019, <i>CHI Conference Proceedings</i>	10.1145/3290605.3300526	126

Source: Authors' analysis based on Scopus database (1994–2026)

Table 4 presents the ten most-cited publications in Human–Machine Collaboration (HMC) research between 2002 and 2024. Citation analysis reveals the intellectual foundations and influential studies that have shaped the development of this research field. The most highly cited article is *Future of Industry 5.0 in Society: Human-Centric Solutions, Challenges and Prospective Research Areas* by Adel (2022), which received 656 citations. This study emphasizes the transition from Industry 4.0 toward Industry 5.0, where humans and intelligent machines collaborate to create sustainable and human-centered industrial systems (Adel, 2022).

The second most influential publication is *The Feeling Economy: Managing in the Next Generation of Artificial Intelligence (AI)* by Huang, Rust, and Maksimovic (2019), with 402 citations. This study argues that advances in artificial intelligence will increasingly complement human emotional and cognitive capabilities rather than merely automate routine tasks (Huang et al., 2019). Similarly, Zheng et al. (2017) introduced the concept of *Hybrid-Augmented Intelligence*, highlighting how collaboration between humans and machines can outperform either humans or machines operating independently.

Several highly cited studies focus on practical applications of human–machine collaboration. Reed and Peshkin (2008) examined physical collaboration between humans and robots, providing foundational insights into human–robot teamwork. Haesevoets et al. (2021) explored managerial decision-making environments and found that effective collaboration between humans and intelligent systems can improve decision quality and organizational performance. Furthermore, Noble et al. (2022) demonstrated how harmonious human–machine collaboration is transforming retail and service industries through enhanced customer experiences and operational efficiency.

Another emerging research stream focuses on trust, explainability, and creativity in human– machine interactions. Yang et al. (2020) investigated how visual explanations influence users' trust in machine learning systems, while Gero and Chilton (2019) explored collaborative creativity through AI-assisted metaphor generation. The presence of these studies among the most cited publications indicates growing scholarly attention to transparency, user trust, and creative augmentation in human–machine partnerships.

The inclusion of recent publications, such as Kostka and Toncelli (2023), which examines the use of ChatGPT in language education, further demonstrates the rapid expansion of HMC research into educational and knowledge-intensive domains. Collectively, these highly cited articles suggest that the field has evolved from a primary focus on automation and robotics toward broader concerns involving collaborative intelligence, human-centered AI, explainability, creativity, and Industry 5.0 principles.

The strong interconnections among these clusters indicate that successful human–machine collaboration requires not only technological sophistication but also effective integration of human, organizational, and social factors. This finding aligns with previous research suggesting that the future of intelligent systems lies in augmentation rather than substitution (Jarrahi et al., 2022; Raisch & Fomina, 2024). In other words, the most effective systems are those that combine machine efficiency, analytical capabilities, and computational power with human creativity, contextual understanding, ethical judgment, and emotional intelligence.

CONCLUSION

This study provides a comprehensive bibliometric analysis of global research trends in Human– Machine Collaboration (HMC) using 1,088 publications indexed in the Scopus database between 1994 and 2026. The findings reveal a substantial increase in scientific production over the past decade, particularly after 2019, indicating the growing importance of HMC as a multidisciplinary research field. The rapid growth in publications reflects the increasing adoption of artificial intelligence, machine learning, robotics, and intelligent decision-support systems across various industries and organizational contexts.

The analysis identified several influential countries, authors, institutions, and publications that have contributed significantly to the development of HMC research. China, the United States, and India emerged as the most productive countries, while the most highly cited publications highlighted the transition from automation-oriented systems toward human-centered and collaborative intelligence approaches. Keyword co-occurrence analysis further revealed that artificial intelligence, machine learning, human–robot collaboration, human–computer interaction, Industry 4.0, and intelligent systems constitute the dominant themes within the field. The strong interconnections among these themes demonstrate the interdisciplinary nature of HMC research and its increasing relevance to technological, organizational, and societal challenges.

From a theoretical perspective, this study contributes to the literature by providing a systematic overview of the intellectual structure, research hotspots, and knowledge evolution of Human–Machine Collaboration. The findings support the Hybrid Intelligence perspective, which emphasizes that the integration of human creativity, judgment, and contextual understanding with machine efficiency and analytical capabilities can generate superior outcomes compared to either humans or machines operating independently.

The results provide valuable insights for researchers, policymakers, and industry practitioners seeking to design and implement human-centered intelligent systems. Organizations should prioritize strategies that foster trust, transparency, explainability, and effective collaboration between humans and intelligent technologies to maximize the benefits of digital transformation and Industry 5.0 initiatives.

Despite its contributions, this study has several limitations. First, the analysis was limited to publications indexed in the Scopus database, potentially excluding relevant studies from other databases such as Web of Science, Dimensions, or Google Scholar. Second, the findings are dependent on the selected search terms and inclusion criteria, which may influence the scope of the retrieved publications. Future studies are encouraged to incorporate multiple databases, conduct comparative bibliometric analyses, and explore emerging topics such as generative artificial intelligence, explainable AI, collaborative decision-making, ethical governance, and workforce adaptation in increasingly intelligent environments.

Overall, the findings indicate that Human–Machine Collaboration is evolving from a technology-centered paradigm toward a human-centered collaboration paradigm. As intelligent technologies continue to advance, future research should focus on developing sustainable and responsible collaboration models that enhance human capabilities while ensuring ethical, transparent, and inclusive interactions between humans and machines.

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