Revue Internationale du Chercheur
ISSN: 2726-5889
Volume 6 : Numéro 1

Cartographie de l'évolution du capital humain à l'ère de l'intelligence artificielle : Une analyse bibliométrique

Mapping the Evolution of Human Capital in the Age of Artificial Intelligence: A Bibliometric Analysis

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Date de soumission : 15/12/2024

Date d'acceptation : 06/02/2025

Pour citer cet article :

AISSA. S ; REGHIOUI. A (2025) «Cartographie de l'évolution du capital humain à l'ère de l'intelligence artificielle : Une analyse bibliométrique», Revue Internationale du Chercheur «Volume 6 : Numéro 1» pp : 358 - 385

Résumé

Dans le paysage contemporain des avancées technologiques rapides, la compréhension de l'intersection entre l'intelligence artificielle (IA) et le développement du capital humain est cruciale pour façonner les stratégies futures en matière de gestion de la main-d'œuvre et d'amélioration des compétences. Cet article présente une analyse bibliométrique complète visant à élucider les tendances, les dynamiques et les contributions essentielles dans ce domaine. S'appuyant sur un corpus de 3 591 documents allant de travaux fondateurs à des résultats de recherche récents, notre analyse met en évidence des thèmes clés, des auteurs influents et des travaux notables qui ont façonné le discours sur l'évolution du capital humain pilotée par l'IA.

Les résultats révèlent une riche de trajectoires de recherche, avec un accent particulier sur la recherche en marketing numérique et en médias sociaux, soulignant le potentiel de transformation de l'IA dans l'élaboration des pratiques de marketing. En outre, des contributions significatives émergent des études axées sur le développement de la main-d'œuvre, la gestion des talents et l'amélioration des compétences, reflétant la reconnaissance croissante de l'impact de l'IA sur la formation de la future main-d'œuvre.

Grâce à des techniques bibliométriques telles que l'analyse des co-citations et le regroupement de mots-clés, cette étude dévoile six groupes distincts représentant différentes facettes du lien entre l'IA et le capital humain. Ces groupes englobent divers sujets allant des implications de l'IA sur le comportement organisationnel au rôle de l'éducation dans la préparation des individus à l'économie pilotée par l'IA.

Mots clés : Intelligence artificielle ; Gestion du capital humain ; Analyse bibliométrique ; Éducation ; Développement économique ;

Abstract

In the contemporary landscape of rapid technological advances, understanding the intersection between artificial intelligence (AI) and human capital development is crucial to shaping future workforce management and skills enhancement strategies. This article presents a comprehensive bibliometric analysis aimed at elucidating trends, dynamics and key contributions in this field. Drawing on a corpus of 3,591 papers ranging from seminal works to recent research findings, our analysis highlights key themes, influential authors and notable works that have shaped the discourse on AI-driven human capital evolution.

The results reveal a rich trajectory of research, with a particular focus on digital marketing and social media research, highlighting the transformative potential of AI in shaping marketing

practices. In addition, significant contributions emerge from studies focused on workforce development, talent management and skills enhancement, reflecting the growing recognition of AI's impact on shaping the future workforce.

Using bibliometric techniques such as co-citation analysis and keyword clustering, this study reveals six distinct clusters representing different facets of the link between AI and human capital. These clusters encompass diverse topics ranging from the implications of AI on organizational behavior to the role of education in preparing individuals for the AI-driven economy.

Keywords : Artificial Intelligence ; Human capital management ; Bibliometric analysis ; Education ; Economic development ;

Introduction

- In recent years, the concept of human capital has regained prominence as advances in artificial intelligence (AI) reshape the global economy. Human capital, traditionally defined as the set of skills, knowledge and experience held by individuals, is now viewed through the lens of AI and its transformative potential. This intersection has given rise to the need to explore how human capital is evolving in response to technological advances, and what this means for future workforce development.

While the skills most frequently required in AI professions concern the Python programming language and machine learning (ML), a number of skill sets are emerging, highlighting the existence of skill complementarities at the heart of AI transformation (Samek & Squicciarini, 2023) .

Artificial intelligence is not just an emerging technology; it's a catalyst for profound change across all sectors. As AI systems become more sophisticated, they are influencing the skills required in the labor market, the nature of work, and the way human capital is developed and used. This dynamic interplay raises vital questions about the future of work, the role of human skills and the strategies needed by individuals and organizations to thrive in an AI-driven world. To understand these changes, it is essential to map the evolution of human capital in this context. A bibliometric analysis provides a systematic approach to reviewing the academic literature on this subject, identifying key trends, influential works and new areas of interest. By analyzing the body of research, we can understand how researchers conceptualize human capital in the AI era, the challenges and opportunities they identify, and the directions this research will take even though knowledge production in this area has increased, there remains a lack of bibliometric work on this issue. Bibliometric analysis offers a valuable tool for researchers who want to capture changes and trends in a field, of particular study, distinct from conventional journals. According to (Ellegaard & Wallin, 2015) this approach uses various objective measures such as citation counts, journal impact factors and author patterns to analyze academic literature

This study uses a bibliometric analysis of the literature on management ideas and methods, with the aim of identifying the countries, journals and authors who have developed them. In order to meet these objectives, this study aims to address the following questions: which countries are the most productive in this field, and what are the practices, trends and research themes in the literature on the evolution of human capital in the age of artificial intelligence? To answer these

questions, we will carry out a bibliometric analysis of the literature on the evolution of human capital in the age of artificial intelligence.

Research on management ideas and methods, based on information provided by the Scopus database. To accomplish this, we'll use VOSviewer software to study over 932 academic articles and identify relevant patterns and trends in this field of study. The paper has the following structure: The Literature Review section focuses on the evolution of human capital and practice in the age of artificial intelligence, highlighting significant advances in management theory and practice. The "Methodology" section describes the data sources and methodologies used in this research. Next, various analytical methods, such as co-occurrence, citation and co-citation, will be employed to identify the articles, authors, countries and organizations with the greatest influence on the field.

1. Literature review

The concept of human capital was developed in the mid-20th century by economists such as Theodore Schultz and Gary Becker. They defined human capital as a stock of skills, knowledge and abilities accumulated by individuals, mainly through education and training, which increase their economic productivity.

Since its origins, the concept of human capital has evolved to encompass a wider range of skills, including soft skills, work experience and mental and physical health. These evolutions reflect economic and technological transformations, notably the rise of artificial intelligence (AI) and its impact on the labor market.

AI and related technologies are transforming the nature of work, and the skills required in the labor market. (Brynjolfsson & McAfee,2014) put forward that AI could lead to a polarization of jobs, where routine tasks are automated while cognitive and creative skills become increasingly valued. AI technologies require advanced data science, analytics and programming skills, while interpersonal and problem-solving skills are also gaining in importance.

To cope with the changes brought about by AI, continuous skills development is crucial. The (OECD ,2019) stresses the importance of lifelong learning and reskilling to enable workers to adapt to the new demands of the labor market. STEM (science, technology, engineering and mathematics) skills and digital literacy are particularly highlighted as essential in an AI-dominated work environment.

Education systems and training policies play a key role in preparing individuals for the AI era. Initiatives such as integrating digital skills into school curricula, developing reskilling programs and promoting adaptive learning are essential. The World Economic Forum (2020) has identified the need to reform education systems to include skills such as critical thinking, creativity and complex problem-solving.

AI also poses significant ethical and social challenges, particularly in terms of bias in algorithms and social justice. Work by (Noble & O'Neil, 2016) highlights the risks of discrimination and inequality inherent in AI systems, which can perpetuate or even amplify existing prejudices. It is crucial to develop inclusive and ethical approaches to AI deployment to ensure that its benefits are shared equitably.

Une analyse bibliométrique des publications académiques sur le capital humain et l'IA révèle plusieurs tendances clés. Les recherches se concentrent de plus en plus sur l'impact de l'automatisation sur les marchés du travail, les stratégies d'éducation et de formation, et les implications éthiques de l'IA.

A bibliometric analysis of academic publications on human capital and AI reveals several key trends. Research is increasingly focusing on the impact of automation on labor markets, education and training strategies, and the ethical implications of AI.Emerging areas include the study of the skills needed to collaborate with AI systems and the long-term impacts of AI on employment and social inequalities.

2. Methodology

This study employs bibliometric analysis, a quantitative approach that applies statistical techniques to examine relationships between various research elements such as authors, publications, keywords, and citations (Ellegaard, 2018). In the context of AI and human capital, bibliometric analysis allows us to track the progression of research over time and uncover key themes and trends in the field. This method has become increasingly popular for understanding the intellectual structure and collaboration patterns within specific research areas.

For this study, we implemented the bibliometric analysis in four steps:

Data Collection:

The literature review was carried out using the Scopus database. We employed the following search string:

TITLE-ABS-KEY ("artificial intelligence" OR AI OR "machine learning" OR "deep learning") AND ("human capital" OR "workforce development" OR "skill enhancement" OR "talent management") AND (LIMIT-TO (SUBJAREA, "BUSI") OR LIMIT-TO (SUBJAREA, "SOCI")) AND (LIMIT-TO (DOCTYPE, "ar")).

The search retrieved 3,591 publications from the time period spanning January 1997 to May 2024.

Data Processing and Bibliometric Analysis:

We collected data on various features of the identified publications, such as titles, authors, countries, keywords, and publication years. The VOSviewer software was used for conducting the bibliometric analysis, which helped in visualizing the connections between research elements. This analysis enabled us to observe the evolution of research themes related to AI and human capital, offering insights into how this field has developed over the years and where future research may be heading.

Keyword Analysis

Using VOSviewer, a keyword co-occurrence analysis was conducted to visualize the relationships between frequently used keywords. Additionally, a frequency analysis was performed to identify the most prominent terms in the dataset. These analyses provide a clear picture of the recurring topics in the literature, allowing us to identify key areas of focus in AI and human capital research.

Cluster Analysis

Cluster analysis was carried out using VOSviewer to group similar terms based on how often they co-occur in the dataset. This technique allowed us to map out the major research themes and their interconnections. The thematic clusters generated by this analysis offer a comprehensive overview of the emerging topics within AI and human capital research, highlighting significant areas of collaboration and intellectual development.

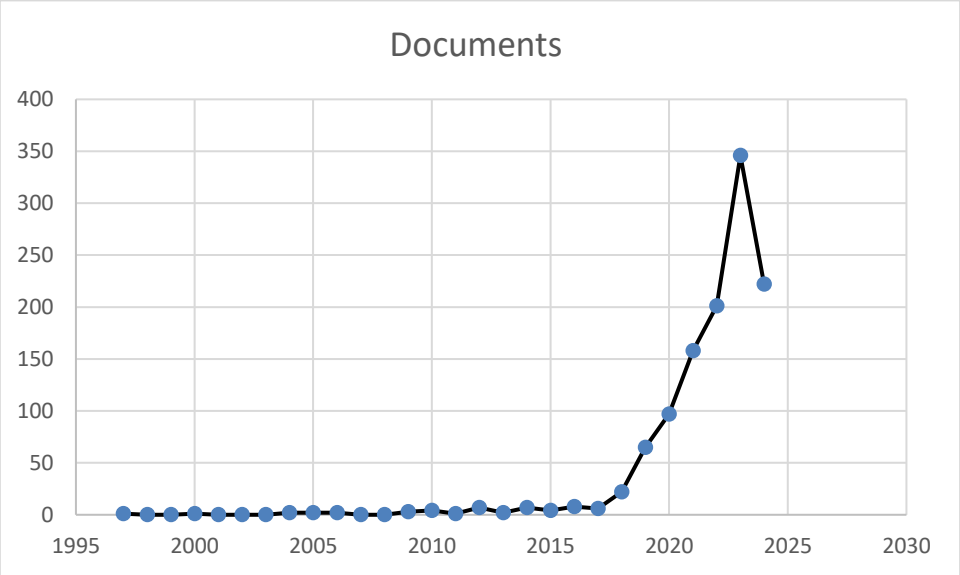
3. Results

workforce development and human capital strategies. The slight dip in 2024 so far might simply reflect that the year is incomplete and that additional publications may follow.

The analysis illustrates a substantial rise in the number of publications over the last decade, highlighting the rapidly growing interest in the intersection of artificial intelligence and human capital, particularly from 2018 onward.

Documents by years

Figure 1: The evolution of documents by year



The bibliometric analysis of documents related to human capital and artificial intelligence from 1997 to 2024 reveals a dramatic shift in scholarly interest, particularly in recent years as shown in figure 1.From 1997 until around 2015, the number of publications remained minimal. For example, only a single document was published in 1997 and 2000, with no publications recorded in several years like 2008 and 2007.

However, the number of publications began to increase steadily after 2015, signaling the growing recognition of the importance of artificial intelligence in the context of human capital management. Notably, the number of publications jumped from 6 documents in 2017 to 22 documents in 2018, followed by a more substantial increase to 65 documents in 2019.

This upward trend continued rapidly into the 2020s, with 97 documents published in 2020, 158 in 2021, and a peak of 346 documents in 2023. By 2024, 222 documents were recorded up to May 28, 2024, indicating that the research activity in this area continues to be strong.

The peak in 2023 could be attributed to several factors, such as the increasing adoption of AI technologies across industries and the rising interest in how these technologies impact workforce development and human capital strategies. The slight dip in 2024 so far might simply reflect that the year is incomplete and that additional publications may follow.

The analysis illustrates a substantial rise in the number of publications over the last decade, highlighting the rapidly growing interest in the intersection of artificial intelligence and human capital, particularly from 2018 onward.

Contribution by Country

The bibliometric analysis identifies a total of 58 countries contributing to the body of research on human capital in the age of artificial intelligence (AI). The distribution of contributions by country reveals significant disparities in the level of engagement with this research topic, with a concentration of publications in a select number of leading nations.

The United States emerges as the dominant contributor, accounting for 282 documents, representing the largest share of research output in this field. The United States' leadership can be attributed to several factors. First, the U.S. boasts a highly developed research infrastructure supported by substantial investments in AI and technology-driven innovation. American academic institutions such as MIT, Stanford, and Harvard are recognized as global leaders in AI research, while U.S. corporations like Google, IBM, and Microsoft are pioneering advancements in AI applications across industries, including human capital management. Moreover, the U.S. government has initiated several AI-related policy frameworks, encouraging academia-industry collaboration, which likely explains its extensive research output.

China ranks second, contributing 197 documents, reflecting its growing prominence as a global leader in AI research and development. In recent years, China has invested heavily in AI technologies, with significant government funding and strategic initiatives aimed at positioning the country as the world leader in AI by 2030. China's rapid expansion in this field is also supported by its large pool of technical talent and the growing number of AI-related academic programs in its universities. Furthermore, China's focus on digital transformation and its implementation of AI in workforce management have made it a significant contributor to the global research discourse on human capital.

In third place is the United Kingdom, with 126 documents. The UK's robust academic system, supported by institutions like the University of Oxford and Imperial College London, and its emphasis on AI ethics and regulation have facilitated its contributions to AI and human capital research. The UK's active participation in EU-funded research projects (prior to Brexit) and its collaboration with U.S. and European researchers also bolster its standing in this field.

Other countries making notable contributions include India (96 documents), Germany (75 documents), and Italy (63 documents). India's position as a major player in the global technology sector, with its large pool of engineers and IT professionals, contributes to its strong showing in AI research. Germany's contributions are driven by its industrial strength, with many of its AI research projects focused on automating and optimizing workforce processes,

particularly in manufacturing. Italy's growing focus on digital transformation and its academic investments in AI-related disciplines have led to its position within the top contributors.

The top 20 countries further include Australia (58 documents), France (49 documents), Canada (44 documents), and the Russian Federation (42 documents). These countries have well-established academic institutions and government-backed research initiatives in AI and workforce optimization, which contribute to their participation in the global research dialogue.

In the second tier of contributors, we find Malaysia (41 documents), Spain (40 documents), the Netherlands (30 documents), Saudi Arabia (27 documents), and Switzerland (26 documents). Malaysia's emergence as a contributor can be seen as part of a broader push among Southeast Asian nations to become leaders in technology adoption. Similarly, Saudi Arabia's Vision 2030 initiative aims to transform its economy through digital and AI-driven technologies, including workforce development.

Countries like Turkey (25 documents), Romania (24 documents), South Korea (24 documents), the United Arab Emirates (23 documents), and Hong Kong (20 documents) round out the top 20. These nations reflect regional hubs of academic research and innovation, often driven by state-led initiatives to integrate AI into national workforce development strategies.

The distribution of research outputs across these 20 leading countries illustrates a concentration of scholarly activity in regions with strong academic infrastructure, government policies promoting AI research, and industries actively adopting AI technologies. North America, Europe, and Asia dominate the landscape, with notable contributions from the U.S. and China leading the global discourse on human capital in the age of AI.

Table 1: Top 20 Countries by Number of Published Documents on AI and Human Capital Research

Country	**Documents**
United States	282
China	197
United kingdom	126
India	96
Germany	75
Italy	63
Australia	58
France	49

Canada	44
Russian federation	42
Malaysia	41
Spain	40
Netherlands	30
Saudi arabia	27
Switzerland	26
Turkey	25
Romania	24
South korea	24
United arab emirates	23
Hong kong	20

Most pertinent documents

document	Titre	citations
Dwivedi et al (2021)	Setting the future of digital and social media marketing research: Perspectives and research propositions	754
raisch (2021)	ARTIFICIAL INTELLIGENCE AND MANAGEMENT: THE AUTOMATION-AUGMENTATION PARADOX	509
tambe (2019)	Artificial Inelligence in human Resource Management Challenges and a path Forward	423
wirtz (2019)	Digital Business Models	342
sima (2020)	Influences of the Industry 4.0 Revolution on the Human Capital Development and Consumer Behavior: A Systematic review	311

almeida (2020)	LES DÉFIS DE L'UTILISATION DE L'INTELLIGENCE ARTIFICIELLE DANS LE SYSTÈME JUDICIAIRE BRÉSILIEN	248
AZAIZI.A& BERBOU (2024)	Repenser La Gestion Des Ressources Humaines A L'ere De L'intelligence Artificielle Rethinking Human Resources Management In The Age Of Artificial Intelligence	246
David,G Sylvan,D Jean,D.Guillame,L Gauchier L	Human capital and IA	227

The evolution of citation of papers and references, in relation to artificial intelligence (AI) and human capital, reflects the rapid changes in academic and professional practices, and several papers have dealt with this subject given the importance of the use of artificial intelligence. A thorough reading of these references and the number of citations in the various countries shows that over 250 papers are published each year, with a total of 750 citations. However, it is necessary to emphasize the interest of this subject in several disciplines

As a result, it incorporates features to facilitate data collection, automating previously tedious tasks, allowing you to concentrate on more creative and analytical tasks.

Although artificial intelligence automates many tasks, human capital remains crucial for making critical decisions, interpreting results and innovating. Artificial intelligence has the capacity to process data on a massive scale, but creativity, strategic vision and ethics in the use of information are essential human skills. Thus, there is a trend towards closer collaboration between AI and human skills, rather than total substitution.

Ethical and validity challenges are also raised by the use of AI in citation and referencing. Algorithms have the capacity to promote certain sources or reproduce biases already present in databases. This calls for further reflection on the design and use of AI tools.

The evolution of citation and referencing under the influence of AI shows a growing synergy between technological capabilities and human capital. The automation of repetitive tasks frees up researchers' time for higher value-added activities, but human judgment remains essential to guarantee the quality, integrity and relevance of work.

Based on an in-depth reading of several articles, we summarize that IA can be defined Machines that are capable of cognitive tasks often associated with human minds, such as learning, interacting, and problem solving, are referred to as artificial intelligence (AI) (Nilsson, 1971).

AI-based solutions have long been used by organizations to automate repetitive operations and logistics chores. Organizations can now adopt AI-based solutions for management activities thanks to recent breakthroughs in processing power, the exponential growth of data, and new machine-learning algorithms(Jumani et al., 2021).

For instance, AI-based solutions are now crucial to Unilever's talent acquisition strategy (Marr, 2018), Netflix's selection of filmmakers, actors, and movie storylines (Westcott Grant, 2018), and Pfizer's medication development and discovery processes (Fleming, 2018).

comprising both rule-based automation and machine learning. In rule-based automation, which is sometimes also called "robotic process automation" (RPA), the machine is static in the sense that it adheres to the explicit rules it has been given (Daugherty & Wilson, 2018: 50; Davenport & Kirby, 2016: 48). In contrast, machine learning gives the machine the ability to learn from experience without being explicitly programmed to do so (Mitchell, 1997) we are confronted with unprecedented advances in digital technology, the "second age of the machine" (Brynjolfsson & McAfee, 2014: 7). Rather than focusing on the mechanical, machines are now taking on cognitive work, which was traditionally an exclusively human domain. However, machines still present multiple constraints, implying that we are entering an era in which humans have a role to play.

The complementary strengths of humans and machines should be synergized, promoting mutual learning and enhancing their capabilities.

Pooling and developing skills. Rather than dreading the consequences of automation and its impact on the labor market, managers should realize that artificial intelligence has the potential to enhance, rather than substitute, human beings in management functions.

It is possible to substitute individuals in management functions(Raisch & Krakowski, 2021).

management science authors distinguish between two implications of artificial intelligence for the organization: automation and augmentation

Automation means that machines take over a human task, augmentation means that humans work closely with machines to accomplish a task.the augmentation is more advantageous while evaluating negative automation ,the organizations should prioritize augmentation, which they

relate to superior performance. In addition, the two more recent books (Daugherty & Wilson, 2018; Davenport & Kirby, 2016) provide managers with ample advice on how to develop and implement such an augmentation strategy managers must define their objectives (Braga & Logan, 2017). Although machines can be responsible to some extent, responsibility, requiring intentionality, remains an exclusively human capability (Floridi, 2008). So, for humans to assume responsibility, they must retain control over the tasks concerned.for complex managerial tasks, machines can only offer several options, but managers must use their judgment and intuition to choose the most suitable option (Brynjolfsson & McAfee, 2014) although AI automates candidate assessment, HR managers are still needed for the final selection, as certain dimensions, such as cultural fit or interpersonal relationships, cannot be fully captured by machines.machines lack human senses, perceptions, emotions and social skills (Braga & Logan, 2017). For example, HR managers use their emotional and social intelligence to build relationships, attract talent and convince others to support their decisions (Davenport & Kirby, 2016)

an increase in a managerial task may enable its subsequent automation, which in turn may lead to a further increase in related managerial tasks. While these dynamics favor increasing augmentation and automation, technological and social limitations prevent the full automation of managerial tasks, particularly in contexts characterized by high ambiguity, complexity (Davis & Marcus, 2015). In these contexts, automation and augmentation offer different, sometimes contradictory, but complementary logics and functionalities. The right balance depends on the AI skills of organizations and their environment.

Recent technological advances have highlighted the tension associated with artificial intelligence (AI) in organizations, leading them to adopt management strategies to deal with it. According to paradox theory, these organizational responses can create cycles that reinforce each other, either positively or negatively (Smith & Lewis, 2011) If an organization fails to recognize the paradoxical nature of this tension, it risks applying partial strategies that cause vicious cycles, thus amplifying the tension. Conversely, an organization that accepts and manages this tension can create virtuous cycles(Schad et al., 2016) .

Vicious cycles often arise when organizations prioritize automation for its short-term cost gains (Davenport & Kirby, 2016). This encourages competitors to do the same in order to remain competitive, creating a situation where work becomes commoditized and margins are squeezed. In the long term, organizations lose the human skills needed to fine-tune their processes, as automation can devalue human skills and make employees complacent (Parasuraman &

Manzey, 2010). Moreover, automation limits organizations' choices by locking them into rigid processes and formal rules. So, while automation can free up resources, it also leads to short-term thinking, loss of human skills and lock-in effects, making it difficult to implement new research activities.

organizations, instead of focusing solely on automation, could opt for augmentation, which requires significant resources for iterative cycles of human-machine learning. Unlike automation, augmentation requires continuous human involvement and experimentation, making each initiative unique and difficult to replicate (Holzinger, 2016). However, due to this complexity and uncertainty, many augmentation efforts fail. Moreover, human biases persist, leading to inconsistent and unreliable results (*Huang T, et al. (2012)* | *SGD*, n.d.). Organizations could then reinforce their augmentation investments despite failure, creating a cycle of increased commitment and successive failures.

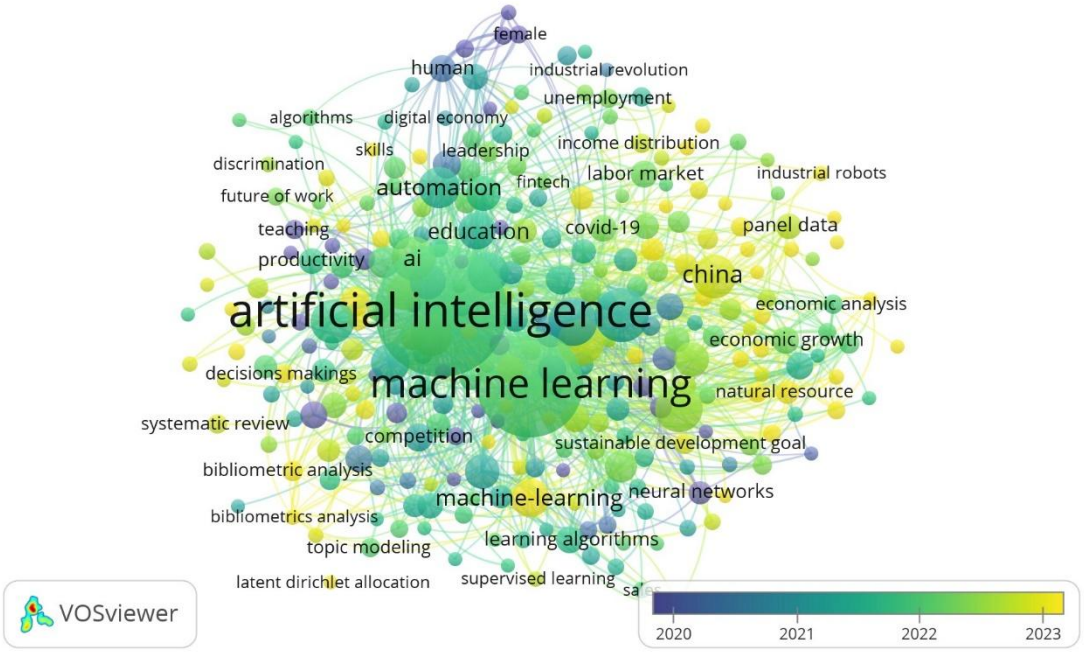
In conclusion, focusing exclusively on automation or augmentation creates vicious cycles by neglecting the dynamic interdependencies between these two AI applications. Managers risk proposing managerial solutions that are partial, incomplete and limited in time and space, while the organizational tension linked to AI persists.

Paradox theory suggests that managing the tensions between automation and augmentation through acceptance and resolution strategies promotes organizational sustainability (Smith & Lewis, 2011). This enables learning, creativity and flexibility, while unleashing human potential. However, excessive focus on either pole can lead to undesirable organizational and societal consequences (Schad & Bansal, 2018).

Organizational outcomes: Organizations can benefit from AI by increasing productivity, improving service quality and fostering innovation. The authors point out that combining human and machine skills improves organizational learning. However, focusing solely on automation or augmentation can be detrimental to long-term performance. Integrating the two enables the unique benefits of each approach to be realized: automation improves the efficiency and rationality of processes, while augmentation harnesses human skills to deliver more creative and innovative solutions.

Keywords analysis

Figure2.Visualization of keywords



Keyword analysis is an essential method in bibliometric studies, as it allows researchers to identify the most prominent topics, trends, and relationships in a particular field. By mapping the connections between various keywords, it provides valuable insights into how concepts are linked and which areas of research are gaining attention over time. In this study, we conducted a keyword analysis to explore the evolution of human capital in the age of artificial intelligence (AI), using VOSviewer software. VOSviewer generated a comprehensive visual map of keywords that not only identifies the most frequently occurring terms but also reveals the strength of their interconnections, helping us understand how different aspects of AI and human capital are intertwined.

The results of the analysis, as visualized in the keyword map, demonstrate the centrality of **Artificial Intelligence (AI)** (427 occurrences, 1,440 total link strength) in the current discourse. AI stands out as the dominant node in the network, indicating its critical role in shaping research, innovation, and applications in various fields. The dense clustering around AI reflects its profound impact on human capital development, economic growth, and technology adoption. This demonstrates that AI is not just a technological advancement but a transformative force influencing the structure and future of human resources, workforce management, and societal dynamics.

Adjacent to AI, **Machine Learning** (274 occurrences, 942 total link strength) emerges as a significant concept. It is intricately linked to AI and represents one of the primary mechanisms through which AI systems operate. Machine learning, with its applications in automating processes and improving decision-making, is reshaping industries by enhancing efficiency and creating new capabilities. The frequent co-occurrence of *machine learning* with terms such as *learning algorithms* and *supervised learning* in the map underscores its relevance to both technological and human capital advancement. This suggests that machine learning is playing a pivotal role in how organizations and individuals adapt to the rapid digital transformations driven by AI.

The analysis also highlights the prominence of **Automation** (41 occurrences, 189 total link strength) as a key outcome of AI advancements. Automation, closely linked to AI and machine learning, is fundamentally altering the dynamics of human capital. The map reveals that automation is tightly connected to labor market considerations such as *employment* and *productivity*. This reflects the ongoing shift in workforce structures, where the automation of repetitive and manual tasks is reshaping job roles and creating new demands for higher-skilled labor. As AI and automation continue to progress, the focus on human capital has shifted towards reskilling and upskilling to meet the needs of an increasingly automated economy.

Crucially, **Human Capital** (60 occurrences, 337 total link strength) itself is a major node in the keyword map. Its strong links with keywords like *education*, *employment*, and *decision-making* highlight how AI technologies are influencing the development and management of human resources. The map suggests that human capital is being redefined in the context of AI, where digital technologies are playing a significant role in enhancing skills and productivity. Education, in particular, is highlighted as a critical factor in preparing the workforce for AI-driven industries. The links between human capital and *sustainability* also suggest that human resource strategies are evolving to support both economic and environmental sustainability in the AI era.

Sustainability (54 occurrences, 354 total link strength) is another critical concept revealed by the keyword analysis. AI's role in promoting sustainable development is evident from its connections to keywords like *economic growth* and *energy efficiency*. The strong links between AI and sustainability reflect the increasing emphasis on leveraging AI technologies to optimize resources and achieve long-term societal and environmental goals. In this context, the evolution of human capital is not only about adapting to technological change but also about aligning workforce strategies with broader goals of sustainability and corporate responsibility.

Education (35 occurrences, 148 total link strength) plays a pivotal role in shaping human capital in the age of AI, as reflected in its prominent position in the map. The integration of AI into education is transforming how individuals learn and acquire skills, preparing them for the demands of an AI-driven economy. The map illustrates the close relationships between education and other key terms like *learning algorithms* and *digital technologies*, highlighting the transformative impact of AI on both formal and informal learning processes. This reflects a growing trend where AI-powered tools are being used to enhance educational outcomes and ensure that the workforce is equipped with the necessary skills to thrive in the digital age.

In addition to education, the map also reveals significant links between AI and **Economic Development** (18 occurrences, 168 total link strength), demonstrating the critical role that AI plays in driving productivity and fostering innovation. The connections between AI and economic growth suggest that AI technologies are not only reshaping industries but also contributing to broader economic advancements by enhancing efficiency and enabling new business models. This underscores the importance of AI in ensuring sustainable and inclusive growth, particularly in the context of human capital development.

The keyword **Big Data** (38 occurrences, 192 total link strength) also emerges as an important term in the network, indicating the crucial role that data analytics plays in the application of AI. The strong association between big data and human capital suggests that organizations are increasingly relying on data-driven insights to optimize workforce management and performance. The integration of big data with AI allows for more sophisticated decision-making processes, enhancing both the effectiveness of human capital strategies and the overall productivity of organizations.

In conclusion, the keyword map generated by VOSviewer provides a comprehensive visualization of the interconnectedness between AI, human capital, and related fields. The analysis reveals that AI is at the center of a complex web of relationships that influence human resource development, economic growth, and sustainable development. The evolving landscape of human capital is shaped by the transformative potential of AI technologies, with machine learning, automation, education, and sustainability emerging as key themes in this evolution. As AI continues to advance, its impact on human capital will only deepen, making it essential for organizations and policymakers to focus on fostering education, upskilling, and sustainable practices to ensure that the workforce is prepared for the future of work in the AI age.

Cluster analysis

Figure 3 .Visualization of clusters

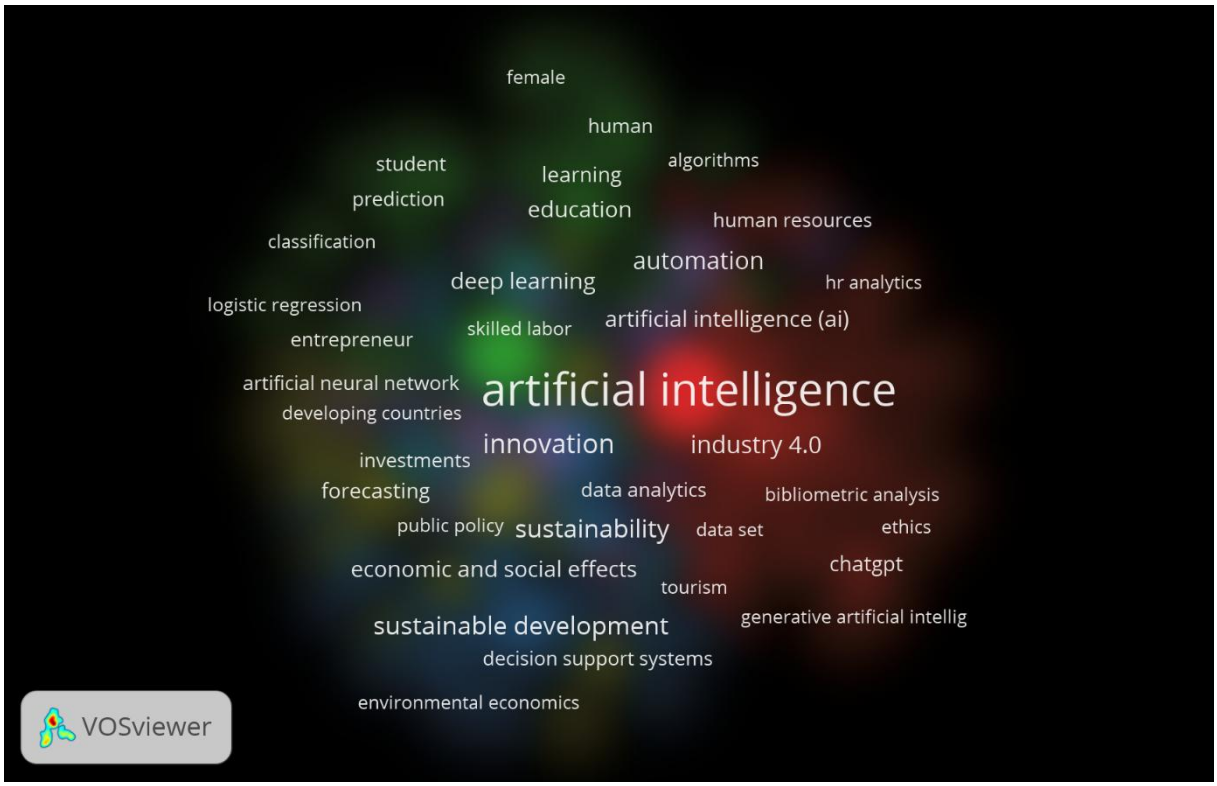


Table2 .Cluster composition

Cluster	Items
Cluster 1	Ai,artificial inetelligence,automation,chatgpt,education,employment,higher education,human,human resource management,industry4.0,labor market,learning,tecgnoloy
Cluster 2	Economic and social effects,economic development,economic growth,human capital,innovation,personnal,sustainability,sustainable development,technology adoption,

Cluster 3	Big data,commerce,competition covid19,decision making,investments,knowledge management,performance
Cluster 4	Algorithm,data mining,deep learning,forecasting,learning algorithms,machine learning

Cluster 1: "Artificial Intelligence and the Future of Human Capital Management"

This cluster delves into the transformative impact of Artificial Intelligence (AI) on the management of human capital, reflecting the ongoing shifts in how organizations approach workforce development, recruitment, and employment strategies in the age of AI and automation. The central themes within this cluster—encompassing AI, automation, and Industry 4.0—underscore the pivotal role that technology is playing in reshaping the labor market and human resource management.

AI technologies, represented by terms like "AI," "artificial intelligence," and "automation," are fundamentally altering the landscape of employment. Automation, driven by AI, is taking over routine tasks across various industries, necessitating a reevaluation of the roles that humans will play in the workforce of the future. This shift is not merely about replacing jobs but rather about transforming them, creating new opportunities that require advanced skills and competencies.

The emphasis on "human," "human resource management," and "labor market" highlights the need for organizations to adapt their HR strategies to this new reality. As AI integrates deeper into HR practices—such as in recruitment processes, performance evaluations, and employee development—there is a growing need for HR professionals to leverage AI tools effectively to enhance decision-making and optimize talent management. This transformation demands a new approach to managing human capital, one that embraces AI as a strategic partner rather than just a tool.

The concept of "Industry 4.0" adds a broader context to the discussion, indicating that these changes are part of a larger industrial revolution characterized by the fusion of digital, physical, and biological systems. In this environment, AI is a key driver, enabling more efficient and innovative processes across industries. Consequently, human capital management must evolve to meet the demands of this new era, focusing on fostering adaptability, continuous learning, and technological proficiency among the workforce.

In summary, this cluster underscores the critical role of AI in shaping the future of human capital management. As AI continues to drive changes in the labor market, organizations must rethink their approach to managing human resources, ensuring that they are equipped to

navigate the complexities of an AI-driven world. This analysis lays the foundation for understanding how AI is not only a technological advancement but also a transformative force in the management of human capital, which is central to the broader discussion in your article.

Cluster 2: "The Role of Human Capital and Innovation in Economic Growth and Sustainable Development"

This cluster focuses on the critical interplay between human capital, innovation, and their collective impact on economic growth and sustainable development. The terms "economic and social effects," "economic development," and "economic growth" indicate a broad interest in understanding how these factors drive prosperity and progress on both macro and microeconomic levels.

At the heart of this cluster is "human capital," which refers to the skills, knowledge, and experience possessed by individuals that are essential for fostering innovation and driving economic growth. As economies evolve, the quality of human capital becomes increasingly important, not only in traditional industries but also in sectors at the forefront of technological innovation. The ability to innovate—represented by the term "innovation"—is deeply connected to the level of human capital available within an economy. A well-educated and highly skilled workforce is better equipped to develop new technologies, improve processes, and create products that contribute to sustained economic growth.

"Sustainability" and "sustainable development" highlight the growing importance of integrating economic growth with environmental and social considerations. The modern approach to economic development is no longer solely focused on increasing GDP; it also involves ensuring that growth is sustainable over the long term. This involves adopting practices and technologies that reduce environmental impact and promote social well-being, aligning with the broader global agenda of sustainable development.

The term "technology adoption" further illustrates the relationship between innovation and economic growth. Economies that are quick to adopt and integrate new technologies tend to experience faster growth, as these technologies enhance productivity and open up new opportunities. However, successful technology adoption also depends on the availability of skilled human capital that can understand, implement, and optimize these technologies within various sectors.

In summary, this cluster captures the essential role that human capital and innovation play in driving economic growth and achieving sustainable development. By focusing on the quality of human capital and its capacity for innovation, economies can ensure that their growth is not

only robust but also sustainable, balancing economic success with environmental and social responsibility. This analysis is integral to understanding the broader dynamics of human capital evolution in the context of artificial intelligence and technological advancement.

Cluster 3: "Big Data and Its Impact on Human Capital Management and Organizational Performance"

This cluster focuses on the role of big data in shaping human capital management and organizational decision-making, particularly in the context of competition and performance enhancement. The terms in this cluster—such as "big data," "decision making," "knowledge management," and "performance"—suggest a close examination of how data-driven strategies are influencing the management of human capital and organizational effectiveness.

At the heart of this cluster is "big data," which refers to the vast amounts of information that organizations now have at their disposal. In the age of AI, big data is increasingly used to inform decision-making processes related to human capital. For instance, data analytics can be applied to identify skills gaps within an organization, optimize workforce planning, and tailor employee development programs. This data-driven approach allows organizations to manage their human resources more effectively, ensuring that they have the right talent in place to meet strategic goals.

"Decision making" and "knowledge management" are critical to leveraging big data for human capital management. Organizations that effectively manage and utilize the knowledge derived from big data can make more informed decisions about hiring, training, and retaining employees. This enhances their ability to remain competitive, especially in environments disrupted by events like COVID-19, where quick and informed decision-making is crucial for survival and growth.

The term "competition" highlights how organizations that excel at using big data in their human capital strategies can gain a significant competitive edge. In a competitive market, the ability to make data-driven decisions regarding workforce management can lead to superior performance outcomes. Companies that harness big data effectively are better equipped to adapt to changes, innovate, and outperform their competitors.

"Commerce" and "investments" in this context refer to the broader implications of big data on business strategy, particularly how investments in data analytics tools and technologies can enhance human capital management. By investing in these technologies, organizations can improve their operational efficiency and performance, ultimately contributing to better overall business outcomes.

Finally, "performance" ties the cluster together by emphasizing the ultimate goal of big data utilization in human capital management: improving organizational performance. By using big data to optimize workforce strategies, organizations can drive better performance metrics, from productivity gains to increased profitability, thereby ensuring long-term success in a competitive landscape.

In summary, this cluster illustrates the significant role that big data plays in modern human capital management and organizational performance. By integrating big data into their decision-making processes, organizations can enhance their human capital strategies, drive innovation, and maintain a competitive edge in the age of AI and technological advancement. This analysis directly links to the broader discussion of how AI and technology are transforming the management of human capital.

Cluster 4: "Predictive Workforce Management: The Role of Machine Learning in Shaping Human Capital Strategies"

This cluster examines the transformative influence of machine learning and advanced algorithms on workforce management, emphasizing how predictive analytics are redefining human capital strategies. The terms "algorithm," "data mining," "deep learning," "forecasting," "learning algorithms," and "machine learning" collectively highlight the growing reliance on these technologies to anticipate workforce needs, optimize talent management, and drive organizational performance.

At the heart of this cluster is "machine learning," a powerful tool that allows organizations to process and analyze vast amounts of workforce data with unprecedented accuracy. By applying machine learning algorithms, companies can predict employee behaviors, such as turnover or performance trends, and identify underlying factors that influence these outcomes. This predictive capability is crucial for developing proactive strategies that address potential challenges before they escalate, ensuring that the organization remains agile and responsive to changes in the workforce landscape.

"Deep learning," a subset of machine learning, takes these capabilities even further by enabling the analysis of more complex, unstructured data sources, such as employee communications or social media activity. This allows organizations to gain deeper insights into employee sentiment and engagement, which are often difficult to quantify through traditional metrics. By understanding these more nuanced aspects of workforce dynamics, companies can craft more targeted and effective human capital strategies that enhance employee satisfaction and retention.

"Data mining" plays a crucial role in this process by uncovering patterns and trends within large datasets that may not be immediately visible. In the context of human capital management, data mining can reveal key drivers of employee performance, highlight areas where skills development is needed, and identify correlations between different workforce variables. These insights enable organizations to make data-driven decisions that are more aligned with their strategic objectives.

The concept of "forecasting" is central to the cluster, as it reflects the use of machine learning models to predict future workforce trends. Whether it's anticipating the need for new skills in response to technological advancements or forecasting shifts in labor market conditions, predictive analytics provide a critical advantage in workforce planning. This forward-looking approach ensures that organizations are not only prepared for future challenges but are also positioned to capitalize on emerging opportunities.

Finally, the term "learning algorithms" underscores the continuous improvement aspect of these technologies. As algorithms are exposed to more data over time, they refine their predictions and become more accurate, allowing organizations to continuously optimize their human capital strategies. This ongoing learning process is essential in a rapidly evolving environment where the pace of change is accelerating due to technological innovation.

In summary, this cluster illustrates the significant role of machine learning and predictive analytics in modern workforce management. By leveraging these technologies, organizations can gain a competitive edge by making more informed decisions about their human capital, ensuring that they are well-positioned to navigate the complexities of the evolving labor market. This analysis ties directly into the broader theme of how AI is reshaping the landscape of human capital management, offering new tools and approaches to optimize workforce outcomes in the age of artificial intelligence.

Conclusion

In conclusion, this article provides a comprehensive bibliometric analysis that maps the evolution of human capital in the age of artificial intelligence (AI). By examining the trends, dynamics, and key contributions in this field, the analysis reveals that AI is not merely a technological innovation but a transformative force reshaping human capital management, workforce development, and skill enhancement. The bibliometric approach, through co-citation and keyword clustering, underscores the global research efforts across various regions, with

particular emphasis on the pivotal role AI plays in digital transformation, workforce automation, and talent management.

The study's findings highlight several emerging themes, including the significant impact of AI on organizational behavior, the necessity for continuous skill development, and the increasing role of education systems in preparing individuals for an AI-driven economy. Moreover, the ethical and social implications of AI, particularly in areas such as algorithmic bias and social justice, further underscore the complexities of integrating AI into human capital development.

Ultimately, this bibliometric analysis provides a valuable resource for researchers, policymakers, and practitioners as they navigate the evolving landscape of AI-driven human capital. It offers critical insights into the ongoing transformation of workforce dynamics, emphasizing the need for adaptive strategies in skill development and organizational management in order to thrive in the AI-enabled future. The growing intersection between AI and human capital continues to be a fertile ground for future research, particularly as industries and economies become more reliant on AI-driven innovations.

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