

Mapping knowledge frontiers: a bibliometric analysis of Industry 4.0, circular economy and human resource management

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Abstract

Purpose – This study presents a comprehensive bibliometric analysis of research trends at the intersection of Industry 4.0, circular economy, and human resource management (HRM).

Design/methodology/approach – This study analyzes 693 documents from 2019 to 2024 using a bibliometric approach, including performance, citation, keyword co-occurrence, thematic mapping and trend topic analysis, highlighting a sharp rise in research driven by digital transformation and sustainability.

Findings – We demonstrate that Industry 4.0 and circular economy practices are well-established, while HRM's role in supporting them is emerging. The role of HRM practices like digital skills, green HRM, and leadership in enabling sustainability is underexplored. The analysis highlights gaps in workforce development for digital and sustainable transformations and the importance of global collaboration.

Practical implications – Theoretically, the study integrates HRM into Industry 4.0 and Circular Economy frameworks; practically, it guides organizations, policymakers and educators in developing workforce competencies, green HRM practices and leadership skills for sustainable digital transformation.

Originality/value – This is the first comprehensive bibliometric analysis integrating Industry 4.0, Circular Economy and HRM. Unlike earlier work focused on technology or operations, it highlights HRM's emerging role in digital and sustainable transformation. The study offers an integrated roadmap for future interdisciplinary research connecting technology, sustainability and human capital development.

Keywords Industry 4.0, Circular economy, Human resource management, Bibliometric analysis

Paper type Literature review

1. Introduction

The convergence of digital transformation and sustainability is reshaping the competitive landscape for modern organizations. Industry 4.0 technologies such as IoT, AI, and blockchain



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enable manufacturing agility, while Circular Economy principles promote responsible resource utilization and waste minimization. A whole-scale industrial transformation occurs due to technological development and the emergence of sustainability requirements. The Industrial Revolution of 4.0 has revolutionized manufacturing through the convergence of IoT, AI, machine learning, and smart manufacturing systems (Khan *et al.*, 2024; Singh *et al.*, 2024). Modern industrial processes experience unprecedented enhancements through these technological innovations, which lead to higher efficiency and productivity and better adaptability as well as data-informed decision-making (Sung, 2018). Industry sectors now advance toward automated, interconnected systems that run on real-time data analytics, predictive modeling, and innovative digital methods because of these technology implementations (Hysa *et al.*, 2024).

Parallel to Industry 4.0, the circular economy model empowers the mitigation of environmental problems by promoting efficient resource use and minimizing waste while establishing complete product life cycles (Geissdoerfer *et al.*, 2017). The circular economy strives to achieve more sustainable outcomes by promoting the maintenance of products beyond traditional manufacturing-dumping cycles and better uses of valuable resources (Panait *et al.*, 2022; Apostu *et al.*, 2023). The approaches demonstrate special value in Industry 4.0 due to digital technologies that achieve improved transparency and traceability, supply chain efficiency, and resource management capabilities.

The multiple changes interlink at various levels, allowing organizations to seize new opportunities and face complicated challenges. The intersection between technological innovation offers organizations advantages, including improved competitiveness and sustainable business operation through optimized production methods (Yousaf *et al.*, 2022). Business organizations encounter substantial difficulties when developing their workforce and the skills needed for transformation. Organizations depend on human resource management to provide employees with digital competencies and sustainable thinking because these components enable essential change leadership. Organizational success requires effective HRM strategies that combine green HRM together with workforce digitalization and continuous learning programs to link human capital with organizational goals (Singh *et al.*, 2025a).

Academic research about Industry 4.0 and the circular economy continues to grow, but several critical gaps remain regarding their relationship with human resource management practices. Research into Industry 4.0 mainly examines its technological components and operational aspects (Frank *et al.*, 2019; Bag *et al.*, 2021a, b) without discussing how to implement fundamental business changes for digital leadership, employee empowerment, and team integration at work. Academic literature on the circular economy predominantly examines resource optimization methods alongside product creation and sustainable supply chain development. Still, it fails to evaluate how human resources management systems develop environmentally proactive workers with innovative capabilities (Chiappetta Jabbour *et al.*, 2019; Singh *et al.*, 2025a).

Organizations struggle to build unified strategic dimensions combining digital transformation with sustainability initiatives (Khan *et al.*, 2023). Digital technology brings fundamental changes to workplaces that necessitate employees to use new equipment while learning innovative position responsibilities. Today's sustainability programs force most companies to adopt environmentally friendly strategies across strategic and operational levels. HRM requires support for adaptive capacity, workforce resilience, and ongoing skill development because organizations emphasize digital innovation and sustainability simultaneously.

While research on Industry 4.0 and the Circular Economy has advanced rapidly (Geissdoerfer *et al.*, 2017; Rajput and Singh, 2019), the integration of Human Resource Management (HRM) into these domains remains underexplored (Chiappetta Jabbour *et al.*, 2019; Shouraki *et al.*, 2024). Existing studies emphasize technological advancements and sustainability frameworks but pay insufficient attention to workforce readiness, leadership

development, and green HRM strategies essential for successful digital-sustainable transitions. This fragmentation limits the development of holistic frameworks that align human capital with digital and environmental priorities. Accordingly, this study addresses the following research questions:

- (1) What are the publication and citation trends in Industry 4.0, Circular Economy, and HRM research?
- (2) Who are the leading authors, journals, and collaborative networks contributing to this intersection?
- (3) What are the key research themes, and how have they evolved over time?
- (4) What gaps exist in integrating HRM into Industry 4.0 and Circular Economy scholarship, and how can future research address them?

This study contributes to the literature by offering the first comprehensive bibliometric mapping of the intersection between Industry 4.0, Circular Economy, and HRM. It uniquely identifies emerging themes in green HRM, digital workforce competencies, and adaptive learning systems that are critical for digital sustainability transitions. Theoretically, the study extends bibliometric knowledge by integrating technological and human factors into a unified framework. Practically, the findings guide organizations, policymakers, and educators in developing integrated strategies that foster workforce readiness and sustainable competitiveness.

The remainder of the paper is organized as follows: [Section 2](#) presents the literature Review, and [Section 3](#) outlines the methodology. [Section 4](#) summarizes key bibliometric results. [Section 5](#) presents a detailed discussion, encompassing both theoretical and practical implications. [Section 6](#) concludes with key findings, limitations, and directions for future research.

2. Literature review

2.1 Industry 4.0 and circular economy

Industry 4.0 and Circular Economy (CE) have both emerged as central paradigms for achieving sustainable industrial transformation. Industry 4.0 introduces disruptive digital technologies such as IoT, AI, blockchain, and big data analytics that revolutionize manufacturing flexibility, supply chain visibility, and resource optimization ([Lopes de Sousa Jabbour et al., 2018](#); [Khan et al., 2024](#)). In parallel, the CE model offers systemic principles for reducing waste and extending product life cycles, thereby aligning economic value creation with environmental stewardship ([Geissdoerfer et al., 2017](#); [Rajput and Singh, 2019](#)).

Existing studies have explored various synergies between these two domains. For instance, [Frank et al. \(2019\)](#) and [Bag et al. \(2021b\)](#) provide empirical evidence on how digital technologies enable CE practices, particularly in supply chain and manufacturing contexts. However, much of this research remains technology-centric, focusing primarily on the operational or technical enablers of CE adoption, while less attention has been paid to organizational and workforce readiness.

2.2 Human resource management: the missing link in Industry 4.0 and CE integration

Although substantial literature exists on Industry 4.0 and CE individually, the integration of Human Resource Management (HRM) within these frameworks remains underexplored ([Chiappetta Jabbour et al., 2019](#); [Shouraki et al., 2024](#)). The successful implementation of advanced technologies and circular practices requires not only technical capacity but also significant shifts in workforce competencies, leadership, and organizational culture ([Whysall et al., 2019](#); [Sharma et al., 2022](#)).

Green Human Resource Management (GHRM), as proposed by [Marrucci et al. \(2021\)](#) offers promising mechanisms for aligning HRM practices with sustainability goals. Yet, most studies focus either on environmental management or digital skills development in isolation, lacking integrated models that address both simultaneously. As noted by [Obeidat et al. \(2023\)](#) a few studies empirically investigate how HRM can serve as a strategic enabler for both digital and environmental transitions.

The existing literature reveals apparent fragmentation across technological, environmental, and human resource domains. Despite the growing recognition of Industry 4.0's potential to advance CE practices, there is insufficient research on how HRM can facilitate the organizational learning, leadership development, and workforce agility required to operationalize such transformations effectively ([Yadiat et al., 2017](#); [Nascimento et al., 2019](#)). As this study's bibliometric analysis shows, the majority of research continues to prioritize either Industry 4.0–CE integration or Industry 4.0–HRM intersections, with limited overlap addressing all three dimensions concurrently.

The literature gap justifies the present study's contribution: a comprehensive bibliometric mapping that integrates Industry 4.0, Circular Economy, and HRM, offering a consolidated understanding of the research landscape while highlighting areas where further empirical investigation is needed.

3. Materials and methods

In response to the complexity and interdisciplinary nature of Industry 4.0, Circular Economy (CE), and Human Resource Management (HRM), this study adopts a bibliometric analysis to systematically map the intellectual structure of existing research. Bibliometric analysis was purposefully selected as it allows for a comprehensive and data-driven evaluation of large, fragmented, and rapidly expanding bodies of literature ([Aria and Cuccurullo, 2017](#)), particularly suited for emerging research intersections where traditional systematic reviews may fall short in scope or depth.

Bibliometric techniques offer several key advantages. First, they permit the identification of underlying research trends, author networks, intellectual collaborations, and thematic clusters. Second, they enable quantitative assessments of publication productivity, citation impact, and research influence. Third, bibliometric mapping facilitates the visualization of evolving themes, offering strategic insights into knowledge gaps and emerging research priorities. This makes the method particularly relevant to an emerging domain, such as the integration of digital transformation, sustainability, and workforce development. [Table 1](#) summarizes the methodology adopted in this study.

3.1 Data collection and screening

Data were collected from the Web of Science (WoS) database, selected for its rigorous indexing standards and multidisciplinary coverage of high-impact academic publications. Following the PRISMA guidelines ([Page et al., 2021](#)), a systematic search strategy was executed. The initial search yielded minimal results for the simultaneous combination of Industry 4.0, CE, and HRM, highlighting a significant gap in integrative scholarship. To address this, a pairwise search approach was implemented to capture studies at the intersections of Industry 4.0 & CE, Industry 4.0 & HRM, and CE & HRM.

A carefully constructed keyword strategy was employed using Boolean operators and variations of key terms to ensure comprehensive coverage of relevant literature. The inclusion criteria limited the dataset to peer-reviewed journal articles, conference proceedings, and review papers published in English. Whereas excluded materials comprised editorials, commentaries, duplicate records, and irrelevant documents.

Table 1. Summary of methodology

Systematic bibliometric analysis	
Initial exploration	The first search for studies combining Industry 4.0, circular economy, and HRM yielded no results, underscoring a significant research gap
Pairwise analysis	Explored the intersections between pairs of topics: 589 papers on Industry 4.0 & circular economy, 104 on Industry 4.0 & HRM, and 43 on HRM & circular economy
Keyword strategy	Utilized variations of key terms and Boolean operators (e.g., AND, OR) to refine and expand search results
Inclusion parameters	Selected peer-reviewed journal articles, conference proceedings, and review papers relevant to the core themes of the research
Exclusion filters	Excluded non-peer-reviewed documents such as editorials, commentaries, duplicates, and unrelated papers
Screening workflow	Conducted a two-stage review: 1) Abstract review for initial relevance, and 2) Full-text review to ensure alignment with study goals
Data analysis focus	Performed bibliometric analysis to assess research productivity trends, authorship influence, and thematic development across topics
Advanced tools	Employed specialized software like Bibliometrix (R package) to perform detailed bibliometric calculations and statistical analysis

Source(s): Constructed by the authors

3.2 Data analysis and ethical considerations

A thorough bibliometric analysis was conducted after the data collection phase (Zupic and Čater, 2014; Dissanayake *et al.*, 2024). To ensure a cohesive and transparent analytical process, the bibliometric analysis was conducted in five sequential steps. First, a performance analysis was conducted to evaluate overall research productivity. This included examining publication trends such as annual growth rates, total document counts, and citation frequencies. Author productivity was evaluated using Lotka's Law, while journal productivity was assessed according to Bradford's Law, allowing the identification of highly active contributors and core publication sources within the field.

Second, citation analysis was employed to identify the most influential authors and journals. Various citation metrics were calculated, including total citations, h-index, g-index, and m-index, offering a quantitative understanding of scholarly impact and research influence across the dataset.

Third, keyword co-occurrence analysis was performed to explore the most frequently used keywords and their interrelationships. This step facilitated the identification of dominant research topics, thematic clusters, and key areas of scholarly attention, helping to structure the intellectual landscape of the field.

Fourth, thematic mapping was conducted using Bibliometrix software, following the developed framework (Aria and Cuccurullo, 2017). This method classified research themes based on their centrality (relevance to the field) and density (level of development), categorizing them into motor themes, niche themes, basic themes, and emerging or declining themes. This mapping provided insights into both the maturity and interconnectedness of various research areas.

Finally, trend topic analysis was applied to visualize the temporal evolution of research themes. This step identified how specific topics have emerged or shifted over time, highlighting evolving research priorities and emerging areas for future investigation.

By applying this robust multi-method bibliometric framework, the study not only maps the current research landscape but also uncovers critical underexplored areas where technological innovation, sustainability goals, and human capital development intersect. All data used were publicly accessible, and strict adherence to ethical guidelines ensured complete transparency and replicability. All data analyzed in this study were obtained from publicly available sources. Ethical guidelines related to data management and reporting were adhered to, ensuring transparency and reproducibility of the research process. No proprietary or sensitive information was used.

4. Results

4.1 Key information

The research dataset, spanning the period from 2019 to 2024, comprises 693 documents sourced from 249 journals and books, reflecting a high annual growth rate of 57.65% and an average document age of 2.64 years, which indicates the recency of the data. On average, each document receives 33.86 citations, with a total of 40,076 references cited across the publications. The dataset includes 1,102 “Keywords Plus” entries and 1,912 “Author’s Keywords,” contributed by 2,053 authors, of whom 44 have produced 47 single-authored works. The average number of co-authors per document is 3.88, and international collaborations account for 50.36% of the publications. The majority of the dataset consists of 637 articles, supplemented by 53 early-access articles, one proceeding paper, and two retracted publications, highlighting a diverse yet predominantly article-based body of scientific output.

4.2 Publication trends and citation patterns in Industry 4.0, circular economy, and HRM

The research output related to Industry 4.0, circular economy, and human resource management has grown significantly from 2019 to 2024. The number of publications increased from 19 in 2019 to 185 in 2024. This surge in publications reflects the heightened global interest in digital transformation, sustainability, and workforce innovation. The consistent rise in the number of documents highlights that these topics are receiving increasing attention across academia and industry alike. [Table 2](#) presents a trend analysis related to Industry 4.0, the circular economy, and HRM studies.

The number of published research articles grows yearly, yet the Mean Total Citations per article has decreased steadily since 2019, reaching 4.56 citations in 2024. The number of citations received by new papers decreases because they have less time to accumulate them, while the increased competition within publications also contributes to this decline. Research from 2020 demonstrated strong visibility, with a mean total citation count of 92 per article and a mean total citation count of 15.33 per year. The study focuses on Industry 4.0, likely to emphasize digital technologies such as automation, artificial intelligence, and smart manufacturing. The growing number of circular economy research papers indicates how society is expediting sustainable waste reduction efforts while achieving higher resource efficiency targets. Human resource management research is simultaneously evolving, with a greater emphasis on digital skills training, workforce adaptability, and the realities of remote work.

Research citations mainly depend on the number of years papers have been available for academic reference. The study’s seven citable years, since 2019, offer it numerous opportunities to receive citations, resulting in higher counts than papers published in 2023 and 2024, which have fewer prospects due to their recent publication. However, these recent studies indicate emerging trends and are expected to influence future research directions.

Table 2. Trend analysis

Year	Mean total citations per article	N	Mean total citations per year	Citable years
2019	100.26	19	14.32	7
2020	92	65	15.33	6
2021	63.57	103	12.71	5
2022	37.11	151	9.28	4
2023	15.22	170	5.07	3
2024	4.56	185	2.28	2

Source(s): Constructed based on Biblioshiny software

Overall, the data reveal a continuous increase in academic contributions to Industry 4.0, the circular economy, and human resource management. This aligns with global economic and technological shifts, as organizations and governments prioritize digital innovation, sustainable development, and workforce adaptability in response to evolving industrial needs.

4.3 Contributions of influential authors and journals

4.3.1 Journal analysis. Bradford's Law is used to illustrate the distribution of publications across different sources, categorizing them into zones based on their productivity. In this dataset, Zone 1 comprises only seven key sources, which account for 237 publications. These sources are the most influential and frequently referenced, contributing a substantial portion of the total research output. Zone 2 comprises 39 sources, generating 242 publications. While these sources are still significant, they exhibit a reduced publication output compared to Zone 1. Zone 3 is the largest, comprising 203 sources with a collective output of 214 publications. These sources have lower individual productivity and contribute less frequently to the total research output. [Table 3](#) presents a summary of Bradford law related to the source analysis.

This distribution illustrates the typical pattern predicted by Bradford's Law: a small number of core sources account for the majority of publications. In contrast, a larger number of sources produce progressively fewer documents.

[Table 4](#) depicts source impact analysis related to Industry 4.0, circular economy, and HRM studies. The dataset's most impactful sources reflect key research areas in sustainability, production management, and business strategy. The Journal of Cleaner Production stands out with the highest h-index (38), g-index (52), and total citations (TC) of 4,688 across 52 publications since 2020, indicating its strong influence in the field. Similarly, Resources, Conservation and Recycling (h-index: 12, TC: 1,999) and Sustainability (h-index: 22, TC: 1,639) have made significant contributions, with Sustainability producing 86 documents since 2019. Business-oriented sources, such as Business Strategy and the Environment and

Table 3. Bradford law summary

Zone	Number of sources	Number of publications
Zone 1	7	237
Zone 2	39	242
Zone 3	203	214

Source(s): Constructed based on Biblioshiny software

Table 4. Source impact analysis

Source	H-index	G-index	M-index	TC	NP	PY-start
<i>Journal of Cleaner Production</i>	38	52	6.333	4,688	52	2020
<i>Resources Conservation and Recycling</i>	12	14	1.714	1,999	14	2019
<i>Sustainability</i>	22	37	3.143	1,639	86	2019
<i>Business Strategy and the Environment</i>	17	34	3.400	1,594	34	2021
<i>Technological Forecasting and Social Change</i>	16	19	3.200	1,193	19	2021
<i>International Journal of Production Economics</i>	11	11	2.200	827	11	2021
<i>Journal of Manufacturing Technology Management</i>	6	6	0.857	731	6	2019
<i>Production Planning and Control</i>	12	13	2.000	714	13	2020
<i>Journal of Business Research</i>	5	5	0.833	526	5	2020

Source(s): Constructed based on Biblioshiny software

Technological Forecasting and Social Change, launched in 2021, have also garnered high h-index values of 17 and 16, respectively, indicating rapid growth in citations in these areas. Technical journals like Production Planning & Control (h-index: 12) and Journal of Manufacturing Technology Management focus on industry-specific advancements, with citation activity and productivity reflecting their continued relevance. Overall, these journals highlight a balanced mix of sustainability, technological innovation, and strategic management research contributing to the ongoing discourse in these domains.

4.3.2 Lotka's law analysis. The analysis of authorship productivity reveals a pattern consistent with Lotka's Law (see Table 5), which suggests that most authors produce a limited number of documents. In contrast, a small number of highly productive authors contribute a disproportionately large volume of research. In this dataset, 1,746 authors (accounting for 85% of the total) have written only one document. A much smaller group of 184 authors (9%) have authored two papers, and 56 authors (2.7%) have produced three documents. As the number of documents increases, the number of contributing authors declines steeply, with only one author writing 17 papers.

This distribution highlights the concentration of research output among a few prolific contributors and a long tail of authors with minimal output. Such patterns are typical in academic publishing and demonstrate the skewed productivity model predicted by Lotka's Law, where a minority of researchers drive most of the knowledge creation in a field. This finding emphasizes the importance of high-impact contributors in shaping research trends and advancing scholarly discussions.

The authors identified in Table 6 represent highly influential scholars within the research domain, as confirmed by author impact metrics. For example, Dr Surajit Bag (h-index: 10, TC: 1880) has established himself as one of the leading contributors to sustainable supply chain management, Industry 4.0, and circular economy frameworks. His widely cited work includes the development of theoretical models that identify critical enablers of sustainable digital supply chains, as well as empirical studies exploring the role of eco-innovation in enhancing small and medium-sized enterprises.

Similarly, Dr Khan Sarfaraz (h-index: 11, TC: 987), Dr Mangla Sachin Kumar (h-index: 9, TC: 939), Dr Gupta S (h-index: 4, TC: 801), and Dr Zhang Yu (h-index: 9, TC: 800) are also recognized for their impactful contributions in adjacent research areas such as resilience, green

Table 5. Lotka law

Documents written	N. of authors	Proportion of authors
1	1,746	0.850
2	184	0.090
3	56	0.027
4	28	0.014
5	14	0.007
6	8	0.004
7	4	0.002
8	2	0.001
9	2	0.001
10	1	0.000
11	3	0.001
12	1	0.000
13	1	0.000
14	1	0.000
16	1	0.000
17	1	0.000

Source(s): Constructed based on Biblioshiny software

Table 6. Author impact analysis

Author	h_index	g_index	m_index	TC	NP	PY_start
BAG S	10	11	1.667	1,880	11	2020
KHAN SAR	11	11	1.833	987	11	2020
MANGLA SK	9	12	1.500	939	12	2020
GUPTA S	4	4	0.667	801	4	2020
YU Z	9	9	1.800	800	9	2021
DHAMIJA P	4	4	0.667	795	4	2020
GARZA-REYES JA	10	16	1.429	794	16	2019
SARKIS J	4	4	0.667	770	4	2020
JABBOUR CJC	11	13	1.833	722	13	2020
SINGH RK	7	14	1.167	722	14	2020

Source(s): Constructed based on Biblioshiny software

supply chain design, and eco-innovation integration with digital technologies. Notably, Zhang Yu has published important empirical studies linking digital infrastructures with remanufacturing and recycling processes, thereby advancing the practical application of circular economy principles within Industry 4.0 frameworks. By integrating both bibliometric impact and content-specific analysis, we aim to provide a comprehensive and objective justification of these authors' significance in the scholarly discourse.

4.4 Key themes and their development over time

4.4.1 *Circular economy and HRM.* Table 7 depicts the Keyword Frequency Analysis related to the circular economy and Human Resource management.

Figure 1 depicts a Word cloud related to Circular Economy and HRM studies. The circular economy concept was referenced 19 times in the paper due to its crucial role in sustainability initiatives. Complementary terms such as “circular economy practices” and “circular economy performance” highlight both the practical implementation and the evaluation of these strategies. The business world now prioritizes waste reduction, resource management, and slope system design to achieve innovative circular economic approaches. Research suggests that circular economy applications are built from various disciplines involving green innovation and supply chain management, green logistics, and corporate social responsibility to create long-term environmental and economic resilience (Kazancoglu *et al.*, 2018; Del Giudice *et al.*, 2020; Karaman *et al.*, 2020).

Human resource management (HRM) defends green human resource management as its key focus when exploring sustainability (7 occurrences) while additionally using “green HRM” and “green human resources” terms. The field of human resource management has

Table 7. Keyword frequency analysis- circular economy and HRM

Words	Occurrences
Circular economy	19
Sustainability	10
Green human resource management	7
Green innovation	4
Green supply chain management	4
Sustainable development	4
Sustainable performance	4
Circular economy practices	3

Source(s): Constructed based on Biblioshiny software



Figure 1. Word cloud -circular economy and HRM. Source: Constructed based on Biblioshiny software

started to receive more attention regarding its contributions to fostering sustainable organizational practices. Green HRM uses employee environmental involvement to develop eco-friendly policies and improve learning programs, which connect human capital strategies to sustainability targets (Marrucci *et al.*, 2021). Proper alignment is essential for achieving sustainable performance goals that repeatedly emerge in the literature. The collection of findings represents an integrated approach to developing organizations that achieve both environmental and economic sustainability by utilizing effective resource management strategies alongside human development tactics.

4.4.1.1 Trend topic analysis. This study examines the evolution of sustainability by investigating the emergence of the circular economy and the increasing significance of green human resource management (GHRM). Figure 2 depicts Trend Topics Analysis related to Circular Economy and HRM studies. The circular economy has become a central topic in current discussions, reflecting its broad adoption as a solution to sustainability challenges (Geissdoerfer *et al.*, 2017). It plays a key role in keeping sustainable development goals prominent in both public and organizational discussions, promoting business models that focus on reducing waste, using resources efficiently, and maintaining long-term environmental stability.

At the same time, GHRM has attracted increasing attention as companies recognize its value in driving sustainable business strategies. By adopting GHRM practices, organizations encourage employees to engage in environmentally responsible activities, which helps

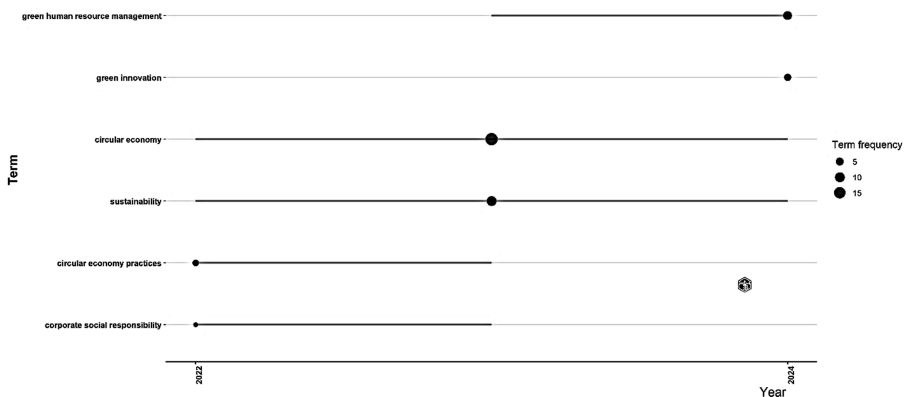


Figure 2. Trend topics analysis- circular economy and HRM. Source: Constructed based on Biblioshiny software

strengthen overall sustainability outcomes. The increasing use of these practices indicates a growing organizational commitment to integrating sustainability into both corporate culture and everyday operations.

In addition, green innovation has become a crucial factor in implementing circular economy principles, particularly in industries that prioritize resource efficiency and compliance with environmental standards. Aligning innovation with sustainability enables organizations to create solutions that not only lessen environmental harm but also support competitiveness in changing markets. This integration of GHRM, green innovation, and circular economy efforts reflects a more holistic path toward sustainable organizational growth.

4.4.1.2 Thematic map analysis. The thematic map organizes sustainability-related topics by assessing both their level of development and their significance, offering insights into current research and practice trends. The circular economy, sustainability, and green human resource management are identified as Motor Themes, showing strong development and central importance. These areas form the backbone of sustainable business strategies, enabling organizations to achieve long-term success while fulfilling their environmental responsibilities. Figure 3 depicts the Thematic Map related to Circular Economy and HRM studies.

On the other hand, Niche Themes such as green human resources, green practices, and organizational learning show considerable progress within specific areas. However, they still need broader applications to make a more substantial impact across the full sustainability spectrum. Basic themes, such as sustainable performance and green HRM, are gaining attention but continue to require additional research and practical improvements to strengthen their effectiveness in real-world operations. Meanwhile, the Emerging or Declining Themes quadrant highlights the intersection of human resource management and circular economy practices as underdeveloped yet promising fields that require increased scholarly and practical attention. The overall analysis highlights the strategic importance of integrating circular economy principles with sustainability efforts, suggesting new avenues for research and application that could enhance the evolving field of sustainable organizational development.

4.4.2 Industrial 4.0 and human resource management. Table 8 depicts Keyword Frequency Analysis- Industrial 4.0 and Human Resource Management.

Figure 4 depicts a Word cloud related to Industrial 4.0 and Human Resource Management. Through 33 references, “Industry 4.0” emerges as the key terminological element in this research because it serves as a primary industrial revolution within modern business operations. Today’s organizations use Industry 4.0 to deploy advanced digital technologies for

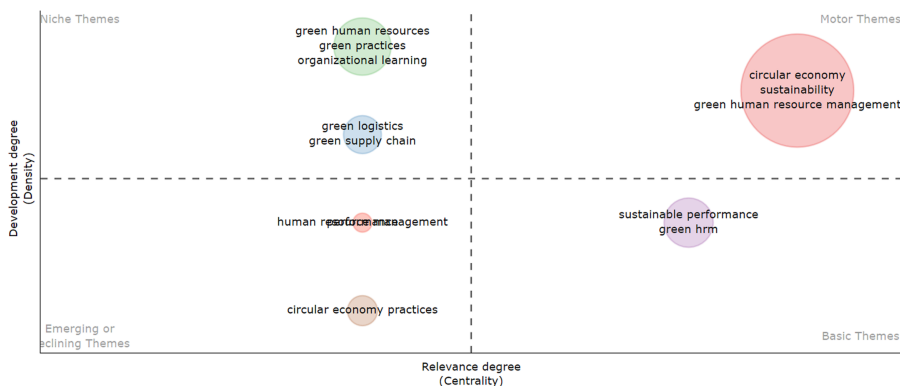


Figure 3. Thematic map- circular economy and HRM. Source: Constructed based on Biblioshiny software

Table 8. Keyword frequency analysis- Industrial 4.0 and human resource management

Words	Occurrences
Industry 4 0	33
Human resource management	26
Industry 4	23
Sustainability	8
Innovation	7
Digital transformation	5
Digitalization	4
Sustainable development	4
Bibliometric analysis	3
Competencies	3
Digitization	3
Education	3
Electronic human resource management	3
HRM	3
Human resource management (HRM)	3
Human resources	3
Industrial revolution	3
Internet of things	3
Manufacturing	3
Organizations	3
Smart factory	3
Sustainable human resource management	3
Technology	3

Source(s): Constructed based on Biblioshiny software



Figure 4. Word cloud-Industrial 4.0 and human resource management. Source: Constructed based on Biblioshiny software

automated manufacturing processes and IoT applications in smart factories. Digital transformation occurs five times in the text along with digitalization (4 times), digitization (3 times), and technology (3 times) as they collectively drive industrial structure modifications with organizational changes. These terms guide organizations in building more connected, data-driven operational systems that enhance performance and adaptability.

The investigation shows that Human Resource Management (HRM) appears 26 times throughout the study because it serves as a fundamental tool for leading and controlling personnel in contemporary technological workplaces (Shouraki *et al.*, 2024). The HRM field

shows two major adaptations through its related terms, “electronic human resource management” and “sustainable human resource management”, which each appear three times in the study (Sharma *et al.*, 2022; Alqarni *et al.*, 2023). As a whole, the text examines human capital growth through “competencies,” “education”, and “organizational learning” approaches, which aim to prepare workers for challenges from Industry 4.0 technology. HRM must establish systems that innovate and develop professional expertise, as this represents a critical requirement for success in an era of rapidly advancing digital technologies and industrial advancements.

4.4.2.1 Trend topic analysis. The trend analysis illustrates the evolution of key concepts related to Industry 4.0 and human resource management (HRM), as well as their increasing significance over time (See Figure 5). The phenomenon of Industry 4.0 remains a topic of great importance, garnering considerable attention for its role in popularizing smart technologies, automation, and digital processes across various industries. Its popularity shows no signs of decline, and organizations will need to consider adapting Industry 4.0 principles in long-term planning and their daily practices.

HRM, at the same time, continues to play a major role, with growing evidence of its alignment with digital transformation initiatives. Businesses have adopted new technologies, and HR functions should take this into account so that the way the workforce is managed does not fall behind in relation to the shifts in the business. The evolution includes not only the process of supporting workplace exchange but also considers the aspects of building digital talent in workers so that they can operate successfully in the conditions of Industry 4.0.

The analysis also highlights the growing importance of digital transformation, sustainability, and workforce competencies. Digitalization is considered one of the key aspects of business modernization and infrastructure upgrading, while sustainability involves the integration of technological development with the careful management of resources. To go hand in hand with that, lifelong learning and the practice of new skills are indispensable in ensuring that employees are ready to sustain performance in their technologically oriented environments. Collectively, these thematic ties demonstrate how Industry 4.0, HRM, and digital transformation are working together in assisting the sustainable and flexible development of organizations.

4.4.2.2 Thematic map analysis. The thematic map (see Figure 6) presented below logically organizes the constructs of Industry 4.0 and human resource management (HRM) according to

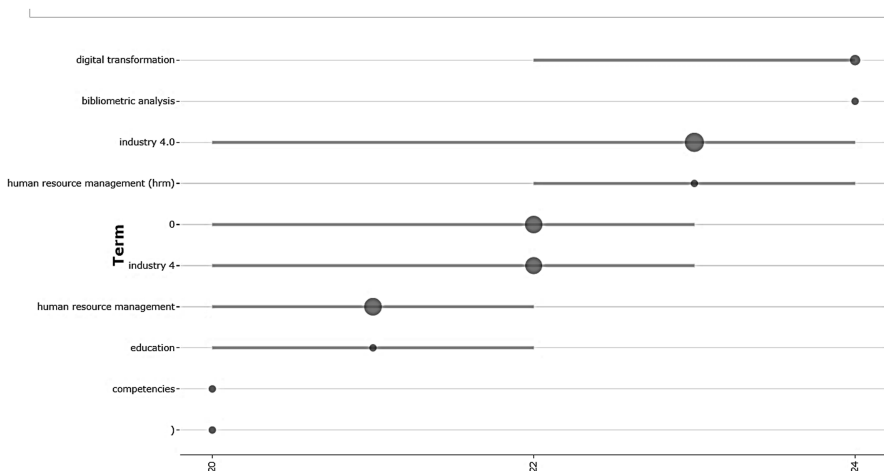


Figure 5. Trend topic analysis-Industrial 4.0 and human resource management. Source: Constructed based on Biblioshiny software

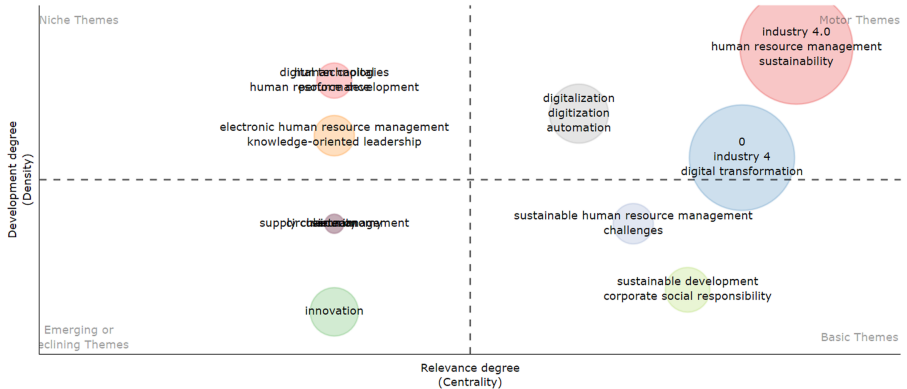


Figure 6. Thematic map-Industrial 4.0 and human resource management. Source: Constructed based on Biblioshiny software

their levels of development and prioritization, thereby explaining the existing direction of the research. Industry 4.0, HRM, and sustainability are referred to as Motor Themes, which highlight their crucial role in promoting technological innovation and supporting the development of strategies to guide the workforce in the digital age. The three themes of the Niche Themes (digital technologies, electronic HRM, and knowledge-based leadership) exhibit substantial progress within the context of a discipline but need further dissemination to increase their impact in diverse industries.

Sustainable development and corporate social responsibility, in their turn, are classified as Basic Themes, which means that their relevance is recognized, but the range of their direct employability is not very large. The perspectives on innovation and supply chain management within the Emerging or Declining Themes quadrant also point to an increasing level of researcher interest and to the future importance that will likely be attributed to these domains in strategic terms as they advance through research and practice. Overall, the findings emphasize the close connection between Industry 4.0, sustainability, and HRM, while also pointing to the need for stronger integration of innovation and digital expertise to drive long-term, technology-supported sustainable development.

4.4.3 *Industry 4.0 and circular economy.* Table 9 depicts Keyword Frequency Analysis-Industrial 4.0 and circular economy.

Table 9. Keyword frequency analysis-Industry 4.0 and circular economy

Words	Occurrences
Industry 4 0	515
Circular economy	322
Sustainability	129
Sustainable development	41
Digitalization	28
Digital technologies	20
Blockchain	19
Supply chain	18
Digital transformation	17
Sustainable development goals	17
Internet of things	16
Sustainable manufacturing	16

Source(s): Constructed based on Biblioshiny software

4.4.3.1 Circular economy. Figure 7 depicts a Word cloud related to Industrial 4.0 and Circular Economy studies. The word “circular economy” was mentioned 322 times throughout the documents, which demonstrates its central role in sustainability projects. The frequency indicates that industries focus heavily on developing waste reduction methods and resource optimization approaches, alongside the execution of industrial cyclic systems. The role of circular principles spreads across different industrial processes and value chains, as demonstrated by the related concepts of sustainable development (41 occurrences), supply chain (18 occurrences), and sustainable manufacturing (16 occurrences) (Khan *et al.*, 2022).

A large number of blockchains, along with digital transformation mentions, illustrate how digital tools work to improve traceability through transparent circular economy practices and enhance operational efficiency (Khan *et al.*, 2024). This circular economy strategy adoption aligns with existing efforts to implement such strategies across digitally connected, smart industrial facilities.

4.4.3.2 Industry 4.0. Industry 4.0 is the most frequently referenced concept in research, with its dominant position described in a total of 515 instances. The high occurrence of this keyword supports the dominant position that technological innovations, including automation, Internet of Things devices, and digital integration systems, maintain in industrial transformation.

Digitalization (28 occurrences) represents one of several technological terms, including digital technologies (20 occurrences) and the Internet of Things (16 occurrences), in the context of Industry 4.0. The industry sector is embracing connected data-based systems to optimize productivity, experience, and flexibility in operations.

Sustainability themes intertwine with technological innovation through their mutual appearance 129 times within the text and 17 times in the form of Sustainable Development Goals. Smart manufacturing and circular economy practices make Industry 4.0 the main driving force behind sustainable industrial transformation.

Industry 4.0 technologies display their capacity to help circular economy implementations and fulfill sustainable development goals through integrated analysis (Lopes de Sousa Jabbour *et al.*, 2018; Nascimento *et al.*, 2019; Rajput and Singh, 2019).

4.4.3.3 Trend topic analysis. Figure 8 depicts Trend Topic Analysis related to Industrial 4.0 and Circular Economy studies. Modern consciousness about the concepts of digital transformation and digital technologies emphasizes the need for expediting the integration of advanced technologies into industrial sector organizations to streamline operations, achieve efficiency, promote innovation, and enhance overall competitiveness. This trend indicates that digital transformation has become a crucial component of modern business strategy development.

Furthermore, the circular economy remains a relevant topic, highlighting its significant role in promoting green industrialization. A global trend toward enclosed-loop systems that optimize resources and reduce waste is evident in the continued importance of this framework, driven by the need to achieve long-term environmental goals as a necessity for overall



Figure 7. Word cloud-Industry 4.0 and circular economy. Source: Constructed based on Biblioshiny software)

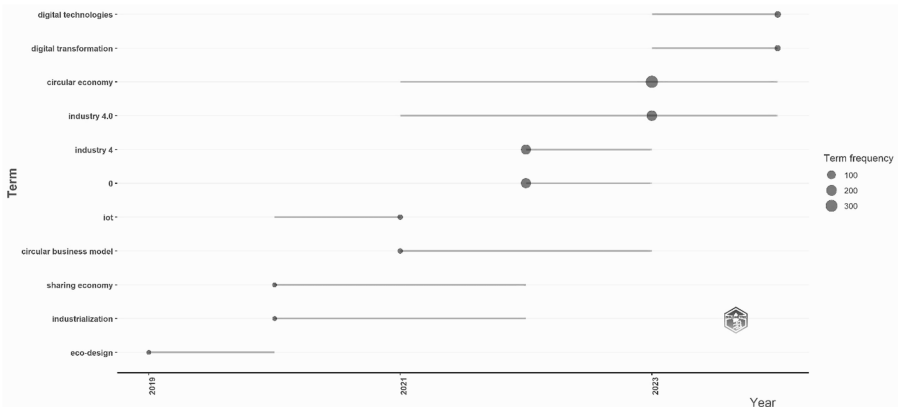


Figure 8. Trend topic analysis- Industry 4.0 and circular economy. Source: Constructed based on Biblioshiny software

ecological sustainability. When combining circular economy concepts and digital technologies, industries will have the opportunity to fundamentally redesign both production and supply chain processes, producing more sustainable results.

The phenomenon of Industry 4.0 is also supported by substantial power, associated technologies such as the Internet of Things (IoT), blockchain, and digitalization as a whole contribute increasingly to the generation of highly active and intelligent systems. At the same time, the emergence of new concepts, including circular business models, the sharing economy, eco-design, and industrialization, indicates an increasing attention from scholars and practitioners to both types of business collaboration and environmentally sustainable business. Together, these developments underscore the convergence of technological progress and sustainability, as industries leverage digital innovations to address environmental concerns while maintaining competitiveness.

4.4.3.4 Thematic map analysis. The thematic mapping (See Figure 9) highlights that Industry 4.0 and circular economy concepts are central to industrial transformation, combining advanced technologies with sustainability goals. Motor themes such as sustainability, the

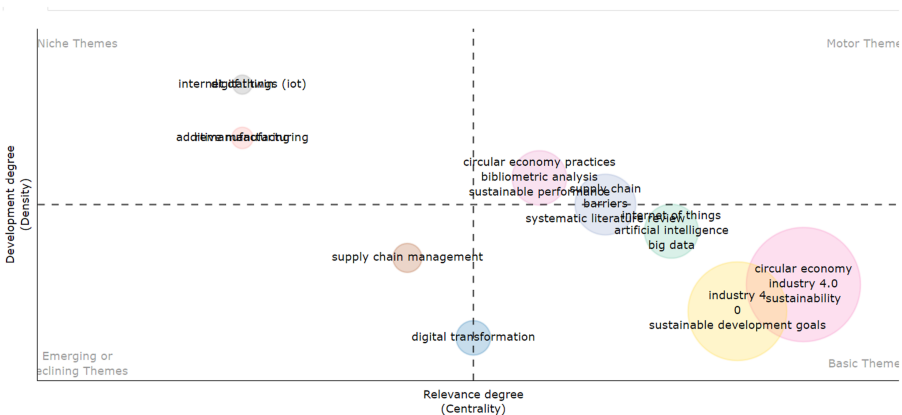


Figure 9. Thematic map-Industry 4.0 and circular economy. Source: Constructed based on Biblioshiny software

circular economy, and Industry 4.0 reflect well-developed areas that drive innovation and organizational change. Meanwhile, niche themes like IoT and additive manufacturing show strong development within specific applications but remain less integrated into broader business strategies.

Basic themes, including digital transformation, artificial intelligence, big data, and supply chain management, serve as essential building blocks but still require further development to support sustainable industrial growth fully. Emerging or declining themes, such as innovation and specific supply chain aspects, are becoming increasingly important as businesses adopt more advanced digital and sustainable practices. Continued research and integration across these areas will be key to realizing the full potential of Industry 4.0 and circular economy frameworks.

4.4.3.5 Thematic analysis and categorization of studies. The bibliometric analysis enabled a more structured categorization of the 693 reviewed studies based on their primary focus areas. This categorization was informed by keyword co-occurrence analysis, which revealed three dominant research clusters: Industry 4.0 and Circular Economy, Industry 4.0 and Human Resource Management (HRM), and Circular Economy and HRM. Most studies (589 publications, representing approximately 85% of the total) focused on integrating Industry 4.0 and the Circular Economy. These studies primarily investigated how emerging technologies such as the Internet of Things (IoT), blockchain, big data analytics, and artificial intelligence facilitate the implementation of sustainable manufacturing, circular supply chains, and resource optimization. The works of scholars such as Bag, Khan, and Mangla have been particularly influential in this domain, offering detailed examinations of the technological enablers that drive the adoption of the circular economy in industrial contexts.

A smaller but significant portion of the literature (approximately 15%, comprising 104 studies) focused on the intersection of Industry 4.0 and HRM. This group of studies explored the human capital challenges associated with digital transformation, emphasizing the need for workforce upskilling, the development of digital competencies, the emergence of electronic HRM (e-HRM) systems, and leadership approaches suitable for navigating Industry 4.0 transitions. The contributions of scholars like Sharma, Whysall, and Nicolás-Agustín have been central in highlighting how HRM functions must evolve to meet the demands of technologically dynamic work environments.

The smallest cluster, comprising 43 studies (approximately 6%), examined the relationship between the Circular Economy and HRM. These studies primarily examined how green HRM practices and sustainability-oriented HR policies can support organizations in adopting circular economy business models. Contributions in this area remain limited but are emerging, with the works of Chiappetta Jabbour, Marrucci, and Obeidat offering valuable insights into how HRM can foster environmentally responsible employee behaviors, organizational learning, and eco-innovation. To support this categorization, [Table 10](#) summarizes the distribution of studies across these primary research focus areas:

The thematic analysis was further conducted using co-word analysis and cluster mapping through the Bibliometrix R package. The resulting clusters were mapped according to the framework proposed by ([Callon et al., 1991](#)) which classifies themes based on two dimensions: centrality and density. Centrality reflects a theme's importance and connectedness to other themes, while density reflects the theme's internal development and maturity. Based on these two dimensions, themes were categorized into motor, niche, basic, and emerging or declining themes.

Motor themes, which are highly developed and central to the field, include Industry 4.0, Circular Economy, Sustainability, Green Supply Chain, and Smart Manufacturing. These topics represent the dominant areas of scholarly inquiry, with well-established empirical studies driving their growth. Niche themes, while highly developed within their subfields, exhibit limited cross-disciplinary integration. Themes such as electronic HRM, digital competencies, organizational learning, and knowledge-oriented leadership fall into this category. Basic themes, such as green HRM, sustainable performance, and corporate social

Table 10. Categorization of reviewed studies based on research focus

Research focus area	Number of studies	Approximate share (%)
Industry 4.0 and Circular Economy	589	85%
Industry 4.0 and HRM	104	15%
Circular Economy and HRM	43	6%

Source(s): Constructed based on the Literature Survey

responsibility, are recognized as important but remain underdeveloped, lacking substantial empirical grounding and theoretical refinement. Finally, emerging or declining themes, which show both low density and low centrality, include HRM and Circular Economy integration, innovation management, and supply chain resilience.

These topics, although still underexplored, offer significant opportunities for future research as organizations strive to integrate digitalization, sustainability, and workforce development in practice. This categorization helps provide a clearer picture of how the field is developing, while also highlighting the ongoing gaps that remain. While much of the current literature focuses on the technological and operational aspects of Industry 4.0 and the circular economy, there is still limited attention given to the role of human resource management in enabling these changes. Addressing this gap requires more empirical research and the development of integrated theoretical models that examine how HRM can support the development of digital skills, leadership growth, and organizational change to achieve sustainable digital transformation.

5. Discussion

This study aimed to analyze publication trends, map research themes, and examine the underdeveloped integration of Human Resource Management (HRM) into Industry 4.0 and Circular Economy (CE) research. The bibliometric analysis directly supports these objectives, offering both quantitative insights and more profound theoretical implications. While scholarly attention to Industry 4.0 and CE has grown substantially since 2019, HRM remains relatively marginalized within this discourse. This gap is not merely numeric but reflects a deeper theoretical imbalance: the literature has predominantly emphasized technological innovation, digital infrastructure, and operational optimization (Geissdoerfer *et al.*, 2017; Bag *et al.*, 2020), while often overlooking the essential human and organizational dimensions necessary to enable such transformations.

Our findings reinforce existing calls (Roscoe *et al.*, 2019; Sharma *et al.*, 2022) for a more integrated research agenda that positions HRM as a central driver of sustainable digital transformation, rather than as a peripheral support function. Critically, the analysis reveals limited engagement with comprehensive frameworks that connect workforce development, leadership, and organizational learning to Industry 4.0 and CE outcomes. Although studies such as (Rajput and Singh, 2019; Khan *et al.*, 2024) highlight the resource optimization potential of Industry 4.0 technologies, they frequently under-theorize how organizations cultivate and sustain the human capabilities required to implement these technologies effectively. This represents a persistent gap in both theory and empirical research.

Several specific areas of inquiry remain underexplored. These include the design of targeted digital upskilling programs for Industry 4.0 environments, the institutionalization of green HRM practices that align workforce behavior with circular economy goals, adaptive leadership models capable of navigating technological and ecological complexity, and strategies to build workforce resilience in volatile and rapidly changing organizational contexts. While early research has begun to address these issues, the field lacks unified theoretical models and cross-disciplinary empirical studies to advance understanding.

Importantly, these findings directly address the study's central aim: to expose how the integration of technology, sustainability, and HRM remains fragmented, and to provide a clear roadmap for future interdisciplinary research that bridges these isolated domains. Incorporating emerging Industry 5.0 perspectives—centered on human-centric innovation, resilience, and social value creation—may offer new theoretical lenses to strengthen this integration (della Volpe *et al.*, 2023; Saikia, 2023). By identifying and articulating these research gaps, this study not only maps the present knowledge frontier but also provides a strategic foundation for advancing theory, informing practice, and shaping more holistic, inclusive, and sustainable organizational transformations.

5.1 Implications

The findings from this bibliometric analysis on Industry 4.0, circular economy, and human resource management (HRM) reveal important implications for researchers, industry practitioners, and policymakers.

5.1.1 Theoretical implications. Theoretically, this study makes several contributions by extending existing debates and highlighting significant gaps. First, consistent with Frank *et al.* (2019) and do Nascimento *et al.* (2019) the findings affirm the synergistic potential of Industry 4.0 and CE to drive innovation and competitiveness. However, unlike many prior studies (e.g., Lopes de Sousa Jabbour *et al.*, 2018) that focus predominantly on technology, our analysis foregrounds the underexplored human dimensions that are critical to achieving these outcomes.

Second, the findings reveal that HRM remains insufficiently integrated into dominant theoretical models of digital and sustainable transformation. This supports the observations of (Chiappetta Jabbour *et al.*, 2019; Obeidat *et al.*, 2023), who argue that green HRM, leadership, and workforce readiness are often marginalized in current research. The low proportion of studies that explicitly link HRM to Industry 4.0 or CE (only 104 and 43 documents, respectively) further reinforces this theoretical fragmentation.

Third, the study challenges technological determinism by advocating for socio-technical frameworks that emphasize the interplay between technology, human agency, and organizational learning (Whysall *et al.*, 2019; Shouraki *et al.*, 2024). The limited focus on adaptive leadership, organizational learning, and competence development suggests the need to theorize transformation as a dynamic, people-centered process rather than a purely technological progression.

To address these theoretical gaps, future research should employ longitudinal studies, comparative analyses, and empirical case studies that examine how HRM practices—such as digital skills development, green HRM, and leadership training—contribute to integrated organizational transformation. These approaches will produce more nuanced, actionable, and context-sensitive models that advance both theory and practice.

In sum, the study contributes theoretically by (1) mapping current fragmentation, (2) demonstrating the need for interdisciplinary frameworks, and (3) proposing new research pathways that unify technological innovation, environmental responsibility, and human capital development.

5.1.2 Practical implications. The study's findings offer important practical implications for multiple stakeholders. For organizations, achieving Industry 4.0 and CE objectives requires more than technological investments; prioritizing workforce development is also essential. HRM should play a central role in designing reskilling programs, adaptive leadership frameworks, and green HRM practices that foster both innovation and sustainability (Singh *et al.*, 2025b). Without sufficient attention to these human factors, technological adoption may fail to yield intended benefits.

For policymakers, national and regional development strategies must integrate workforce preparation alongside digital infrastructure and sustainability initiatives. Policymakers should support cross-sector collaboration between governments, educational institutions, and

industry to develop comprehensive training ecosystems that address both digital and environmental challenges (Panait *et al.*, 2022; Apostu *et al.*, 2023).

For educators and professional trainers, there is an urgent need to revise curricula to incorporate interdisciplinary competencies. Educational programs should combine technical skills (e.g., data analytics, AI, blockchain) with leadership, change management, and green HRM knowledge to prepare the next generation of Industry 4.0 professionals (Sharma *et al.*, 2022).

For emerging economies, where resource constraints and institutional readiness may differ, tailored capacity-building programs are essential. Policymakers and practitioners must recognize local contextual challenges and design interventions that address both institutional and human capital deficits (Singh *et al.*, 2023).

In summary, organizations and policymakers alike must recognize that successful Industry 4.0 and CE integration depends on developing not only technological capacity but also the human capabilities necessary to sustain innovation and resilience.

6. Conclusions

This study offers a comprehensive bibliometric analysis of research trends at the intersection of Industry 4.0, Circular Economy, and Human Resource Management (HRM). The findings reveal significant growth in research output over recent years, with particular emphasis on technological advancements, digital transformation, and sustainability practices. While the literature on Industry 4.0 and Circular Economy has matured considerably, the integration of HRM into these discussions remains underdeveloped, signaling a critical gap that warrants further scholarly attention.

This study contributes to the literature by bridging technology-focused research with the often-neglected human dimension. It emphasizes that successful digital and sustainable transitions are not solely dependent on technological capability but also on the readiness of the workforce, organizational learning capacity, and leadership adaptation. The results extend prior research (e.g., Chiappetta Jabbour *et al.*, 2019; Shouraki *et al.*, 2024) by offering a more integrated perspective that positions HRM as a strategic enabler in Industry 4.0 and Circular Economy transformations.

For practitioners, the findings underscore the importance of aligning technological investments with workforce development initiatives, including digital skills training, green HRM practices, and leadership development, to foster sustainability-driven innovation. HRM functions must evolve from administrative roles to strategic partners that enable organizations to adapt to rapidly changing digital and environmental demands. Additionally, policymakers can use these insights to design education, training, and policy frameworks that promote an adaptive, sustainable, and digitally competent workforce.

Like all research, this study has limitations. The bibliometric analysis relied primarily on the Scopus and Web of Science databases, which may have excluded relevant literature indexed in other databases. The focus on English-language publications may also limit generalizability across non-English-speaking regions. Moreover, bibliometric methods focus on publication patterns and keyword co-occurrence but do not capture deeper theoretical development or empirical validation.

Several promising avenues for future research emerge from this study. First, further empirical work is needed to investigate how HRM practices can effectively support the integration of advanced technologies through digital reskilling, adaptive leadership, and continuous learning frameworks. Second, future studies should explore how HRM can embed circular economy principles more centrally into organizational cultures across different industries and national contexts. Third, cross-disciplinary collaborations between HRM, sustainability, and technology scholars can develop more holistic and actionable frameworks that address both technical and human factors in digital-sustainable transitions. Fourth, research should extend beyond developed economies to examine how emerging markets

implement Industry 4.0 and Circular Economy principles under varying institutional, socio-economic, and resource constraints. Lastly, longitudinal studies are needed to track how organizations evolve and sustain integrated Industry 4.0, Circular Economy, and HRM strategies over time.

By identifying these gaps and future directions, this study not only maps the current research landscape but also provides a clear roadmap for advancing both theory and practice at the critical nexus of digital transformation, sustainability, and human resource management.

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