A Bibliometric Study of SMEs' Digital Transformation Patterns in The Decade of Industry 4.0 Integration

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Abstract: Small and Medium Enterprises (SMEs) play an essential role in global economic development, contributing significantly to employment, innovation, and national GDP across both developed and emerging economies. Regardless of their significance, SMEs face several challenges, including a slowdown in growth caused by the COVID-19 pandemic, intense competition among producers, and limited adoption of e-based solutions. Therefore, applying digital technologies has become essential to enhance the productivity and performance of SMEs. Despite the burgeoning systematic literature review on digital transformation and Industry 4.0, it predominantly focuses on large enterprises and often overlooks the strategic responses of SMEs. This study offers a novel bibliometric synthesis that not only maps the intellectual landscape of SMEs' digital transformation but also concentrates exclusively on the digital transformation of SMEs that is directly aligned with the core pillars of Industry 4.0. Using 510 articles retrieved from Scopus and analyzed with VOSviewer and R Studio software, the findings reveal five key clusters addressed by SMEs over the past decade. These five clusters are business model and competitive advantage, business performance and digital marketing, digital entrepreneurship and digital innovation, business model innovation, and big data analytics.

Keywords: business performance; digital transformation; digitalization; industry 4.0; SMEs

1. Introduction

1.1. Background

Digital transformation under Industry 4.0 has emerged as one of the most crucial factors in driving the growth and sustainability of Small and Medium Enterprises (SMEs). It becomes more pronounced amidst the accelerating integration of technology in the global economic landscape[1)]. This transformation not only facilitates operational improvements but also drives innovation in business models, fosters penetration in the new markets, improves productivity and efficiency, as well as strengthens their competitiveness in business operations[2,3)]. Digital transformation in Industry 4.0 refers to the integration of advanced technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), Big Data Analytics, Cloud Computing, and Cyber-Physical Systems, which enable SMEs to optimize their operation, enhance decision-making, and improve customer experiences[4,5,6,7,8)]. As a result, digital transformation has become strategically important for SMEs aiming to improve their performance and achieve sustainable growth, particularly during turbulent periods such as the COVID-19 pandemic[9,10,11)]. Moreover, the digitization of business processes requires systematic approaches to data collection, management, and utilization, which supports more informed and agile responses to market dynamics[12)].

Despite those benefits, SMEs encounter distinct challenges in adopting digital transformation in Industry 4.0. Unlike large companies with extensive resources, SMEs' progress is often constrained by limited resources, including resources, financial and human capital limitations[13)]. Overcoming these barriers requires tailored strategies, supportive policies, and targeted investments to enable

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SMEs navigating their digital transformation effectively[14,15]. First, many SMEs struggle to secure sufficient funding for digital technology investments, which restricts their ability to modernize operations[16]. Second, low digital literacy among business owners and managers hinders their ability to understand and effectively leverage technology for business transformation[17]. Third, resistance to change within established organizational cultures and uncertainties regarding the success of technology adoption further exacerbate these barriers[11, 18].

Recently, digitalization among SMEs under Industry 4.0 has extended across diverse sectors and business models. In the retail sector, many SMEs are leveraging electronic commerce (*e-commerce*) platforms and digital marketing to expand their market reach, both nationally and internationally[19,20]. Additionally, in the manufacturing sector, SMEs are integrating automation, robotics, and data analytics, utilizing machine learning[21,22] and quantum computing[23], to streamline production, enhance efficiency, and anticipate market demand[24]. Furthermore, in the service sector, SMEs are employing digital applications to provide flexible and on-demand services tailored to customer needs[2]. Digitalization is also applied in agriculture sector to detect the quality of fruit[25,26]. Notably, some SMEs—particularly larger or better-capitalized firms—are implementing Enterprise Resource Planning (ERP) systems to integrate operations and optimize resource management, though widespread adoption remains constrained by financial barriers[27].

In summary, digital transformation in the era of Industry 4.0 has become essential for the growth and sustainability of SMEs. It offers significant advantages and prospects for SMEs businesses[10]. As consumers increasingly demand faster, more efficient, and digitally enabled services, SMEs must adopt smart technologies to remain competitive[28] Furthermore, digital transformation not only allows innovation in products and services but also expands market reach and strengthens customer relationships[24,29]. Therefore, understanding how SMEs navigate this digital shift is critical for shaping strategies that support their adaptation, resilience, and long-term performance in a rapidly evolving digital economy.

1.2. Research Gap and Novelty of the Study

Existing literature has acknowledged the importance of SMEs' digital transformation in Industry 4.0, highlighting considerable variations in technology adoption levels[30], success factors, and challenges across different industries and regions. These studies, both conceptual and empirical, discuss how SMEs navigate digital transformation, with some achieving substantial improvements in efficiency, productivity, and competitiveness[24,31,32]. In contrast, others struggle due to resource constraints and technical barriers in infrastructure and human resources[33,34]. Additionally, several studies have employed systematic and narrative review methods to examine the adoption of Industry 4.0 by SMEs from multiple perspectives.

For example, an empirical study by Costa and Castro[33] in the retail sector discussed that SMEs in developing countries, particularly those operating in local markets, tend to adopt e-commerce to access wider markets. However, the study also notes that low digital literacy poses a significant barrier to the effective implementation of e-commerce. On the other hand, Chen, Lyu, and Chen[42] investigate the manufacturing sector in Chinese SMEs and reveal that while many have adopted automation and robotics technologies, they face challenges related to inadequate technological infrastructure and a lack of workforce readiness to operate and manage these advanced systems. Another study from[24] discusses SMEs that successfully implement digital technologies with specified algorithm[35,36] and gain significant benefits in terms of operational efficiency and competitiveness[37,38]. However, they emphasize the importance of government policy and financial institutions in providing funding[39] and training to mitigate existing barriers. Additionally, Scuotto argue that partnerships with major technology companies and ongoing training programs are also key success factors for SMEs' digitalization[40].

The digital transformation of SMEs in Industry 4.0 plays a crucial role in reducing energy consumption and improving energy efficiency through the integration of smart technologies, which may optimize their business processes[41]. The employment of digital technologies, such as the Internet of Things (IoT) and intelligent energy management systems, enables real-time monitoring and control of energy consumption, improving operational efficiency and cost reduction[42,43,44]. Additionally, digitalization reduces paper usage and other resource expenditures, promoting eco-friendly manufacturing practices[45]. The integration of digital marketing strategies further reduces the need for physical transportation, contributing to lower carbon emissions[46]. Collectively, these advancements position digital transformation as a key driver of sustainable green manufacturing in SMEs[47,48,49].

In addition, several studies have employed review methods to examine the digital transformation of SMEs in Industry 4.0, highlighting both the opportunities and challenges. For example, Mittal et al[50]. critically review the applicability of Smart Manufacturing (SM) and Industry 4.0 maturity models to SMEs, highlighting that current models fail to account for the specific requirements of SMEs because they are designed for large enterprises[59,60]. Additionally, da Silva et al[51] emphasize that while Industry 4.0 adoption leads to better system integration, organizational efficiency, and enhanced value chains, SMEs struggle with limited financial resources, skill shortages, and adaptation difficulties. Furthermore, Ghobakhloo and Fathi[52]

conducted a systematic review and argued that, despite enhancements in operational efficiency, including competitiveness, and innovation, SMEs face major obstacles such as high implementation costs, cybersecurity risks, lack of skilled personnel, and limited government support. Expanding on this, a recent review study by Santos and Sant'nna[14] systematically examines how digital transformation in Industry 4.0 contributes to Sustainability in SMEs, including workforce upskilling, waste control, and production process optimization. Together, these studies underscore the need for tailored strategies, supportive policies, and scalable solutions to help SMEs fully leverage Industry 4.0.

Despite growing academic interest in this topic, a comprehensive study that specifically examines the digital transformation of SMEs in Industry 4.0 integration remains absent[53]. A broader perspective is essential to understand the complex framework better and contribute to more nuanced theoretical development on this topic. Previous bibliometric studies, which offer a more comprehensive review, have only discussed SMEs' digitalization in general, without focusing on digital transformation in the context of Industry 4.0 integration. For instance, Tripathi[54] examines the importance of digitalization for SMEs in the Middle East to remain competitive and sustainable. Furthermore, Sarango et al[55] map the evolution of SME digitalization research trends using Web of Science data. Additionally, Margarida[56] examines SMEs' adoption of digital technologies in relation to business model innovation, global value chains, collaboration, and performance. However, these studies do not specifically address digital transformation within Industry 4.0 integration or utilize Scopus-indexed literature, highlighting the need for further research in this area.

Table 1 highlights that, although prior bibliometric studies exist, this study contributes to a more structured, cluster-based perspective on the digital transformation of SMEs. Unlike the broader thematic reviews by Tripathi (2024) and Margarida and Alves (2020), this approach offers granular insights into knowledge domains and evolving patterns. It also aligns with the empirical challenges faced by SMEs, complementing previous studies by Ghobakhloo et al. (2021, 2022) and Santos et al. (2024). By doing so, this study bridges theoretical mapping with practical relevance, thereby deepening our understanding of how SMEs navigate digital transformation under real-world conditions.

Although the literature on SME digitalization continues to grow, most studies remain focused on general technology adoption without explicitly addressing its integration within the Industry 4.0 framework. This study fills that gap by concentrating exclusively on the digital transformation of SMEs that is directly aligned with the core pillars of Industry 4.0—namely, the IoT, AI, Big Data Analytics,

Table 1: Previous Literature Review (Bibliometric) Study Related to Digital Transformation

Author	Key Findings	Challenges/ Barriers	Success Factors
Santos, et al. (2024)	Digital transformation supports sustainability (skills, waste control).	-	Tailored strategies & scalable solutions.
Tripathi (2024); Margarida & Alves (2020)	General SME digitalization (not Industry 4.0-specific).	Lack of focus on Industry 4.0 integration.	-
Ghobakhloo et al. (2022)	Increased operational efficiency, competitive pressures, government support, and the need for real-time data. Key technologies: IoT, AI, big data analytics, cloud computing.	High investment costs, lack of skilled human resources, resistance to change, and cybersecurity concerns. Limited infrastructure and a lack of understanding of the benefits of Industry 4.0.	Visionary leadership, collaboration with technology suppliers, employee training, and external funding (grants/ loans).
da Silva, et al. (2022)	Improved system integration & organizational efficiency.	Limited finances, skill gaps, & adaptation difficulties.	-
Ghobakhloo et al. (2021)	Digitalization, intelligent automation, integrated supply chains. Sustainability Drivers: Energy efficiency, circular economy, waste reduction. Increased productivity, product innovation, and customer satisfaction.	Complexity of system integration, fragmentation of technology standards, and data security risks. Lack of a clear regulatory framework.	Phased adoption (roadmap), collaborative ecosystem (corporate-government-academic), focus on sustainability.
Mittal et al. (2018)	Critique of Industry 4.0 maturity models for SMEs.	Existing models tend to favour large enterprises over SMEs.	-

Cloud Computing, Cyber-Physical Systems, and Smart Manufacturing—while excluding administrative digitalization or pre–Industry 4.0 technologies. Furthermore, it employs a bibliometric approach using globally sourced, Scopus-indexed data to map research trends, key themes, and patterns related to Industry 4.0 integration in SMEs. This area has not been comprehensively examined to date. In addition, the study identifies critical success factors and major barriers, including infrastructure readiness, digital literacy, and policy support, that are specifically relevant to SMEs in the Industry 4.0 era. By doing so, this research not only advances theoretical understanding of SME digital transformation within the context of Industry 4.0 but also provides a knowledge map that can inform policymakers, practitioners, and researchers in strengthening the global competitiveness of SMEs.

Addressing this gap, a comprehensive study on the digital transformation of SMEs in the context of Industry 4.0 integration is both timely and necessary. This study, therefore, employs bibliometric analysis to examine the accumulated scholarly research on this topic. A bibliometric approach enables the identification of research trends, key themes, and patterns in SME digital technology adoption and implementation, particularly within Industry 4.0[57]. Additionally, this analysis provides insights into the key determinants of successful digitalization within SME, including infrastructure readiness, digital literacy, and government policy support[5]. By mapping these factors, the study aims to inform future research directions and policy frameworks, providing practical recommendations to enhance SME digitalization strategies. The findings are expected to serve as a foundation for stakeholders, enabling them to develop targeted strategies that improve the competitiveness and resilience of SMEs in the Industry 4.0 era.

This study defines the concepts of digital transformation, digitalization, and digitization in relation to their roles in SME development. First, digital transformation is the process of adopting and implementing digital technology within an organization to create new or modify existing products, services, and operations by translating business processes into a digital format[58,59]. Second, according to Gartner's IT Glossary, digitalization involves leveraging digital technologies to transform a business model and create new opportunities for revenue generation and value creation. Third, digitization refers to the process of converting analog information into digital form[60].

This study is explicitly confined to examining digital transformation and digitalization of SMEs within the specific framework of Industry 4.0 integration. The scope does not extend to general forms of digitalization that are unrelated to the adoption of Industry 4.0 technologies. Only digital technologies and processes that align with the core pillars of Industry 4.0—namely the IoT, AI, Big Data Analytics, Cloud Computing, Cyber-Physical Systems, and Smart Manufacturing—are considered. Digital practices that are purely administrative, basic IT adoption (e.g., use of standard office software), or pre-Industry 4.0 technologies are excluded from the analysis. Furthermore, this research focuses exclusively on SMEs and does not address large enterprises or micro-enterprises. The geographical scope is global, with no restrictions on a specific country or region; however, the bibliometric dataset only includes literature indexed in Scopus. As such, the findings should be interpreted within the context of Industry 4.0-driven digital transformation in SMEs and not generalized to broader digitalization phenomena.

2. Research Method

This paper employs a bibliometric approach to examine digital transformation patterns in SMEs within the context of Industry 4.0, focusing on the development, productivity, and key thematic areas relevant to SMEs' digital transformation studies. Bibliometric analysis is a powerful tool for examining the evolution and productivity of scholarly articles, as well as exploring the relationships between articles[61]. It also helps identify global research trends, such as those in big data, and highlights the most relevant areas of study in the field[61].

Industry 4.0 adoption remains a major challenge for SMEs, with persistent barriers occurring, such as limited financial resources, low digital literacy, and inadequate infrastructure. These difficulties prevent many SMEs from fully leveraging digital tools, including automation, IoT, and big data analytics. As such, discussions around Industry 5.0, which emphasizes human-machine collaboration, product personalization, and sustainability, are still in their early stages and are more relevant for large industries with advanced technological capabilities. The discussion on Industry 4.0 for SMEs is considered more aligned with the current condition before progressing further.

The data was collected from the Scopus website on November 11, 2024. Scopus is a comprehensive abstract and indexing database covering all fields of science [62,57] and offers a sorting feature to easily access over 27 million abstracts and citations[57]. Several stages are carried out in the course of gathering literature data, including: First, identifying the keywords from the articles to be analyzed. This study applied the following keywords: (SMEs OR MSME OR "small business" OR "small business enterprise") AND ("patterns digital transformation" OR "digital transformation" OR digital) OR ("industry 4.0 integration"). Based on these keywords, a total of 4,230 articles were initially identified. Second, conducting a screening of the data obtained based on the keywords. The articles are screened based on five criteria, namely: (1) the publications year is limited to the period 2015-2024; (2)

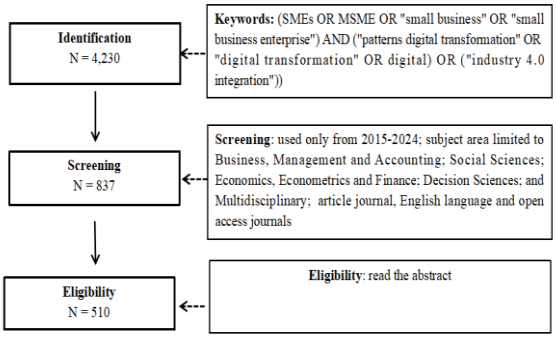

Fig. 1: Data Collection Process

the subject area is restricted to Business, Management and Accounting; Social Sciences; Economics, Econometrics and Finance; Decision Sciences; and Multidisciplinary; (3) document type is limited to only journal articles; (4) language is only English; and (5) source type is open-access journals. This process narrowed the selection to 837 articles. In an effort to minimize bias and enhance the eligibility of articles for analysis, the research team conducted a further thorough screening process, which involved reading, reviewing, and verifying the articles, resulting in the exclusion of 327 articles from the analysis. As a result, 510 articles published between 2015 and 2024 that are directly relevant to SMEs' digital transformation were identified as the basis for this bibliometric analysis (see Figure 1).

3. Results and Discussion

3.1. Results

3.1.1. The Development and Productivity of Journals

Table 2 presents a comprehensive summary of 510 selected articles from the Scopus database on digital transformation in the context of Industry 4.0 integration (2015–2024). With an annual publication growth of 49 papers and an average of 18 citations per document, the topic remains highly relevant and continues to attract significant academic interest. Moreover, research on SMEs' digital transformation still has potential relevance to the current problems, particularly in digitalization, Industry 4.0, integration, and SMEs' business development. This argument is further supported by contributions from 1,665 authors, with nearly 27% engaging in international co-authorship, indicating strong global collaboration and a significant interest in the field.

An analysis of annual publication trends on SMEs' digital transformation reveals significant growth. The number of articles increased from four in 2015 to 146 in 2023, with 145 articles recorded by November 2024 (see Figure 2). This surge aligns with the increased adoption of digital technology by SMEs over the past decade, reinforcing its relevance as a critical research area. Key aspects of interest include digital transformation patterns, factors influencing digital adoption, and the resulting impact on SME business performance[63,64].

An analysis of citation trends reveals significant variation

Table 2: Data Sources Characteristics

Description	Results
Primary Data Information	
Timespan	2015:2024
Documents	510
Annual growth rate %	49,02
Document average age	1,73
Average citations per doc	18,01
Refs.	32.122
Document Contents	
Keywords plus (ID)	784
Author's keywords (DE)	1.587
Authors	
Authors	1.665
Authors of single-authored docs	45
Authors Collaboration	
Single-authored docs	47
Co-authors per doc	3,44
International co-authorships %	26,86
Document Types	
Article	510

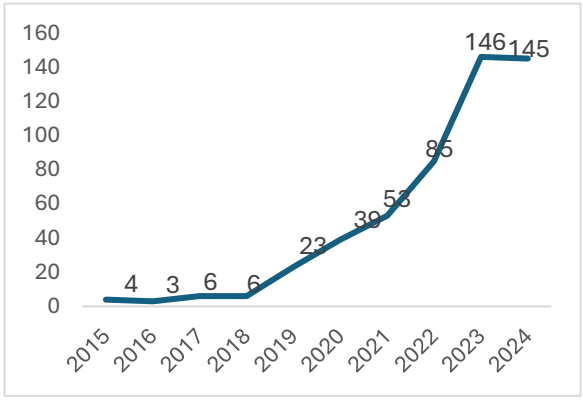

Fig. 2: The Number of Articles' Growth

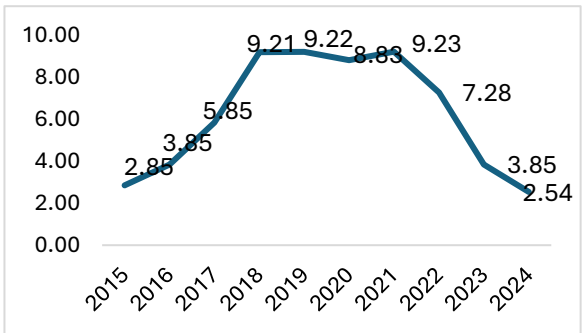

Fig. 3: Average Citations per Year

in the mean number of citations per article over the years. The growth was positive from 2015 to 2022, with the average number of citations per article increasing from 2.85 in 2015 to 9.21 in 2018, peaking at 9.23 in 2021. However, this trend declined after 2022, dropping to 2.54 in 2024 (see Figure 3). This decline is likely due to the substantial number of articles published during the 2023–2024 period. Although many authors may have cited these recent works, their citations have yet to be registered, as the citing works are still pending publication.

The bibliometric analysis highlights key publication sources that have significantly contributed to research on the digital transformation of SMEs in the context of Industry 4.0 integration, focusing on both publication volume and citation impact. Table 3 presents the Top 10 most influential open-access journals in this field. First, "Sustainability (Switzerland)" emerges as the most prolific journal, publishing 65 articles during the observation period and underscoring its central role in this discourse. Second, "Cogent Business and Management" ranks as the second-largest contributor, with 21 articles, followed by "Technological Forecasting and Social Change", which has published 13 key articles. While the remaining journals have contributed fewer articles, their combined output of 41 articles across eight journals provides valuable insights, further enriching the discourse on SMEs' digital transformation in the context of Industry 4.0 integration. Other reputable publishers, such as Elsevier, Growing Science, LLC, Business Perspective, Springer Nature, and Sage Publications, are included in the list of most influential journals in this study.

Table 3: Top 10 Most Influential Journals

Sources	Publisher	Articles
Sustainability (Switzerland)	Multidisciplinary Digital Publishing Institute (MDPI)	65
Cogent Business and Management	Tylor & Francis	21
Technological Forecasting and Social Change	Elsevier	13
Heliyon	Elsevier	11
International Journal of Data and Network Science	Growing Science	8
Problems And Perspectives in Management	LLC Business Perspectives	8
Journal Of Innovation and Entrepreneurship	Springer Nature	7
Journal Of Open Innovation: Technology, Market, And Complexity	Multidisciplinary Digital Publishing Institute (MDPI)	7
Systems	Multidisciplinary Digital Publishing Institute (MDPI)	7
Sage Open	Sage Publication	6

Nearly half of the 510 analyzed articles were published by top-tier publishers, with Elsevier (57 articles), Springer Nature (52 articles), Taylor & Francis (44 articles), Emerald (38 articles), Wiley-Blackwell (14 articles), and SAGE Publications (10 articles) making the most significant contributions. It highlights the academic rigour and scholarly attention towards the topic, which also reflects the growing institutional recognition of the subject. In evaluating productivity and impact, ten journals have been identified as the most productive and influential in the field. This research evaluates the productivity and impact of sources and authors using three widely recognized metrics: the h-index, g-index, and m-index, as summarized in Table 4. First, the h-index is a metric that assesses an author's productivity by considering the number of articles published and the citations received[2,27]. It reflects the author's ability to produce high-quality and impactful research consistently[27,28,65]. Second, the g-index provides more weight to highly cited publications and represents the largest number, g, such that the top g publications collectively receive at least g^2 citations[17,18,33]. Third, the m-index calculates the average number of citations per paper within the h-core[34,40]. It is derived by dividing the h-index based on the duration elapsed since the author's

Table 4: Number of Articles in Top-Tier Publishers

Publisher	Number of Articles
Elsevier	57
Springer Nature	52
Taylor & Francis	44
Emerald	38
Wiley-Blackwell	14
SAGE Publications	10

Table 5: Ranking of the Most Productive and Influential Journal

		h-index	g-index	m-index
1.	Sustainability (Switzerland)	23	38	3,833
2.	Technological Forecasting and Social Change	9	13	1,5
3.	Journal Of Open Innovation: Technology, Market, And Complexity	6	7	1,2
4.	Administrative Sciences	5	5	1,667
5.	Journal Of Innovation and Entrepreneurship	5	7	1,667
6.	Heliyon	4	8	1,333
7.	International Journal of Data and Network Science	4	8	1
8.	Problems And Perspectives in Management	4	5	0,667
9.	Technology Innovation Management Review	4	4	0,8
10.	Cogent Business and Management	3	6	0,75

initial publication[40,41]. Together, these three metrics provide a comprehensive evaluation of the productivity and impact, offering deeper insights into the contributions of key sources and authors in the field.

Table 5 presents the most productive and influential journals, as determined by the three metrics: h-index, g-index, and m-index. Among these, "Sustainability (Switzerland)" stands out as the most productive publication related to SMEs' digital transformation in industry 4.0 integration, with the highest values across all three metrics: an h-index of 23, a g-index of 38, and an m-index of 3.83. These results firmly establish "Sustainability (Switzerland)" as a leading publication in this field of discourse. The second most productive publication is "Technological Forecasting and Social Change", with an h-index of 9, a g-index of 13, and an m-index of 1.5. Although its m-index is slightly lower than those of "Administrative Sciences" and "Journal of Innovation and Entrepreneurship", an m-index of 1.5 is still considered above average, highlighting its significant impact within the academic discourse on SMEs' digital transformation in Industry 4.0 integration.

3.1.2. Network Analysis

Tracking all study themes in bibliometric analysis commonly involves co-citation analysis[66]. Two publications are considered co-cited when a third publication refs. both. When additional publications also cite these two articles, their interrelationship is further reinforced[67]. Using VOSViewer's co-citation analysis, five dissimilar clusters were identified, each represented by a unique color corresponding to a specific research theme. These clusters group articles with similar topics. Figure 4 describes the co-citation pattern by citing at least 25 journal articles among the 510 analyzed articles. First, in the red cluster, "Kraus and Wang" are the most cited authors. Second, the blue cluster features "Del Giudice and Chesbrough" as the most cited authors. Third, "Teece and Hess" are the most cited authors in the green cluster. Fourth, "Sarstedt and Ringle" dominate the most cited authors in the yellow cluster. Lastly, "Parida" is the most cited author in the purple cluster. These clusters correspond to the following key research themes: digital transformation, Industry 4.0, digitalization, technology adoption, and competitive advantage, as well as the sustainability of SMEs.

Derived from the findings of the co-occurrence analysis with a minimum threshold of eight author keywords, five clusters related to articles on SME digital transformation patterns were identified (see Figure 5). First, the red cluster discloses the relationship between business models, competitive advantage, digital technologies, digitalization, innovation, performance, and sustainable development. In today's highly competitive era, SMEs must adapt to the latest business practices, particularly through digitalization

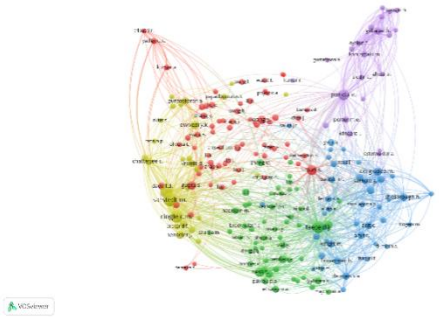

Fig. 4: Co-citation by Refs.

or digital transformation. The implications will be substantial for both goods and service providers and their customers[68]. The late leveraging of digital technologies can swiftly render products, processes, and business models obsolete, disrupting entire markets[69,70,71]. Therefore, SMEs must evolve and reconfigure their business models to stay competitive[72,24,34] suggest that continuously promoting and advancing digital transformation will be a critical development trend for enterprises in the future[73,74,75]. For example, digitalization enables business owners to collaborate with diverse partners, maintain efficient partnerships[76], and mitigate risk using a digital platform or application[77,78,79,80]. The effective implementation of digital transformation and technologies may lead to performance improvements and competitive advantage for firms, including higher labor productivity, increased average wages, and stronger sales growth[81,82,83,84].

Second, the green cluster encompasses business performance, COVID-19, digital marketing, digital platforms, e-commerce, SMEs, and social media[85]. Advances in digital technologies have transformed business operations into various strategies, including digital marketing, digital supply chain management, and the utilization of digital platforms[86,87]. Digital marketing is one of the most critical strategies, defined as the use of online communications to reach target audiences, engage customers, and drive sales[88,19,89,90]. Electronic commerce (e-commerce) and social media are two widely utilized channels in digital marketing. E-commerce facilitates the exchange of products and services through online networks, encompassing activities such as online payments, inventory management, logistics, and customer support[33,19,91]. Social media, on the other hand, refers to web-based platforms that facilitate communication, interaction, and collaboration among individuals, communities, and organizations discuss the positive relationship between the strategic incorporation of social marketing and the enhancement of SMEs' performance[17,40,92]. Furthermore, digital strategies have also played a crucial role in safeguarding businesses during crisis periods, such as the COVID-19 pandemic, by ensuring continuity and resilience.[88,18,93]

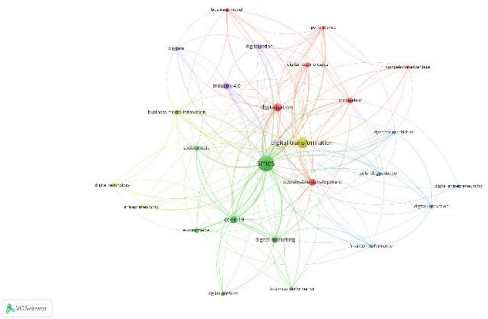

Fig. 5: Co-occurrence by Author Keyword

Third, the blue cluster interconnected themes of digital entrepreneurship, digital innovation, dynamic capabilities, financial performance, and technology adoption. Technology adoption and digital innovation are essential for enhancing the productivity, operational efficiency, and economic performance of SMEs, ultimately improving their competitive edge[94]. According to Saputra et al., successful adoption requires sensing capabilities for comprehensive market insight, a learning-oriented culture to enable technological proficiency, and capabilities integration by effectively assimilating digital technologies into established operational methodologies and functions[65,95]. Other key strategies to advance SMEs' digital transformation also include prioritizing resource allocation, product and service innovation, IT expansion, and organizational agility[96,63,97]. For example, the use of information technology may assist SMEs in logistics operations; thus, they may sustain their business in the long term[98]. Furthermore, SMEs are encouraged to leverage i-FinTech for continued operational efficiency, mitigating market downturns, and sustaining operations[97]. However, many SMEs confront difficulties in adopting digitalization. One common obstacle is the owners' and managers' attitudes towards digital and technology adoption, which range from passive to proactive attitudes[99]. Addressing this requires raising awareness of digitalization's benefits to encourage a shift from traditional to digital entrepreneurship[100], ensuring sustained growth[101] and competitiveness[96,102,103, 104].

Fourth, the yellow cluster highlights the intersection of business model innovation, digital technology, digital transformation, and entrepreneurship. In the context of Industry 4.0, digital transformation encourages SMEs to reconfigure their business models by adopting digital technologies such as big data analytics, artificial intelligence, and digital platforms[105,106]. This integration not only enhances operational efficiency but also enables the creation of new revenue streams and deeper customer engagement[72,24]. As an entrepreneur, an SME owner is expected to possess an entrepreneurial orientation, including proactiveness and innovativeness in experimenting with and implementing new business models[107,108]. Studies have shown that digitalization transforms business models, encourages innovation in business models, and mediates the relationship between digital strategies, market complexity, and SME performance[33,27]. However, barriers such as technological insecurities, financial constraints, and leadership challenges persist[109,110]. To overcome these challenges, SME leaders should develop digital literacy, invest in talented human resources, and foster an innovation-driven organizational culture to advance digital transformation initiatives successfully[11,111,112].

Fifth, the purple cluster focuses on the interconnection between big data, digitalization, and Industry 4.0. Big data plays a pivotal role in enabling digitalization within the Industry 4.0 framework, including for SMEs. It involves transforming vast volumes of raw information into actionable insights that support strategic decision-making and operational efficiency[109,113]. Big data analytics empower SMEs to optimize production efficiency, cost-effectiveness, customer experiences, and engagement, as well as predict market trends, which can improve efficiency and competitiveness[109,107,114]. However, the effectiveness of big data adoption is contingent on several factors, including management support, employee training, financial resources, IT infrastructure, government regulations, and support from providers[113,115]. Despite these benefits, SMEs often struggle with resource limitations, technical complexity, and a lack of awareness of the strategic value of big data and digitalization. In response, recent research suggests that developing models that incorporate cloud-based platforms and open-source analytical tools can enhance big data analytics and digitalization[107,115].

Based on the five clusters discussed above, certain themes related to SMEs' digital transformation remain underexplored, particularly budget control and forecasting, with a specific focus on financial and demand/sales forecasting using digital tools tailored for SMEs.

3.2. Discussion

3.2.1. Theoretical contributions

This study maps key knowledge clusters, influential authors, and thematic evolution in the literature of SMEs, digital transformation, and Industry 4.0, offering three theoretical contributions. First, it highlights that SMEs' adoption of Industry 4.0 is not only a technological upgrade but also a strategic configuration of business models, resources, and dynamic capabilities. Second, it discloses a shift from a technology-centric focus to a more strategic, integrated, and networked process. Third, it highlights regional disparities in research, informing future inquiries into context-specific digitalization challenges and their corresponding adaptations.

3.2.2. Practical Implications

This study offers practical insights for SME owners,

policymakers, and technology providers navigating digital transformation. For SME owners, it underlines the need to adopt digital technologies, including e-commerce, social media, big data analytics, and cloud-based platforms, not only to enhance performance but also to ensure operational resilience during disruptions such as the COVID-19 pandemic. Furthermore, they are encouraged to enhance digital literacy, build innovation-oriented cultures, and align technology with strategic goals. For policymakers, the findings underscore the importance of addressing infrastructure gaps, supporting the development of digital skills among SMEs, and facilitating technology adoption through targeted initiatives. For technology providers, the study highlights the demand for scalable and user-friendly digital solutions designed to meet the specific needs of SMEs.

3.2.3. Future Research Directions

While this study provides a macro-level bibliometric overview of SMEs' digital transformation in the Industry 4.0 era, future research direction should delve deeper into the intersection of digital transformation and financial management in SMEs. Specifically, there is a need to examine how digital technologies – such as artificial intelligence (AI), big data analytics (BDA), enterprise resource planning (ERP), and cloud-based platforms – can improve the financial decision-making process in SMEs. These tools offer significant potential to enhance budget planning, optimize costs, facilitate real-time financial tracking, and inform sales forecasting.

Furthermore, future studies could explore how SMEs in different sectors adapt to digital financial tools differently and what other factors, such as leadership, skilled workers, government policies, and regulations, influence this adoption. Additionally, comparative research between sectors, such as manufacturing, retail, or services, would also enrich the identification of bottlenecks and best practices in implementing digital transformation for SMEs.

4. Conclusion

This research examines the digital transformation patterns of SMEs in the Industry 4.0 era, analyzing publication trends, citation metrics, and thematic clusters. The growth in published articles reflects significant progress, with notable variations in average citations per year and key metrics such as the h-index, g-index, and m-index across different journals. The bibliometric analysis identifies high levels of co-citations among authors, with a minimum threshold of 25 co-citations forming five clusters of dominant contributors. These contributors are Parida, Dell Giudice, Teece, Sardedt, and Kraus. Additionally, the results of the co-occurrence analysis classify issues related to SMEs' digital transformation in Industry 4.0 into five key groups: (1) business model and competitive advantage, (2) business performance and digital marketing, (3) digital entrepreneurship and digital innovation, (4) business model innovation, and (5) big data. These findings offer insights into the academic landscape and emerging research directions in the Industry 4.0 transformation of SMEs.

Digital transformation in Industry 4.0 has a demonstrably positive impact on SME business performance, particularly by enhancing innovation, optimizing business models, and improving market competitiveness. Furthermore, it enables SMEs to identify new opportunities, streamline operations, and strenghten customer engagement. However, the success of digital transformation in SMEs is influenced by several key factors, including employee training, management support, IT infrastructure, government policies, organizational competence, inter-firm collaboration, digital transformation tools, and the quality of decision-making.

Despite these advancements, certain critical areas remain underexplored, particularly budget control and financial forecasting. Future research should focus on developing digital tools customized for SMEs that facilitate accurate financial planning, demand forecasting, and sales projections. Future research should focus on developing digital tools tailored for SMEs that facilitate accurate financial planning, demand forecasting, and sales projections. Hence, SMEs can optimize their budget allocation, predict demand, mitigate operational and economic risks, and improve overall business processes.

The bibliometric study has followed a systematic, transparent, and reproducible process that aligns with established methodologies in the literature; however, it still has certain limitations. First, the selected database may have constrained the number of articles found. While Scopus is a reputable and comprehensive database, it represents only a subset of scientific publications, meaning that some relevant studies may have been omitted. Future research could address this limitation by integrating multiple databases to enhance the breadth of coverage. Second, the articles examined consist solely of open-access articles, meaning that not all Scopus-indexed publications were included in the analysis. Open-access journals provide unrestricted access to scholarly research, allowing others to benefit from the latest findings, particularly those who may lack institutional access to subscription-based journals. It also supports data transparency and replicability by making both articles and supporting data openly available. However, open-access journals may have excluded high-impact factor journals, since some of them still operate under paywalls. This exclusion presents a potential research gap, as some of the most influential studies may not have been captured.

Disclosure statement

The authors declare that they have no conflict of interest.

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