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DEVELOPING COUNTRIES AND THE INDUSTRY 4.0 MOVEMENT: RESEARCH MAPPING FOR PRACTICAL INSIGHTS

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ABSTRACT

This paper investigates the adoption of Industry 4.0 in developing countries, emphasizing the unique challenges these economies face compared to advanced nations. Despite the global spread of digital technologies such as automation, big data analytics, and the Internet of Things (IoT), adoption in resource-constrained contexts remains limited due to inadequate infrastructure, financial restrictions, skill gaps, and organizational resistance. To address these issues, the study employs a bibliometric methodology, analyzing 398 journal articles indexed in Web of Science through co-word and bibliographic coupling techniques. This approach enables the mapping of dominant themes, influential research clusters, and key gaps in the literature. The results highlight five thematic areas: global technological developments, sustainability integration, adoption barriers, implementation practices, and strategies for overcoming obstacles. Findings indicate that while challenges are considerable, Industry 4.0 can enhance productivity, stimulate Innovation, and support sustainability by strengthening supply chains and promoting efficient resource use. The study also reveals that transformative benefits can only be realized when supportive policies, international collaboration, private-sector participation, and workforce development are followed in a coordinated manner. The research contributes to theory by linking Industry 4.0 adoption to sustainability frameworks such as the Circular Economy and the Sustainable Development Goals. It also offers practical guidance for policymakers, SMEs, and managers on designing context-sensitive strategies tailored to developing economies. By providing a structured overview of challenges and opportunities, the study lays a foundation for future empirical research and offers actionable insights for advancing sustainable industrial transformation.

INTRODUCTION

Technology-based processes connect different traditional industries across the ongoing technological revolution called Industry 4.0 (Alaloul et al., 2018). Industry 4.0 integrates technologies such as automation, big data, and IoT, shifting economies from product-based to service-oriented models (Javaid et al., 2024). This transformation has enhanced industrialization, data utilization, and process efficiency, generating significant economic and social value. Nonetheless, its application in realizing productivity, efficiency, and effective decision-making is currently limited in developing nations because of capital and infrastructure limitations (Verma et al., 2020). The Fourth Industrial Revolution is based on the prior Industrial Revolution (IR) progress of steam power (IR1.0), electricity (IR2.0), and computer automation (IR3.0). Industry 4.0, characterized by networked technology and self-organized systems, has revolutionized industrial systems worldwide, particularly in developed industrialized countries.

However, there are specific barriers to adopting technology in developing countries, including sparse computer literacy, a lack of modern infrastructure, and cultural resistance to change. The significance of developing a more thorough understanding of the region's social and economic realities and designing approaches tailored to these conditions to overcome these challenges is emphasized (Xu et al., 2018). The current revolution is generally termed Industrial Revolution 4.0 (IR 4.0), based on the concept of the Internet of Things (IoT) and the implementation of robotics in industrial processes to achieve higher production efficiency (Khan et al., 2022).

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This paper provides the following benefits of Industry 4.0 adoption across various Industries: increased flow of communication and cooperation, increased productivity and Innovation, and efficient decision-making. As such, the outlined benefits of organizations are as follows: These stem from the execution of innovative technologies, including IoT, automation, and data analytics, which increase productivity, lower costs, and optimize functions. Thus, IR 4.0 supports real-time collaboration, efficient resource utilization, and the actual enhancement of project execution, all driven by positive advancements across various fields (Alsehaimi & Sanni-Anibire, 2024).

This paper discusses the issues likely to arise in developing countries concerning Industry 4.0. This research is against emerging knowledge on how Industry 4.0 can enhance economic development and welfare and respond to significant development issues. Therefore, the purpose of this study is to assess the current state of Industry 4.0 adoption in developing nations, with a particular focus on the technological, societal, and infrastructural factors shaping its implementation. The study also aims to highlight key barriers and opportunities, providing practical insights and recommendations that can guide policymakers, industry leaders, and researchers in promoting sustainable digital transformation.

Unlike previous bibliometric studies that have primarily focused on global or developed economies, this paper contributes a distinct perspective by exclusively examining Industry 4.0 adoption in developing countries. By focusing on contexts characterized by resource constraints, institutional voids, and infrastructural limitations, this study generates insights that are directly applicable to policymakers, SMEs, and practitioners operating in these economies. This approach offers novel contributions by mapping not only the challenges but also practical pathways that align Industry 4.0 implementation with the unique social and economic realities of developing nations.

LITERATURE REVIEW

Industry 4.0 represents the integration of advanced technologies, including automation, the Internet of Things (IoT), artificial intelligence (AI), big data analytics, and cyber-physical systems, into industrial processes. In developed economies, these technologies have accelerated productivity, Innovation, and sustainability transitions. However, in developing economies, adoption remains uneven due to resource constraints, institutional gaps, and socio-technical challenges that are not adequately addressed in existing studies (Ghobakhloo, 2020; Nara et al., 2021; Ocelík et al., 2023; Xu et al., 2018). Several studies have identified persistent barriers that hinder Industry 4.0 adoption in developing nations. These include inadequate digital infrastructure, financial constraints, a shortage of skilled human capital, and cultural resistance to change. Weak institutional support and policy uncertainty further complicate the adoption process, particularly in small and medium-sized enterprises (SMEs). Research emphasizes that limited access to capital and insufficient workforce readiness remain among the most critical challenges, restricting the ability of firms to implement and sustain advanced digital technologies (Ayalew & Xianzhi, 2020; Chauhan et al., 2021; Gupta et al., 2022).

Despite these barriers, Industry 4.0 presents significant opportunities for economic transformation in resource-constrained contexts. Digital manufacturing technologies can strengthen supply chain resilience, improve operational efficiency, and enable green Innovation through more efficient use of resources. For example, empirical research highlights the role of digital technologies in supporting sustainable supply chains in Vietnam. At the same time, other studies show that SMEs in South Asia experience improved performance and innovation capability when adopting digital tools. These findings suggest that even in environments characterized by structural weaknesses, Industry 4.0 adoption can deliver measurable benefits if tailored strategies are applied (Akbari & Hopkins, 2022; Bag et al., 2021). The relationship between Industry 4.0 and sustainability has also gained prominence in recent scholarship. Integrating frameworks such as the Triple Bottom Line (TBL), Circular Economy (CE), and Sustainable Development Goals (SDGs) provides a holistic basis for assessing the impacts of digital transformation. Research demonstrates that Industry 4.0 can promote environmental sustainability through robotics and energy-efficient production, enhance social sustainability through workforce upskilling, and drive economic sustainability through Innovation and competitiveness.

However, successful adoption requires coordinated efforts, including supportive policy frameworks, international collaboration, and active engagement of the private sector to overcome institutional voids and strengthen long-term readiness (Alojail & Khan, 2023; Elheddad et al., 2021; Giovannoni & Fabietti, 2013). This review highlights that while Industry 4.0 has transformative potential, developing economies face persistent barriers that distinguish their adoption patterns from those in advanced economies. At the same time, opportunities exist to align digital transformation with sustainability objectives, particularly when policies, resources, and human capital development are addressed in an integrated manner. What remains missing from the current body of literature is a systematic overview that synthesizes these barriers and opportunities specifically in the context of developing nations. Therefore, the purpose of this study is to conduct a bibliometric analysis of Industry 4.0 adoption in developing countries to identify key challenges and opportunities, map the thematic clusters of research, and provide practical insights for policymakers, industry leaders, and researchers.

MATERIALS AND METHODS

Bibliometric methodology makes use of quantitative science mapping to analyse bibliographic sets. The analysis supports the qualitative systematic literature review (SLR) approach and the more quantitative meta-analysis approach.

Bibliographic coupling: Bibliographic coupling measures the similarity of articles in one way by the number of references that two articles have. Articles that mention comparable sources probably have a conceptual link, and it can be argued that the more references two articles share, the closer they are to one another in a bibliographic network (Zupic & Čater, 2015).

Co-word analysis: Co-word analysis, as opposed to shared citations, focuses on sets of terms that documents share (Delecroix & Epstein, 2004). Co-word analysis examines the co-occurrence of keywords to identify groups of related terms (Mangalaraj et al., 2023).

Web of Science was selected as the sole database because of its rigorous indexing standards, comprehensive coverage of peer-reviewed journals, and reliable citation tracking system. While this choice excludes some publications indexed in Scopus or Google Scholar, it ensures consistency and reliability of metadata. The thresholds applied in this study 41 citations for bibliographic coupling and 19 keyword occurrences for co-word analysis were adopted to minimize noise, enhance visualization clarity, and highlight the most influential works in the field. These criteria are consistent with established practices in bibliometric mapping, ensuring that the analysis captures robust and meaningful clusters.

As indicated in Table 1, publications containing pertinent keywords were found using the following search query. The search query relates to Industry 4.0 in developing countries and associated terms and is based on literature, identical terms, and a thesaurus. The search topic was used to search the Web of Science database. This option covers publications with keywords in the title, abstract, and authors. Furthermore, this analysis only includes journal publications; editorials, book chapters, novels, and conference proceedings are excluded. By restricting the study to journal articles alone, the caliber of peer-reviewed papers included in the science mapping analysis is ensured.

Table 1. Search string in Web of Science database

No	Keywords	Justification
1	"Industry 4.0" OR "IR 4.0" OR "Fourth Industrial Revolution"	To identify the technological advancements associated with Industry 4.0.
2	"Developing Country" OR "Developing Countries" OR "Developing Economy" OR "Developing Economies" OR "Emerging Countries" OR "Emerging Economies"	To identify the implications of Industry 4.0 in developing countries and emerging trends.

RESULTS

The search was conducted on 25th December 2024. A total of 513 documents were retrieved from the database using the search query created explicitly for this investigation. After journal publications were eliminated, 398 papers were completed. According to the publication trend, research increased steadily in 2017 and peaked in 2023. This rise reflects growing recognition of the significance of Industry 4.0 in developing countries. The continuous increase in citation rates shows how important older work is despite a slight decline in publications in 2024. Over the coming years, a slight rise in research production and impact is anticipated (Figure 1).

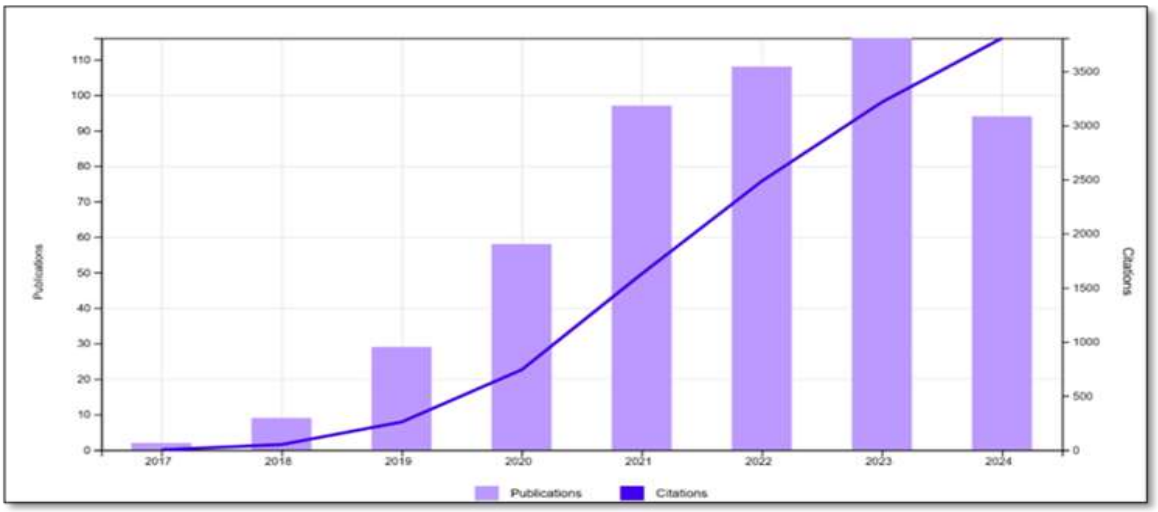

Figure 1. Number of Papers published per year

Bibliographic Coupling

Out of the 513 documents, 44 documents met a threshold of 41 citations. These 44 documents create 5 clusters. The top-3 documents based on total link strength (TLS) are (Nara et al., 2021) 214 TLS, (Tortorella & Fettermann, 2018) 202 TLS, and (Luthra et al., 2020) 180 TLS. In this bibliographic coupling, Table 2 displays the top ten documents. Bibliographic coupling refers to the strength of the coupling between the linked documents; hence, the more important the documents in the network, the higher the total link strength (TLS).

Table 2. List of top 10 documents in bibliographic coupling

Rank	Publication	Scope	Citation	TLS
1	Nara et al. (2021)	An examination of the expected impacts of Industry 4.0 technologies on sustainable development in the context of Brazil's plastics industry.	122	214
2	Tortorella and Fettermann (2018)	Lean manufacturing and Industry 4.0 implementation in Brazilian industrial firms.	247	202

3	Luthra et al. (2020)	An examination of the powerful influence of drivers in an emerging economy reveals how Industry 4.0 facilitates the diffusion of sustainability in supply chains.	225	180
4	Kumar et al. (2020)	Examining the challenges in integrating Industry 4.0 technology for ethical and sustainable business practices in SMEs.	240	174
5	Tortorella et al. (2021)	A comparison of manufacturers in developed and emerging countries with respect to Lean Production and Industry 4.0.	64	170
6	Chauhan et al. (2021)	An empirical examination of emerging economies' performance impacts and adoption hurdles for Industry 4.0.	151	165
7	Gillani et al. (2020)	Causes and Consequences of Implementing Digital Manufacturing Technology.	115	165
8	Bag et al. (2021)	An empirical study of the key resources for sector 4.0 adoption and its effects on sustainable production and the circular economy.	223	161
9	Raj et al. (2020)	Obstacles to Industry 4.0 Technology Adoption in Manufacturing: A Comparative Analysis of Different Countries.	507	146
10	Sharma et al. (2021)	Incorporating Industry 4.0 for sustainability into emerging economies' multi-tiered manufacturing supply networks.	134	125

Figure 2 illustrates the network visualisation of bibliographic coupling analysis. The five groupings are independent of each other. The following covers emerging and upcoming Industry 4.0 developments in developing nations. The clusters are labeled using inductive interpretation by re-examining representative papers within the clusters and synthesising them based on common themes and research streams.

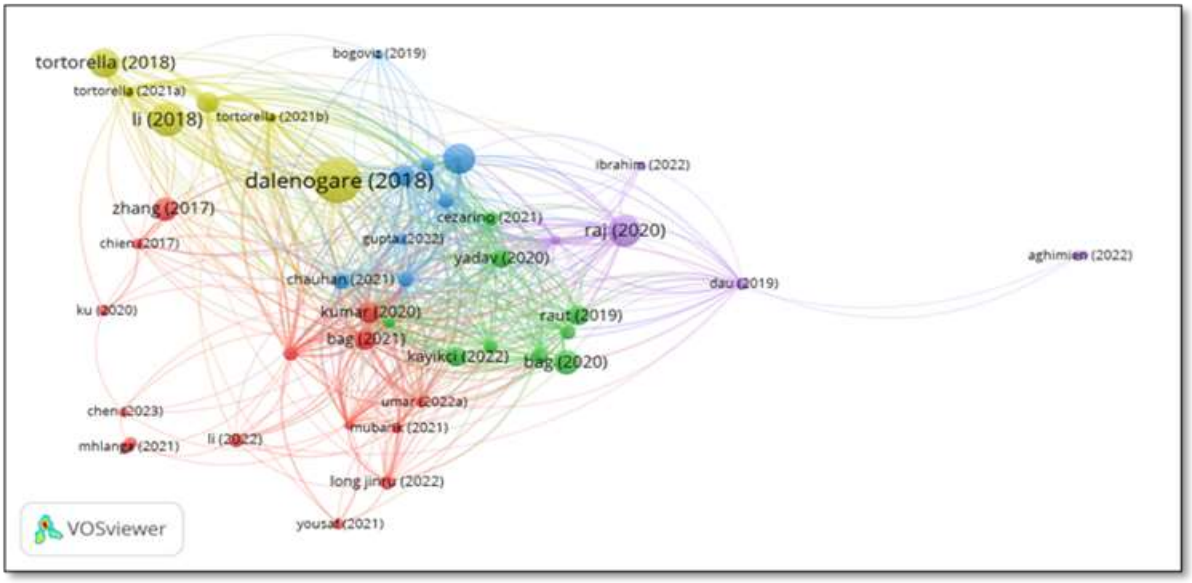

Figure 2. Bibliographic coupling of Industry 4.0 in developing countries: emerging and future trends

Cluster 1 (Red): Global Developments and Industry 4.0 Technologies' Effects on the Environment

The adoption of Industry 4.0 technology worldwide is revolutionizing industrial processes by addressing the challenges of environmental sustainability and promoting economic growth. Industry 4.0 aims to enhance industrial intelligence by intelligent output with the help of upgraded technologies, namely automation, big data, and cyber-physical systems (Chien et al., 2017). Industrial robots, a fundamental component of Industry 4.0, lower carbon intensity through increased energy efficiency, productivity, and green Innovation. Their environmental benefits are increasingly noticeable in industrialized countries and industries like manufacturing, agriculture, and utilities (Y. Li et al., 2022). Due to the reduction of the distance between different types of firms, digital transformation influences the innovative activities of non-SOEs, non-high-tech, and non-polluting enterprises more significantly (Chen & Kim, 2023). The Fourth Industrial Revolution has had a profound impact on our lives and interactions, resulting in significant economic changes and heightened environmental concerns (Elheddad et al., 2021).

Cluster 2 (Green): Industry 4.0 Adoption and Sustainability in Developing Economies

The adoption of Industry 4.0 in developing nations can revolutionize sustainability by filling administrative and technological gaps and bringing industrial practices into line with sustainable development objectives. Supply chains in Vietnam are anticipated to be most impacted by drones, analytics of big data, and the Internet of Things (Akbari & Hopkins, 2022). The impact of talent capabilities on employee development and sustainable supply chain results was less pronounced but still noteworthy. The report offers managers two approaches to enhance the mining industry's sustainable supply chain results (Bag et al., 2020). These economies may align industrial practices with sustainable development goals by overcoming obstacles such as limited digitization and economic volatility by promoting cooperation between politicians and industry leaders.

Cluster 3 (Blue): Opportunities and Difficulties of Industry 4.0 Adoption in Developing Nations

Developing nations face financial and institutional challenges, and as a result, their Industry 4.0 formation process differs from that of industrialized nations. In affluent nations, the initiative strategy, started by economic subjects, offers more flexibility and efficacy than the prescriptive approach (Bogoviz et al., 2019). Both internal and external constraints severely impact digitalisation, yet adoption increases supply chain competency and functional effectiveness (Alaloul et al., 2018). Indus. Industry 4.0 initiatives can transform the way products are designed, produced, delivered, and disposed of, but they pose challenges for developing nations, particularly India (Luthra & Mangla, 2018). The most highly ranked drivers are the sustainable aspects, which encompass both environmental and social factors, whereas the most highly ranked barriers are the organizational and environmental dimensions (Sharma et al., 2021). These obstacles demonstrate that targeted approaches are necessary to overcome them and capitalize on the benefits of Industry 4.0. They also emphasize how crucial it is to successfully overcome structural and financial constraints to deploy Industry 4.0 in developing countries.

Cluster 4 (Yellow): Implementation of Industry 4.0 in Various Economies

Industry 4.0 is being implemented in several economies to drive Innovation, streamline industrial structures, improve labour competencies, and remove technology and resource barriers for long-term performance improvement. The initiative seeks to improve industrial capability through Innovation, industry structure optimization, quality emphasis, talent training, and green manufacturing (Tortorella et al., 2021). However, in implementing this ambitious plan, the industry often faces challenges like resource constraints and technological barriers (L. Li, 2018). Larger performance (LP) gains result from the LP technique's good association with Industry 4.0 technology, according to data from a survey of 110 businesses. Contextual variables also play a role, although not all aspects are equally significant (Tortorella & Fettermann, 2018). Industry 4.0 impacts operational performance improvement through process-related technologies, reducing low setup effects and positively influencing flow practices, while process-related technologies negatively influence low setup effects (Tortorella et al., 2019).

Cluster 5 (Purple): Overcoming Obstacles to Industry 4.0 Adoption

Smart cities are significantly influenced by environmental, technological, social, and legal challenges (Aghimien et al., 2022). In addition, the structures made of glass are capable of supplying lighting resources, solar energy, and water management. All three can be applied in the same context, namely the triple bottom line, corporate social responsibility, and Industry 4.0, to enhance the sustainable healthcare supply chain 4.0 (Daú et al., 2019). Technology infrastructure is necessary in developed nations, but in underdeveloped nations, standards and laws might be improved to encourage adoption (Raj et al., 2020). Overcoming these obstacles requires awareness campaigns, improved resource allocation, and simplified legislation to support easier transitions to Industry 4.0. Unlocking the full potential of Industry 4.0 across multiple sectors will undoubtedly require both proactive measures and technological improvements.

A Summary of the bibliographic coupling analysis is presented in Table 3, which includes cluster number and color, cluster label, number of publications, and representative publications.

Table 3. Bibliographic coupling analysis on Industry 4.0 in developing countries: emerging and future trends

Cluster color and number	Cluster label	Number of publications	Representative publication
1 Red	Global Developments and Industry 4.0 Technologies' Effects on the Environment	15	Chien et al. (2017), Y. Li et al. (2022), Chen and Kim (2023), Elheddad et al. (2021)
2 Green	Industry 4.0 Adoption and Sustainability in Developing Economies	9	Akbari and Hopkins (2022), Yadav et al. (2020), Raut et al. (2019), Bag et al. (2020)
3 Blue	Opportunities and Difficulties of Industry 4.0 Adoption in Developing Nations	8	Bogoviz et al. (2019), Chauhan et al. (2021), Luthra and Mangla (2018), Sharma et al. (2021)
4 Yellow	Implementation of Industry 4.0 in Various Economies	6	L. Li (2018). Tortorella and Fettermann (2018), Tortorella et al. (2021), Tortorella et al. (2019)
5 Purple	Overcoming Obstacles to Industry 4.0 Adoption	6	Aghimien et al. (2022), Daú et al. (2019), Raj et al. (2020)

Co word Analysis

Using the same database, three clusters were produced when 35 of the 2277 keywords displayed by the co-word analysis satisfied 19 thresholds. The terms “industry 4.0” (194 occurrences), “Industry 4” (91 occurrences), and “management” (81 occurrences) are the most often occurring keywords. Table 4 displays the top 15 keywords in the co-occurrence of keywords analysis.

Table 4. The top 15 keywords in the co-occurrence analysis

Rank	Keyword	Occurrences	TLS
1	Industry 4.0	194	600
2	Industry 4	91	425
3	Management	81	355
4	Sustainability	63	337
5	Challenges	60	306
6	Performance	75	305
7	Innovation	85	300

8	Future	58	294
9	Internet	51	283
10	Barriers	46	261
11	Impact	60	234
12	Model	47	234
13	Framework	46	232
14	Supply chain	45	221
15	Things	22	221

The network structure of co-word analysis is displayed in Figure 3. Three clusters in the artwork stand for three different subjects. The three clusters are given labels based on the author's inductive interpretation. These clusters depict three themes based on the keywords covered below.

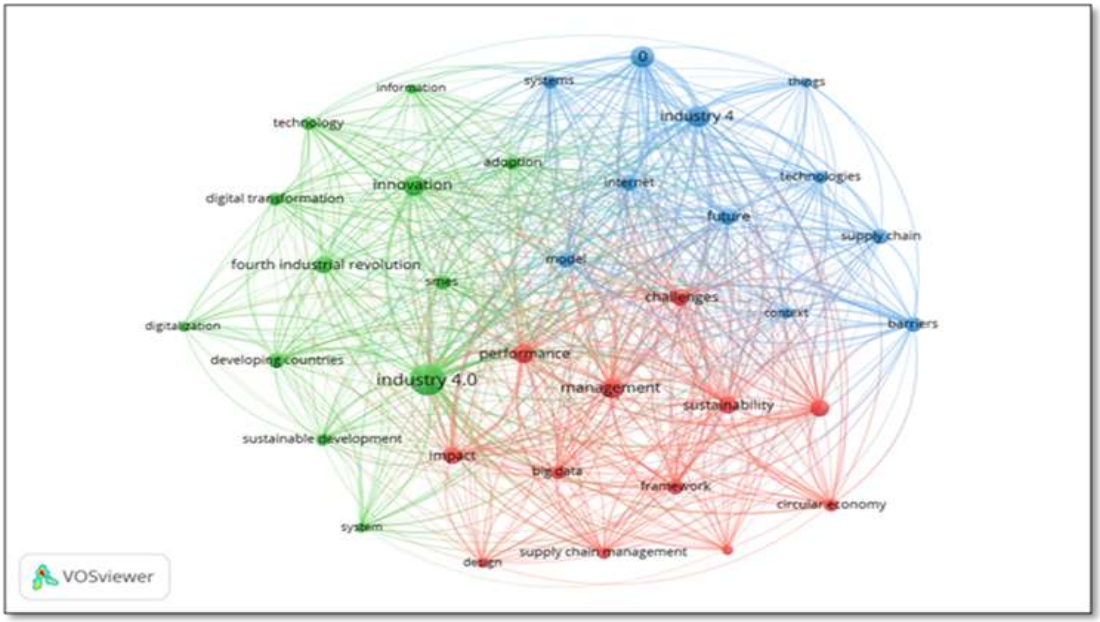

Figure 3. Analysis of co-occurrence in Industry 4.0 in developing countries, emerging, and future trends

Cluster 1 (Green): Sustainable Development and Industry 4.0

With the introduction of cutting-edge technologies like cloud computing, IoT, and cyber-physical systems (CPS), Industry 4.0 revolutionises automation and connectivity. However, a lack of clarity and defined ready frameworks makes it difficult for many firms to grasp and implement (Aghimien et al., 2022). Building on the developments of earlier industrial revolutions, the fourth one uses connected technology to combine the digital and physical worlds. It drives Innovation, changes modern life and production, and presents new opportunities and difficulties (Xu et al., 2018). A modern perspective on sustainable development highlights key global challenges, including poverty, climate adaptation, and ecological balance, emphasizing the evolving strategies and collaborative efforts to address these issues, particularly in developing nations (Elliott, 2012).

Cluster 2 (Red): Combining Industry 4.0 with Sustainability

Sustainability and Industry 4.0 encourage innovative approaches to addressing challenging sustainability issues and maximizing long-term value across various sectors. Sustainability is a multifaceted idea and promotes an integrated strategy to deal with its issues. With an emphasis on integrated reporting, it addresses the functions of reporting systems, business models, and governance (Giovannoni & Fabietti, 2013). The attitude impacts skills and task performance in fraud risk assessment for accountants amid the changing work environment due to emerging technologies. It aims to influence policy and capacity building in the public sector (Popoola et al., 2018). In order to optimize life cycle value and improve sustainability, the paper explores incorporating Industry 4.0 principles into various industries. To promote the industry's use of digital technology, it highlights research gaps and the necessity of specialist techniques (Alaloul et al., 2018).

Cluster 3 (Blue): Influence and Function of New Technologies on Sustainability, Industries, and Healthcare

Emerging technologies like IoT, AI, blockchain, and Industry 4.0 are changing healthcare, industries, and sustainability by promoting efficiency, transparency, and Innovation. The roles that IoT, Industry 4.0, AI, and blockchain play in day-to-day operations while examining their effects on healthcare, industries, and society (Tabassum et al., 2021). Blockchain and Industry 4.0 technologies are converging in reshaping business models by enhancing transparency, efficiency, and data security. Their integration brings significant developments, particularly in healthcare and supply chain management (Chand Bhatt et al., 2021). Industry 4.0's sustainability features emphasize how it affects environmental, social, and economic sustainability. Industry 4.0 tools are deployed in production, addressing issues such as managing a circular supply chain, servitization, and production planning.

Co-word analysis, including cluster number and color, cluster label, number of keywords, and sample keywords, is summarised in Table 5.

Table 5. Summary of co-word analysis on Industry 4.0 in developing countries: emerging and future trends

Cluster color and number	Cluster label	Number of keywords	Representative Keywords
1 (Green)	Sustainable Development and Industry 4.0	12	Fourth industrial revolution, Innovation, Industry 4.0, technology
2 (Red)	Combining Industry 4.0 with Sustainability	12	Sustainability, emerging economy, challenges
3 (Blue)	Influence and Function of New Technologies on Sustainability, Industries, and Healthcare	11	Industry 4, future, model, technology

DISCUSSIONS

The study has significant theoretical and managerial consequences for developing and implementing Industry 4.0 technologies, especially in developing economies. Theoretically, this study advances knowledge of how Industry 4.0 concepts impact Innovation and sustainability. This is related to cluster 3 ("Opportunities and Difficulties of Industry 4.0 Adoption in Developing Nations"). This study explores the impact of contextual factors on digital transformation, highlighting Industry 4.0's potential to foster Innovation, productivity, and sustainability while addressing sustainability issues (Alhammadi et al., 2024). The revolutionary role that Industry 4.0 technologies play in improving the performance of green Innovation through resource efficiency and sustainability. Open Innovation is an important collaborative model that significantly enhances the process of generating environmentally friendly innovations. For instance, the application of TBL (Triple Bottom Line), CE (Circular Economy), and SBMs (Sustainable Business Models) can help fix institutional challenges and help foster sustainable development in developing countries. The present work extends current theories on digital transformation by including findings on the institutional and economic constraints on integrating sophisticated technology. Theoretical impacts particularly demonstrate how Industry 4.0 technologies enable several types of creativity that incorporate TBL, CE, and SBMs to foster sustainability. To boost the SDGs' contribution, this research calls for more focus on relatively underexplored domains of innovation research that encompass marketing and organizational innovations (Alojail & Khan, 2023).

The paper also stresses the importance of managers mitigating the challenges of Industry 4.0 adoption in terms of its managerial aspects. In this way, the managers can avoid challenges such as reluctance to change, lack of experience, and poor support. Sustainable solutions involve calls for strategic investments in digital technology, collaboration ecosystems, and building the healing capacity of the nation's workforce. The similar results also underscore the significance of co-optation as well. Real sustainability improvements are realized when an organization's digital change agenda is designed to support the organization's achievement of the Sustainable Development Goals (Alojail & Khan, 2023). The study suggests that advanced analytics tools can enhance supply chain management and organizational efficiency, allowing managers to incorporate big data, machine learning, and predictive insights for flexibility. Proactive strategies address work pressure and talent retention. Organisations could enhance their performance, comprehend supply chain dynamics, and make far more precise demand predictions with the aid of real-time data or even predictive and machine learning (Agrawal et al., 2023). Organizations must address challenges like resistance, inexperience, and poor infrastructure through strategic investments in digital technology, collaborative ecosystems, and workforce development, aligning with Sustainable Development Goals for improved long-term sustainability (Alojail & Khan, 2023). The study emphasizes the potential of advanced analytics and data-driven decision-making in supply chain optimization, encouraging managers to adopt technologies like big data and machine learning. These difficulties from Cluster 3 (Opportunities and Difficulties of Industry 4.0 Adoption in Developing Nations) and Cluster 5 (Overcoming Obstacles to Industry 4.0 Adoption) are made worse in developing nations by poor acquisition of new technologies and constrained finances and infrastructure (Ayalew & Xianzhi, 2020).

Managers must adopt advanced technology like AI, Machine learning, and IoT for real-time data-driven decisions in resource-sensitive settings. Industry 4.0 promotes smooth digitization, and sound risk management strategies are essential for enhancing operational performance and meeting Quality 4.0 standards (Mohamed et al., 2019). Combining Six Sigma techniques with business 4.0 technology can enhance performance across industries by prioritizing middle management training, integrating innovative technologies, and optimizing production processes (Akanmu & Nordin, 2022). Tailored strategies that address resource limitations, foster resilience, and stimulate creativity can significantly aid developing economies.

CONCLUSIONS

The primary purpose of this study was to investigate the adoption of Industry 4.0 in developing countries by systematically identifying the barriers, opportunities, and future directions through bibliometric mapping. Industry 4.0, a technological shift enabling automation, analytics, and IoT, could remove growth constraints in developing countries, encourage Innovation, and advance sustainability. However, overcoming barriers like infrastructural, financial, and staff preparedness is crucial. Policymakers must promote investments in digital enablers and provide enabling policies and regulatory environments. Further research should investigate the applications of blockchain and AI technologies across various industries. Harmonizing these technologies with sustainable development goals could foster a robust approach. Industrialized nations have fundamental variations from developing economies regarding institutional and economic

constraints (Bogoviz et al., 2019). Another limitation is the possibility of bias from the qualitative character of the co-word analysis and bibliographic coupling employed in this investigation. The findings may not be as objective as they would be if the grouping and theme trends are subjectively interpreted.

The study focuses on broad patterns in developing countries, and not specific contextual elements. Institutional, cultural, and economic factors influence the adoption of Industry 4.0. Future studies should perform comparative analysis and examine grey literature and real-time data for a comprehensive understanding of the rapidly developing topic. If empirical studies are used in several industrial contexts, a more comprehensive view of Industry 4.0 implementation and challenges could be acquired (Ghobakhloo, 2020). Technologies that have received less attention, such as blockchain, quantum computing, and artificial intelligence, require focus to capture their disruptive nature correctly (Gökalp et al., 2017). Also, there is a need to understand how government policies and collaborations with international partners can help break down barriers to adoption, especially concerning infrastructure and end-user readiness (Ibrahim et al., 2022). However, studies on integrating Industry 4.0 with the Sustainable Development Goals remain important, as they suggest that such integration will benefit resource-deficient regions of the developing world (Mubarak et al., 2021).

Future research should extend beyond bibliometric mapping to include comparative empirical studies across developing countries, particularly in SMEs and agriculture-based industries. Mixed-method approaches that combine bibliometric, survey, and case study evidence would provide richer insights into adoption patterns and barriers. Emerging technologies such as blockchain, quantum computing, and AI also require deeper investigation to capture their disruptive potential in resource-limited contexts. Furthermore, the role of government policy and international partnerships deserves closer scrutiny to understand how coordinated efforts can overcome institutional voids and accelerate Industry 4.0 adoption.

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