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IMPLEMENTATION OF SUSTAINABILITY AND CIRCULAR ECONOMY AIMING FOR PERFORMANCE IN THE CONTEXT OF INDUSTRY 4.0 PROJECTS

IMPLEMENTAÇÃO DE SUSTENTABILIDADE E ECONOMIA CIRCULAR VISANDO O DESEMPENHO NO CONTEXTO DE PROJETOS DA INDÚSTRIA 4.0

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Abstract:
This research aims to provide an up-to-date overview of the scientific knowledge produced through publications that associate sustainability, the circular economy, and performance in the context of Industry 4.0 projects. For this purpose, a systematic and bibliometric review was conducted using articles published in the Scopus database from 2013 to 2024. Inclusion and exclusion criteria were defined, resulting in 61 selected articles. The results show that studies focus on the areas of environmental science, business, management, accounting, and engineering. Additionally, they indicate that research on these topics has grown exponentially in recent years, evolving and deepening significantly during this period. This study directly contributes to researchers seeking references, concepts, gaps, and trends in research on these topics, as well as to managers interested in implementing sustainability and the circular economy, ensuring or even enhancing the performance of their companies through disruptive projects that utilize Industry 4.0 technologies.

Keywords: Digital technologies. Sustainable performance. Sustainable development. Sustainable operations. Circular economy practices.

Resumo:
Esta pesquisa tem como objetivo fornecer uma visão atualizada do conhecimento científico produzido por meio de publicações que associam sustentabilidade, economia circular e desempenho no contexto de projetos da Indústria 4.0. Para esse fim, foi realizada uma revisão sistemática e bibliométrica utilizando artigos publicados na base de dados Scopus entre 2013 e 2024. Critérios de inclusão e exclusão foram definidos, resultando em 61 artigos selecionados. Os resultados mostram que os estudos se concentram nas áreas de ciência ambiental, negócios, gestão, contabilidade e engenharia. Além disso, indicam que as pesquisas sobre esses temas cresceram exponencialmente nos últimos anos, evoluindo e se aprofundando significativamente durante este período. Este estudo contribui diretamente para pesquisadores que buscam referências, conceitos, lacunas e tendências em pesquisas sobre esses tópicos, bem como para gestores interessados em implementar a sustentabilidade e a economia circular, garantindo ou até mesmo aprimorando o desempenho de suas empresas por meio de projetos disruptivos que utilizam tecnologias da Indústria 4.0.

Palavras-chave: Tecnologias digitais. Desempenho sustentável. Desenvolvimento sustentável. Operações sustentáveis. Práticas de economia circular.

Introduction

Organizations are gradually adopting more concepts of Industry 4.0 (I4.0) and the Circular Economy (CE) in their business practices (Luthra & Mangla, 2018). This trend is expanding and encouraging industries to improve their understanding of environmental impacts, adopt cleaner production strategies, and enhance product reuse through the adoption of digital technologies (Mwangi et al., 2021). Additionally, motivated by the interest in updating the business environment, sector managers are implementing innovative concepts and technologies such as I4.0, the Internet of Things (IoT), and the CE (Frank et al., 2019). The inclusion of I4.0 and CE practices has become essential for manufacturing organizations wishing to compete globally (Okorie et al., 2018).

I4.0 addresses innovative digital technologies as the main driver for improving companies' competitiveness. The goal of the CE concept is to achieve waste reduction through product reprocessing instead of disposal, removal of harmful chemicals, and improvement of material and product design (Okorie et al., 2018). The term CE is not recent, having emerged in the 1970s, suggesting an efficient approach to increase resource efficiency and provide stability between society and the environment (Dwivedi et al., 2020). The I4.0 and CE concepts help companies reduce pressure on natural ecosystems and achieve sustainability, environmental safety, cleaner production, manufacturing system automation, and flexible processes in their supply chains (Garetti & Taisch, 2012).

Researchers, such as Rosa et al. (2020) and Rajput and Singh (2019), have declared I4.0 and the CE as emerging technological and organizational trends that enhance sustainable company production. In this context, sustainable development is defined by Seuring and Müller (2008) as development that can preserve present resources for current use while meeting the needs of future generations. The pursuit of sustainable development in industry must be aligned with innovations that enable material transformation and reduce environmental impacts (Tseng et al., 2021). Complementing this understanding of environmental importance, there have been advances in waste management, such as the use of blockchain (Khan et al., 2021).

Blockchain technology is being applied in waste management to enhance traceability and transparency throughout the entire waste lifecycle. It enables tracking from generation to disposal, combating fraud and improper practices (Saberi et al., 2019). The immutability of data provides a robust solution for disposal and recycling records. In the context of the CE, blockchain facilitates the tracking of recyclable materials and resource reuse, promoting

sustainable practices (Upadhyay et al., 2021) highlight that technology helps overcome barriers by providing a clear view of material flow, fostering collaboration across the value chain.

Blockchain-based incentive programs are being used to reward good recycling and disposal practices. Biswas and Gupta (2019) note that these systems increase citizen and corporate engagement in sustainable waste management, while Zeng et al. (2021) show that blockchain improves logistics and efficiency in waste management. Addressing these increasingly emerging topics in society, the following research question was formulated: 'What is the current overview of publications that associate the Circular Economy, Sustainability, Industry 4.0 and Performance?' To answer this question, the present study aims to provide an up-to-date overview of publications that associate these concepts in the context of I4.0 projects. To meet this objective and answer the research question, a systematic and bibliometric literature review was conducted for the period between 2013 and 2024, based on the Scopus database.

Based on the results presented in the article, researchers will be able to identify unaddressed gaps, guiding future investigations on these topics. Similarly, organizations will have access to projects and results that can inspire new ideas, strategic actions, and guidelines to improve their performance. The use of I4.0 technologies, combined with the principles of the CE, will be essential for maximizing sustainable outcomes, promoting greater operational efficiency and a positive impact on resource management practices and waste reduction.

Profit-oriented organizations (companies) will be able to establish a strategic vision, build a consistent roadmap, and develop a portfolio of real projects aimed at achieving feasible and long-lasting results. It is also important to consider that government organizations are increasingly enacting laws with targets for the implementation of CE, such as the European Union’s Directive 2000/53 on end-of-life vehicles (ELVs).

This study is organized into six sections. Section 1 presents the context and the research question. Section 2 describes Materials and Methods. Section 3 presents the results of the final set of articles and statistical information. Section 4 addresses the concepts and themes that are the focus of this study. Section 5 offers a brief discussion of the results, and Section 6 presents the conclusion.

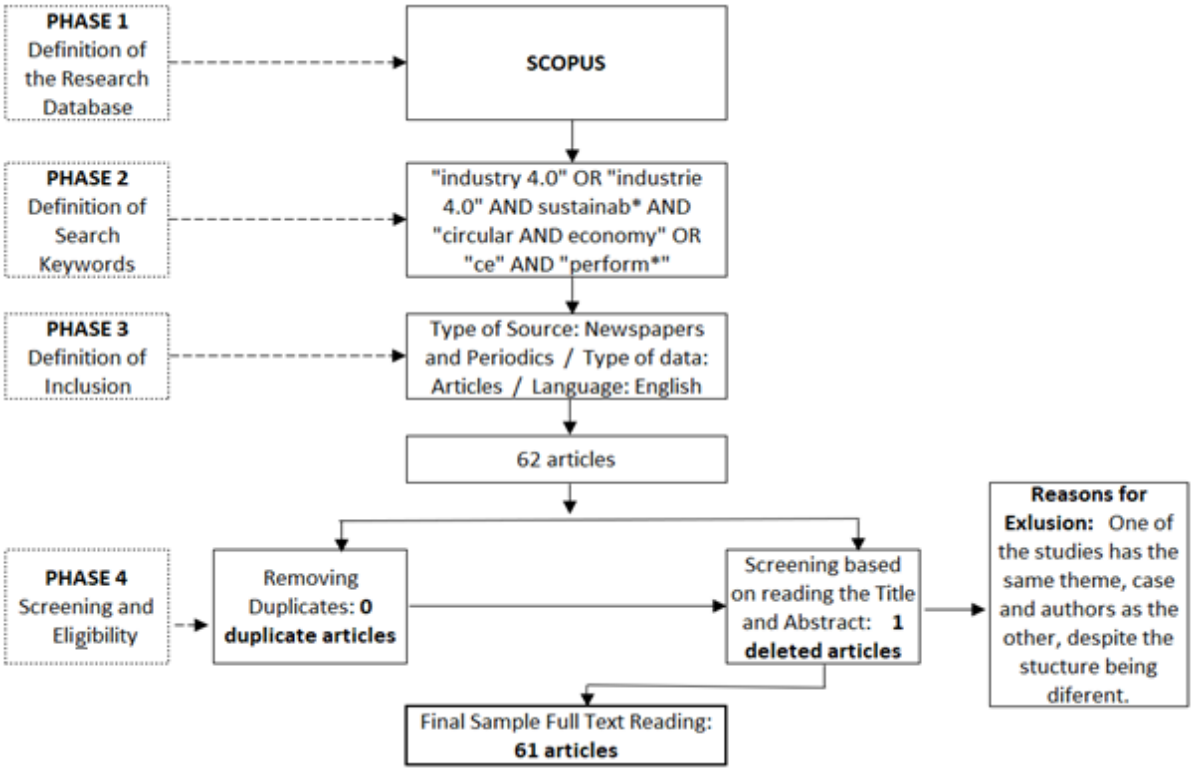
Materials and methods

This article adopts a systematic literature review and bibliometric analysis as its method (Alcântara & Martens, 2019), using the keywords "Indústria 4.0" or "Industrie 4.0", "Sustainab*", "Circular Economy" or "CE" and "Perform*". Figure 1 presents the diagram with

the flow of the systematic review adopted in this study. The scope of this work was limited to selecting only works written in the English language. Additionally, the search was restricted to articles in the final stage of publication, published in recent years, between 2013 and 2024, in the Scopus database.

Figure 1

Flowchart of the Literature Review Process



Source: Prepared by the authors.

The selection was updated until March 2024 using the following query: (Title (Industry 4.0) Or Title (Industrie 4.0) And Title-Abs-Key (Sustainab*) And Title-Abs-Key (Circular Economy) Or Title-Abs-Key (Ce) And Title-Abs-Key (Perform*)) And (Limit-To (Doctype, “Ar”)) And (Limit-To (Language, “English”)) And (Limit-To (Pubstage, “Final”)).

The approach is qualitative, as it aims to deepen the understanding of the implementation of sustainability and CE in the context of I4.0 and its influence on organizational performance. Table 1 presents the inclusion and exclusion criteria applied to the Scopus database. We developed a systematic and bibliometric analysis with the help of

VOSviewer software. This software utilized network analysis to define the main clusters, followed by content analysis to identify the primary outputs among the constructs of our study.

Table 1

Inclusion and Exclusion Criteria

Research Criteria	Inclusion Criteria	Exclusion Criteria
Database	Scopus	Other databases
Fields	Title, Abstract and Keywords	Words not present in title, abstract and keywords
Publication Period	2013 to 2024	Documents published outside this period
Document type	Article and Reviews	Other documents
Publication stage	No restrictions	No restrictions
Source	Journals	Books and Conferences
Language	English	Other languages

Source: Prepared by the authors.

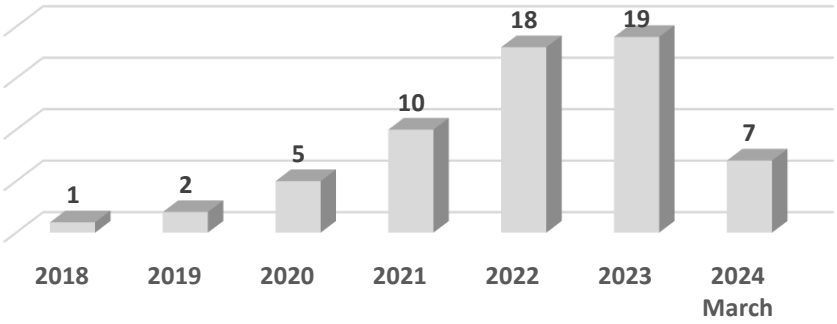
Results

After applying the inclusion and exclusion filters, the search returned 62 publications. The articles were then read for sample selection, resulting in 61 works, which were subjected to systematic and bibliometric analysis using Mendeley and VOSviewer software. Subsequently, exploratory statistical analyses were applied to characterize the sample articles and analyze the content related to the concepts.

The first result observed when applying the search string was that no articles on these themes were published until 2017. The first article was only published in 2018. As shown in the graph in Figure 2, 2022 and 2023 had the highest number of publications, with 37 articles in these two years. It is also evident that since 2018, when more specific literature on the subject began, there has been a sharp growth curve, with significant rates of 100%, 150%, 100%, and 80% for the years 2019, 2020, 2021, and 2022, respectively, repeating the same performance in 2023 as the previous year. In 2024, there is already a relevant cumulative number of publications, considering that only completed publications until March 2024 are included.

Figure 2

Number of Articles Per Year

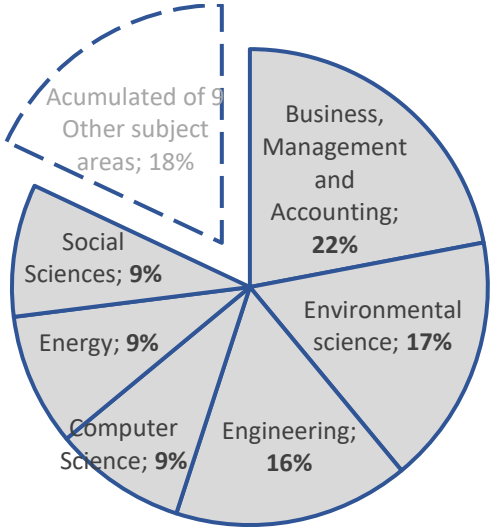


Source: Prepared by the authors with Scopus data.

However, we observed that the growth rate decreased from 2022 onwards compared to previous years when the number of publications increased more significantly. Figure 3 shows the distribution of articles by fields of knowledge, with 17% of the publications focused on Environmental Sciences, 22% on Business, Management, and Accounting, followed by Engineering at 16%, and Energy, Social Sciences, and Computer Science, each with 9%. Another 9 fields of knowledge accounted for 18% of the publications.

Figure 3

Articles Published by Field of Knowledge



Source: Prepared by the authors with Scopus data.

In Figure 4, we can observe the contributions by country for the selected articles in the research. India leads with 20 articles, representing 16% of the total studies in the area. This indicates a strong interest and focus from Indian institutions on research related to I4.0, CE, and Performance. The Indian production accounts for nearly one-third of all global publications on the topic, highlighting the country's importance in the international research landscape.

The United Kingdom follows closely with 18 articles, representing 14% of the total. The British focus on high-quality research and its academic tradition contribute to its prominent position in the literature on I4.0 and CE, with British institutions playing a significant role in studies that combine technological innovation and sustainability. France, China, and Spain also showed significant contributions, with 8, 6, and 6 articles, respectively. France, with 8 publications, represents an important research hub in Europe, while China and Spain, each with 6 articles, demonstrate growing interest and investment in sustainable technologies and CE practices.

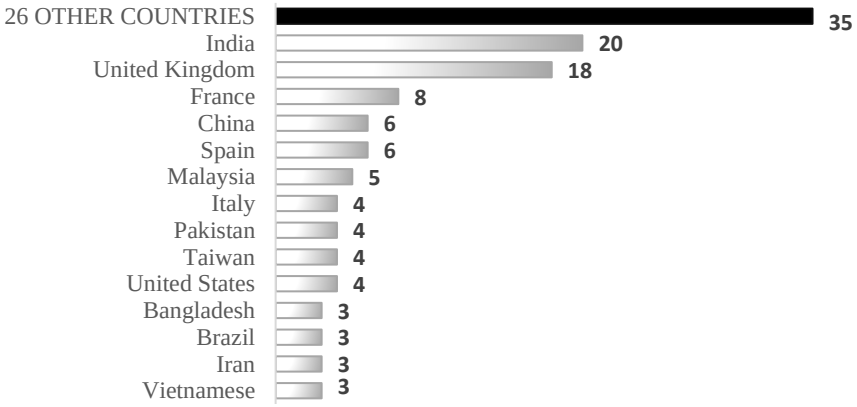
Malaysia, the United States, Taiwan, Pakistan, and Italy contributed with 4 to 5 articles each, indicating an interest in the subject, though not as dominant as the leaders. Countries like Vietnam, Iran, Brazil, and Bangladesh contributed 3 articles each. Although these contributions are smaller in number, they are important for diversifying the global perspective on I4.0 and CE. For example, Brazil has the potential to significantly expand its contributions as investments in research and development in these areas increase.

Brazil has significant scientific potential, especially in biotechnology, renewable energy, sustainable agriculture, and public health. The country’s biodiversity is a key asset, enabling the development of innovative technologies, such as those promoted by Embrapa, which contribute to the advancement of sustainable agriculture (Silva & Mendonça, 2021). In the field of renewable energy, Brazil stands out with the RenovaBio Program, focused on biofuel production, positioning the country as a global leader in clean energy. Investments in R&D could boost scientific production and patents in this area (Santos & Costa, 2020).

The National Strategy for Science, Technology, and Innovation (ENCTI) 2016-2022 sets goals to increase the number of researchers and international publications. In 2020, Brazil was the 13th largest producer of scientific publications, with room for growth through collaborations and increased investment (Clarivate Analytics, 2021; Ministry of Science, Technology, and Innovations, 2016).

Figure 4

Articles by Country

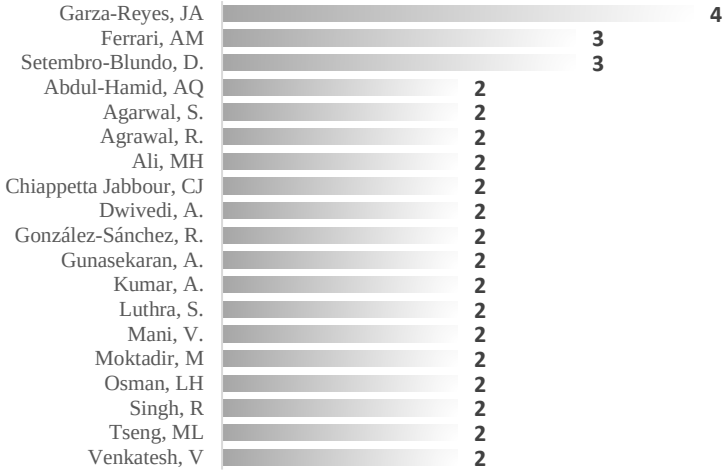


Source: Prepared by the authors with Scopus data.

Figure 5 presents the distribution of related articles by authors, where Garza-Reyes J.A., with 4 articles, is the author with the highest number of publications. Authors Anna Maria Ferrari and Davide Settembro-Blundo are just below, with a total of 3 works each. Considering the top three authors, their publications represent 16% of all works in the field, standing out as key references for their contributions in this area of study.

Figure 5

Articles by Authors



Source: Prepared by the authors with Scopus data.

In addition to the authors mentioned in Figure 5, other authors also stand out for their contributions, each with 2 publications in their respective research areas, as shown in Table 2.

Table 2

Authors Considered in the Research and Their Areas of Study

Author	Research Area
Abdul-Hamid, A.-Q.	Sustainability and energy efficiency.
Agarwal, S.	Sustainability and innovation in production processes.
Agrawal, R.	Supply chain management and logistics.
Lopes de Sousa J. A. B.	Environmental management and sustainable development.
Dwivedi, A.	Digital transformation and information technology.
González-Sánchez, R.	Technological innovation and operational efficiency.
Gunasekaran, A.	Supply chain and production management.
Kumar, A.	Operations management and sustainability.
Luthra, S.	Adoption of green technologies and sustainable practices.
Moktadir, M	Reverse logistics and sustainability in the supply chain.
Osman, L.H.	Process optimization and quality.
Sharma, M	Business ethics and corporate social responsibility.
Tseng, ML	Operations management and energy efficiency.
Venkatesh, V.	Information systems and technology.

Source: Prepared by the authors.

In analyzing the journals in which the articles considered in this study were published, the distribution is presented in Table 3. The Journal of Cleaner Production stood out with the highest number of publications, totaling 9 articles. This number represents a significant portion of the total publications analyzed. With an impact factor of 10.96, this journal is one of the leading platforms for disseminating research related to clean production, sustainability, and the circular economy.

In addition to the Journal of Cleaner Production, other journals also had relevant participation, each with a focus on their respective areas of specialization:

- Business Strategy and the Environment: With 7 publications, this journal addresses business strategies that promote environmental sustainability, being an important source for studies that intersect CE and sustainable management.
- Sustainability (Switzerland): With 6 published articles, this journal focuses on interdisciplinary research on sustainability, covering a wide range of topics from public policies to sustainable business practices.
- Production Planning and Control: Published 4 articles, concentrating on issues related to production planning and control, with an emphasis on efficiency and optimization of industrial processes.

- Technological Forecasting and Social Change: Also with 4 publications, this journal examines the interactions between technological advances and social changes, contributing to the understanding of the impact of I4.0 technologies on society and sustainability.
- Computers and Industrial Engineering: With 3 articles, this journal explores the application of computing and industrial engineering to improve the efficiency and effectiveness of production systems.
- Operations Management Research: Also with 3 publications, it focuses on research on operations management, addressing topics from logistics to the implementation of advanced technologies.
- Resources, Conservation and Recycling: With 3 articles, this journal makes relevant contributions to studies on natural resource management, recycling, and conservation, strongly aligning with the principles of the circular economy.

Table 3

Articles by Journal

JOURNAL	ARTICLES		
	Qtd	Cum	Part.
Journal of Cleaner Production	9	9	15%
Business Strategy and the Environment	7	16	26%
Sustainability (Switzerland)	6	22	36%
Technological Forecasting and Social Change	4	26	43%
Resources, Conservation and Recycling	3	29	48%
Computers and Industrial Engineering	3	32	52%
Operations Management Research	3	35	57%
International Journal of Production Economics	2	37	61%
Benchmarking	2	39	64%
BioResources	1	40	66%
Engineering Economics	1	41	67%
Social Sciences	1	42	69%
Frontiers in Psychology	1	43	70%
Environmental Science and Pollution Research	1	44	72%
Philosophical Transactions of the Royal Society A	1	45	74%
Industrial Robot	1	46	75%
Other Publications	15	61	100%

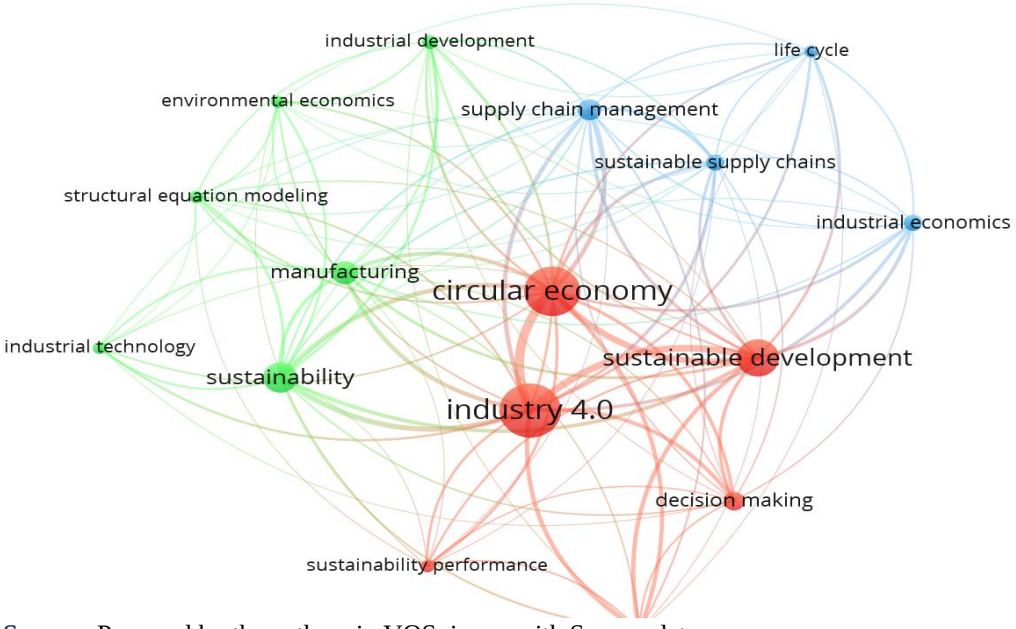
Source: Prepared by the authors using Scopus data.

The analysis of the journals where the articles were published reveals a diversity of theoretical and methodological approaches, as well as the broad relevance and interest in the topic across different fields of knowledge. The predominance of publications in high-impact journals, such as the Journal of Cleaner Production, highlights the quality and importance of research conducted in the field of sustainability and CE in the context of I4.0. This study provides a comprehensive view of the main research sources and underscores the continuous need to explore and integrate new disruptive technologies to promote more sustainable and efficient industrial development.

Using VOSviewer software, based on the network of 61 articles extracted from the SCOPUS database, the visualization of the connection network of terms found in titles and abstracts was performed, as shown in Figure 6. The thinner the connection lines (edges), the weaker the connection. Additionally, the larger the points (nodes), the more relevant the terms. This graph groups the terms into clusters, which are formed by affinity or proximity. A direct and strong connection is observed between the terms I4.0, CE, and sustainable development, suggesting a complementary dependency and synergy between the themes supported by the triple bottom line concept.

Figure 6

Network Map of Link Occurrences of Words in Titles and Abstracts



Source: Prepared by the authors in VOSviewer with Scopus data.

The analysis of the articles considered the occurrence of a term at least 10 times for it to be represented in the connection network. This was the main criterion in the analysis, revealing the existence of three clusters, formed by the colors red, green, and blue, as shown in Figure 6. The red cluster, composed of six terms, upon more detailed analysis of the articles within this cluster and their respective associations, showed that the correlation between the terms led to similarities in themes and propositions, regardless of the segment of activity. This cluster clearly identified opportunities and the need for updates, but also pointed out that it is necessary to overcome basic premises identified as barriers and challenges.

In the green cluster, composed of six terms too, we observe an evolution compared to the red cluster. The basic premises mentioned in the red cluster are not identified here, indicating that this cluster is at a more advanced stage regarding the application of I4.0 concepts and technologies. This cluster even points to the CE as a reference element related to performance, which is also considered a benchmark for implementing the set of I4.0 concepts, technologies, and practices.

The third cluster, in blue, with four terms, highlights issues of sustainable activity performance. It no longer segregates sustainable actions as complementary competitive differentiators but incorporates them into issues of feasibility or even the continuity of certain industrial and business practices. When this combination is used correctly, the results tend to be not only positive but also lasting and potentially replicable.

This trend has been generating competitive differentials that, in some moments or situations, are determining factors in performance. More importantly, in the medium and long term, these characteristics are necessary to propose growth plans, expansion, and investments for the consumer market and investors. Adopting sustainable practices goes beyond an ethical or social responsibility issue, directly impacting the long-term success of organizations. When sustainability is integrated into operations, it contributes to the creation of economic, social, and environmental value, resulting in competitive advantages. Porter and Kramer (2011) highlight that companies incorporating sustainability into their strategies can reduce costs, innovate in products, and capture new market opportunities.

Moreover, sustainable practices improve corporate reputation and strengthen relationships with stakeholders, leading to greater customer loyalty and attracting investors. The adoption of a CE, for example, helps reduce waste and maximize resource utilization, increasing operational efficiency and decreasing environmental impact (Geissdoerfer et al., 2017). This reinforces the idea that sustainability can drive innovation and business growth.

Sustainable practices also offer resilience in times of crisis, as companies that adopt them are better prepared to manage environmental and social risks. This improves their ability to adapt to market changes, strengthening long-term performance (Carter & Rogers, 2008). Therefore, sustainability, in addition to being an increasing demand, is a key factor for the continuity and success of organizations.

Exploring concepts of the main themes

Sustainability

Sustainability is structured around three pillars, also known as the Triple Bottom Line (TBL), which are: (1) economic, (2) environmental, and (3) social. Along with these pillars, the concepts of the 6Rs are also considered, which include the activities of reduction, reuse, recycling, redesign, recovery, and remanufacturing (Jayal et al., 2010). In addition to these initial sustainability concepts, Cleaner Production (CP) stands out as a way to increase consumption efficiency and reduce and recycle waste at all stages of production and operation. By considering CP in their production processes, organizations better evaluate their manufacturing phases: (1) the use of resources and their quality, (2) the energy consumed, transportation, and shipping to transfer products from manufacturing to distribution, (3) the use of recyclable product packaging, and (4) how the product will be recycled at the end of its lifecycle (Mantovani et al., 2017; Ramos et al., 2018).

To be considered sustainable, products need to be manufactured using environmentally friendly processes, socially viable practices, and economically sound methods. Production systems based on ethical and sustainable manufacturing processes are highly efficient in saving energy and natural resources. The well-directed use of digitization tools can make manufacturing processes more efficient and sustainable, as it also improves quality control (Shivajee et al., 2019).

Research on sustainability worldwide aims to understand this phenomenon in various segments, such as Kumar et al. (2020) study on small and medium enterprises (SMEs) in developing countries like India. This study indicated that these organizations are unable to ensure the operations of manufacturing processes due to the high cost of sustainable practices, lack of skills and training, lack of standardized metrics, and lack of adoption of emerging technologies.

According to Beier et al. (2020), I4.0 is a sociotechnical construct that integrates technological, social, and organizational perspectives. The connection between sustainability and I4.0 needs to be deepened, given the potential for energy savings, scrap reduction, and reduced environmental impact, steering the industrial value chain towards sustainability (Fatimah et al., 2020). An important point is the transparency of operations as a challenge for sustainable and ethical services. Developing countries face challenges in ensuring operational transparency due to the lack of IT infrastructure, poor organizational culture, lack of legislation, and insufficient application of advanced technologies (BRICS Business Council, 2017).

Researchers like Rosa et al. (2020) and Rajput and Singh (2019) emphasize I4.0 and the CE as emerging technological and organizational trends that enhance sustainable company production, where sustainability goals increase the importance of using I4.0 technologies (Umar et al., 2021).

Circular economy

CE aims to optimize the use of resources and eliminate waste (Ramos et al., 2018). Despite organizations intending to adopt concepts that contribute to achieving sustainability, there are obstacles, mainly the lack of capacity to take initiatives that aim to update technological processes and thus become more competitive in a globalized market (Enyoghasi & Badurdeen, 2021). Conceptually, the CE seeks to improve remanufacturing, reuse, and recycling operations as a way to address the natural resource scarcity created by the linear approach (produce, consume, discard). Adopting CE offers a significant business opportunity, as it is expected to benefit European countries by 1.8 trillion euros alone by 2030 (Bressanelli et al., 2018).

Organizations are increasingly shifting from a linear economy model to the new circular economy model. Adopting the CE concept by SMEs can provide them with emerging business opportunities (Mura et al., 2020). According to Lieder and Rashid (2016), organizations must adopt CE principles to be sustainable in their operations. Technologies can also help organizations achieve CE goals (Prieto-Sandoval et al., 2019; Rosa et al., 2020).

According to Machado et al. (2019), a modern business environment, organizations must pursue the CE model and utilize technologies to achieve ethical and sustainable values, not just for profit. It is important to balance different operational perspectives, ensuring long-term growth with ethical, sustainable, and transparent business models without exploiting

human values. Therefore, with greater attention to the CE, organizations have started to seek innovative and sustainable technologies (Kumar et al., 2019).

CE includes different practices such as circular purchasing, which is linked to cooperation with suppliers and the purchase of materials that can be easily remanufactured and recycled (Khan & Yu, 2020; Muranko et al., 2019). Circular design facilitates reverse logistics and green manufacturing and is linked to the design and manufacture of products or materials in a way that produces less emission damage and waste (Dumée, 2021; Khan et al., 2021).

The CE approach significantly improves resource use and offers economic and environmental benefits (Geissdoerfer et al., 2017). I4.0 and CE are hot topics right now, as these concepts have supported significant growth and have gained considerable attention in recent years (Awan et al., 2021). Many studies show the relationship between the impact of I4.0 on CE (Kumar et al., 2021; Razzaq et al., 2021; Massaro et al., 2021). This includes managing the entire supply chain process, which essentially comprises the stages of procurement, manufacturing, design, and product delivery, using various I4.0 technologies such as cloud computing, AI, IoT), and blockchain (Ranta et al., 2021).

Industry 4.0 and performance

The concept of I4.0 was initiated in 2011 by the German government (Roblek, 2016). I4.0 technologies have played a crucial role in achieving higher levels of accuracy, precision, and movement with a focus on automation (Thames & Schaefer, 2016). These technological advancements are integrated between equipment and humans (Gupta et al., 2021; Jabeen et al., 2020). With increasing global competition in an international industrial network, it is essential to investigate the challenges of this sector in the I4.0 era (Mishra et al., 2019). Organizations must also consider ethics, along with social, economic, and environmental measures, in conjunction with operations for sustainable growth (Guarnieri & Trojan, 2019).

Among the I4.0 technologies are IoT, cloud computing, additive manufacturing, cybersecurity with blockchain, augmented reality with IA, big data, system integration, simulation, and autonomous robots (Kerin & Pham, 2019; Gurtu & Johny, 2019). For example, the use of blockchain alone can help industrial companies create green systems and products that promote the processes of reuse, recycling, and management of circularity outcomes (Mubarik et al., 2021).

The application of I4.0 technologies can provide a positive direction for corporate social responsibility and sustainable operations (Kamble et al., 2020; Luthra & Mangla, 2018).

According to Battaglia et al. (2018), the experience of organizations in the global market will aid in acquiring technologies and innovating their processes. The implementation of technologically advanced sustainable practices provides a competitive advantage to industrial organizations in developed economies (Yadav et al., 2020; Mastos et al., 2021). I4.0 technologies will help transition from a linear to a CE (Garcia-Muiña et al., 2018). Advanced Industry 4.0 practices can reduce costs, improve sustainability, and make products customizable for customers (Turner et al., 2019; Machado et al., 2019). Research with SMEs suggests that I4.0 can improve communication, information flow, and help achieve efficient processes and cost reduction (Linder, 2019).

With I4.0, machines can communicate, collect information, and make informed decisions by gathering real-time data through tools like IoT, AI, big data, and cloud computing (Dutta et al., 2020; Tiwari & Khan, 2020). Customers demand and product inquiries can be collected in real-time using smart technologies. I4.0 technologies will aid in effective product lifecycle management in the CE era (Zhou et al., 2020; Bag et al., 2020). Therefore, to provide a new innovative environment in the industry, managers need to adopt and implement the latest technologies, including 3D printing, IoT, and cyber-physical systems (Almada-Lobo, 2015; Song & Wang, 2018).

Countries like Australia, China, and Thailand are also working on adopting I4.0 technologies (Orzes et al., 2020), as manufacturing processes can be made efficient and sustainable through the effective use of process digitization and quality control tools (Shivajee et al., 2019). Ghobakhloo (2020) noted that the effectiveness of I4.0 technologies, production efficiency, process innovations, and sustainability can be improved. To survive and excel in the current business landscape, SMEs need to implement emerging technologies for sustainable growth (Kumar et al., 2015).

The use of I4.0 is recognized as a vital enabler of the circular economy in companies (Ranta et al., 2021). By utilizing smart sensors, intelligent machines, and devices, efficiency and resource quality are enhanced (Umar et al., 2021), making the system flexible and efficient, and increasing the supply chain's capability in information sharing, coordination, response, and integration. This manages the entire supply chain process, from production to logistics operations.

For SMEs, I4.0 also facilitates the integration and sharing of information within the supply chain, improving coordination and traceability. This enables a faster response to demand changes and better resource management throughout the entire production cycle (Umar et al.,

2021). In this way, I4.0 becomes a viable tool for implementing CE practices in small businesses. The adoption of I4.0 is crucial for increasing the competitiveness of SMEs, as it optimizes processes and helps turn environmental challenges into business opportunities. This not only facilitates adaptation to new regulatory requirements but also creates economic and environmental value in a sustainable way (Ranta et al., 2021). Therefore, technology emerges as a strategic differentiator for SMEs in the CE landscape.

Incomplete implementation of sustainable and innovative technical processes can impact the performance of organizations, especially SMEs (Shashi et al., 2019). Radziwon et al. (2014) found that I4.0 technologies can help improve sustainability and operational efficiency. By applying emerging technologies, SMEs can increase productivity, flexibility, responsiveness, and environmental performance (Pedersen et al., 2016). Kumar et al. (2014) noted that SMEs face challenges in managing their supply chains due to a lack of effective strategies using I4.0.

Digital practices can significantly contribute to sustainability by reducing the carbon footprint, utilizing renewable energy, and providing suitable technological solutions for individuals and society (Kumar et al., 2020). The evolution of I4.0 assists in the optimized use of resources more transparently (Dutta et al., 2020). Implementing I4.0 practices can improve productive efficiency and innovation, influencing social and environmental sustainability (Ghobakhloo, 2020; Bag et al., 2021).

I4.0 technologies have played a significant role in achieving higher levels of accuracy, precision, and movement towards automation (Thames & Schaefer, 2016), transforming economic and organizational performance. Authors observed that the lack of motivation from partners and customers in applying I4.0 technologies is the main challenge. The fear of failure of I4.0 technologies is the principal concern among affected groups. The study's conclusions will help SMEs formulate strategies for implementing I4.0 technologies for ethical and sustainable business processes (Kumar et al., 2020).

Using I4.0 increases transparency and traceability, ensuring product validity and legitimacy (Centobelli et al., 2021). Pal and Yasar (2020) analyze how green supply chain practices and information technology (IT) skills affect a company's environmental, economic, and operational performance. The results indicated that operational and technological competencies increase market competitiveness and sales, positively impacting profitability.

According to Tang et al. (2022) blockchain technology plays an important role in incorporating CE practices to improve environmental, economic, and organizational

performance. According to Fatima et al. (2021) and Kazancoglu et al. (2018), consumers preferred low-carbon products after this green revolution and are more willing to pay more for green products. Studies confirm that CE practices increase a company's profitability, while green practices (Zhu & Li, 2021) enhance environmental sustainability but increase material costs, which can affect economic performance.

Discussion

The research reveals that recent studies on the implementation of sustainability and CE in the context of I4.0 projects have concentrated on several areas, primarily Environmental Science, Business, Management, Accounting, and Engineering. Additionally, many new studies have emerged in these fields. Another noteworthy point is that India and the United Kingdom have a considerable number of works, indicating that these countries are leaders in scientific production on the mentioned topics.

The United Kingdom, on the other hand, has a long tradition of academic excellence and industrial innovation, which enables it to be a pioneer in research related to the CE and sustainability. The UK Industrial Strategy and the CE Package are examples of policies that encourage the transition to a more sustainable and resilient economy, integrating I4.0 as a key enabler (Govindan & Hasanagic, 2018). Continuous investment in research and development and collaboration between universities and industries create a favorable environment for technological advancements that promote sustainable growth. Both countries recognize that the integration of I4.0 and the CE is crucial for addressing global challenges such as resource scarcity and climate change.

The combination of advanced technologies with sustainable production models is seen as a long-term competitive strategy. According to Bocken et al. (2017), the CE combined with digitalization offers significant opportunities to innovate in processes and products, improving efficiency and reducing environmental impacts. This positions both India and the United Kingdom at the forefront of solutions for sustainability in the context of I4.0.

Furthermore, the authors Anna Maria Ferrari and Davide Settembro-Blundo are the researchers who have most contributed to the literature on this subject, which is the focus of this review. The journals Journal of Cleaner Production, Business Strategy and the Environment, and Sustainability (Switzerland) are the main journals publishing most of the works in this area. Anna Maria Ferrari and Davide Settembre-Blundo have made significant contributions in the field of I4.0, sustainability, and the CE, focusing on how these areas interact

to enhance the competitiveness and efficiency of companies. In their studies, they demonstrate how digitalization, combined with circular practices, can reconfigure production processes to reduce environmental impacts and improve resource efficiency. The integration of tools such as life cycle assessment (LCA) and eco-engineering helps companies monitor and optimize material use, minimizing waste and boosting the circular economy (Ferrari et al., 2021; Settembre-Blundo et al., 2018).

Moreover, Ferrari and Settembre-Blundo explore how I4.0 can facilitate companies' transition from a linear to a CE by incorporating technologies like the IoT and big data. These technologies increase organizational resilience and enable a systemic approach to managing supply chains, promoting the reduction, reuse, and recycling of materials (Settembre-Blundo et al., 2021). The authors' work highlights the importance of integrating sustainability and digital innovation to create more competitive and environmentally responsible business models.

The journals Journal of Cleaner Production, Business Strategy and the Environment, and Sustainability (Switzerland) are the leading publications that feature most of the work in this area. The Journal of Cleaner Production is a key reference for topics such as I4.0 and the CE, addressing the integration of digital technologies to enhance resource efficiency and reduce waste. The journal frequently explores how digitalization and automation facilitate the transition to cleaner and more sustainable production practices (de Sousa Jabbour et al., 2018). Its interdisciplinary approach makes it essential for understanding the application of emerging technologies in industrial sustainability.

Business Strategy and the Environment stands out for examining how I4.0 can serve as a strategic advantage for implementing the CE. The journal focuses on the alignment between sustainable innovation and business competitiveness, analyzing how companies can respond to social and regulatory pressures with green strategies (Dangelico & Pujari, 2010). It contributes to understanding how sustainable practices can generate economic value and competitive advantage.

Lastly, Sustainability (Switzerland) takes a broad approach and concentrates on how technologies like IoT and big data can drive the CE. The journal publishes studies discussing how these technologies optimize production processes and minimize environmental impacts, with a focus on integrating sustainable business models (Moktadir et al., 2020). It offers a holistic view of how digitalization can support sustainability across various sectors.

Analyzing the number of publications over the last 10 years, it is evident that studies associating I4.0, sustainability, the CE, and performance are recent, emerging from 2018 and

growing considerably in recent years. The selected articles rarely mention the word "performance," as do other non-selected articles. However, it was found that the themes of I4.0, CE, and sustainability address the issue of results or even the internationalization of organizations, which is somewhat related to performance. Since performance is a topic already characterized in the literature as a financial and profitability indicator, it is understood that this might be why it has been less used in the context of CE and sustainability.

Table 4 summarizes and groups the theoretical and practical contributions identified based on the articles in the sample studied.

Table 4

Contributions of the Evaluated Articles

	I - Theory	II - Practice	III - Theory + Practice
DEFINITION	Added value to existing theories, enriching current thoughts not necessarily by introducing entirely new concepts, but through significant contributions that have the potential to influence and transform the already established theoretical framework.	The utilization of concepts and theories in case studies and practical scenarios allowed for concrete results and the analysis of the effects of these applications. This approach not only validates the proposed theories but also provides insights into how these theories can be adapted or improved to face real challenges and positively influence the study area.	Integration of theoretical validation with practical application, observing the respective developments and necessary adjustments. This collaborative approach allows not only testing theories in real contexts but also adapting them as needs arise, optimizing results and the effectiveness of the proposed solutions.
CONTRIBUTIONS	The need to share information has been identified as essential for resource optimization and agile, sustainable implementation of I4.0 (Dutta et al., 2020; Tiwari & Khan, 2020). This process requires effective communication between departments and complete system integration, ensuring that all parts of the organization can access crucial data for quick decisions. The main goal is to facilitate a technological transition that not only improves operational efficiency but is also ecologically sustainable and economically viable (Ghobakhloo, 2020; Bag et al., 2021).	The demonstration of the compatibility of new technologies with humans highlighted that, although technology and processes are essential tools, the human role is indispensable. It emphasized the importance of integrating technology in a way that complements and amplifies human capabilities rather than replacing them, ensuring that technological innovation serves as a support to human work, and not as a substitute (Kumar et al., 2019; Gupta et al., 2021; Jabeen et al., 2020).	Decision-making by managers is based on theories, fundamentals, and recommendations that not only allow for practical application but also facilitate adjustments and the identification of new gaps needing improvement. This dynamic process of application and review enriches managerial practice, leading to the continuous evolution of strategies and the improvement of operations and organizational effectiveness (Tang et al., 2022; Kumar et al., 2020; Kamble et al., 2022).

	I - Theory	II - Practice	III - Theory + Practice
CONTRIBUTIONS	The main challenges for implementing I4.0 and CE have been listed. Even well-established models like Lean need to be adapted. The transition from a linear to a circular chain and the respective risk mitigation must be addressed (Okorie et al., 2018).	Decision-makers used frameworks and theoretical foundations to guide their actions. This structured approach allowed them to apply solid concepts in their decisions, ensuring that the choices made were aligned with best practices and available theoretical evidence (Mani et al., 2021; Zhou et al., 2020; Bag et al., 2020). Barriers to I4.0 and CE include operational challenges, the need to accelerate operations, and cost reduction (Chiappetta Jabbour et al., 2022).	
	The performance benefits of integrating I4.0 and CE have been presented. This includes criteria for selecting suppliers and partners, and their importance throughout the entire chain. It also discusses the dynamic capabilities that can be developed and how to position I4.0 and Sustainability as a strategic action (Kumar et al., 2020).	Based on theories and studies, managers formulate policies for implementing I4.0 according to the principles of the CE (Almada-Lobo, 2015; Song & Wang, 2018). Evidence of productivity improvements, and consequently performance, with I4.0 technologies in the context of CE techniques (Rosa et al., 2020; Rajput & Singh, 2019). Small, and medium enterprises can benefit from using I4.0 in their processes (Kumar et al., 2020; Dutta et al., 2020). Different production models, such as lean or clean, combined with I4.0, have a positive impact on the CE (Abdul-Hamid et al., 2022).	The propositions were confirmed through field tests, complemented by a solid theoretical base. This process not only validated the initial hypotheses but also enriched theoretical understanding, providing a more robust and applicable view of the theories in a practical context (Umar et al., 2021; Ranta et al., 2021).
		Foundation for implementing I4.0 concepts, technologies, and practices to simultaneously achieve financial and sustainability goals (Shashi et al., 2019).	The adoption of I4.0 has led to sustainable production practices that have further improved national performance on relevant SDGs, especially in developed countries (Abdul-Hamid et al., 2022).

	I - Theory	II - Practice	III - Theory + Practice
CONTRIBUTIONS	Research gaps have been identified for Industry 4.0 to contribute to sustainability goals (Chiappetta Jabbour et al., 2022). Guidelines have been developed for companies seeking to achieve sustainability goals by integrating Industry 4.0 practices, emphasizing the importance of adopting technologies that promote energy efficiency, emission reduction, and waste minimization (Abdul-Hamid et al., 2022). The guidelines recommend implementing intelligent systems such as IoT, AI, and advanced automation, which allow precise monitoring and control of production processes. Continuous training in new technologies and sustainable methods is also vital to keep the team updated and engaged with the company's goals. Additionally, it is essential to cultivate an organizational culture that values sustainable practices, encouraging innovation and environmental responsibility among employees (Kumar et al., 2020).	Application of mathematical models for simulations and finding better solutions, with a focus on the structural equation method, which is widely used in these research projects (Mani et al., 2021; Zhou et al., 2020; Bag et al., 2020). The demonstration of the compatibility of new technologies with humans emphasizes that, despite technologies and processes being essential tools, the human element remains indispensable (Walter Colombo et al., 2021). This analysis shows that technological innovations should be designed and implemented to complement and amplify human skills, not replace them. The focus is on creating systems where technology serves to increase efficiency and productivity, but where critical decisions, creativity, and empathy still intrinsically depend on the human touch. This balance ensures that technology is an ally of the worker, contributing to a more productive and satisfying work environment (Gupta et al., 2021; Jabeen et al., 2020).	The identification of opportunities highlighted in the literature allowed for the application of recommendations with necessary adjustments, resulting in consistent and reliable outcomes. This approach, which integrates theory and practice, enabled not only the validation of the proposed strategies but also their optimization for specific contexts. Thus, application informed by previous studies and adapted to local conditions proved to be an effective methodology for achieving tangible and lasting improvements (Khan & Yu, 2020; Mubarik et al., 2021).

Source: Prepared by the authors

The research reveals a strong synergy between I4.0 practices and the CE, where technologies such as IoT, blockchain, and automation enable efficient resource management and waste reduction. Companies that adopt these innovations not only improve operational efficiency but also significantly reduce environmental impacts, positioning themselves competitively in markets that value sustainability. The adoption of CE and sustainable practices is directly linked to better long-term outcomes, reducing costs, promoting innovation, and capturing new market opportunities. This highlights sustainability as not only a moral responsibility but also a business necessity, offering better financial results and a stronger market position for companies that integrate these practices.

However, SMEs face challenges such as high costs, lack of experience, and inadequate infrastructure, especially in developing countries. The research recommends investment in advanced technologies and collaboration between industries, academia, and governments to overcome these barriers, along with public policies that encourage the adoption of sustainable practices, as seen in countries like the UK and India. For researchers and professionals in project management, this topic is highly relevant as it highlights the need to develop technological solutions that combine innovation and sustainability. Integrating I4.0 and CE into projects can transform how resources are managed and processes optimized, which is crucial for success in a market increasingly driven by efficiency and environmental responsibility.

Final remarks

The study identified areas where the implementation of sustainability and the circular economy in the context of I4.0 projects has been applied objectively, providing an overview of related research over the past 10 years. Despite advancements, studies applying these concepts are still in their infancy, primarily focusing on models, frameworks, and exploratory analyses. One gap identified in this study is the need for a more detailed search for performance, encompassing synonyms or related terms. Given that I4.0 is a broad topic, focusing on specific technologies could represent a valuable opportunity for future research.

The selected articles mention the word "performance" infrequently. However, it was observed that the themes of I4.0, the CE, and sustainability often address issues of results or internationalization of organizations, which are somewhat linked to performance. Performance is frequently characterized in the literature as a financial and profitability indicator, which may explain its lesser emphasis in the context of the circular economy and sustainability. Table 4 in the study highlights theoretical and practical contributions based on the analyzed articles.

Studies applying I4.0 concepts are still in the early stages, predominantly focusing on models, frameworks, and exploratory analyses. Currently, the most highlighted technologies in this field are IoT and blockchain, indicating a concentration of interest and development in these areas. This initial phase suggests that there is ample room to explore and integrate other disruptive technologies, such as artificial intelligence, advanced robotics, and big data analytics, expanding the scope and depth of I4.0 applications in various sectors.

Interest in the topic has grown significantly over the past five years. This work can serve as a foundation for researchers in the field, offering initial guidance in identifying key references and contributing to the construction of future empirical research. The research revealed that recent studies on the implementation of sustainability and CE in the context of I4.0 primarily focus on Environmental Science, Business, Management, Accounting, and Engineering, with new areas continuously emerging.

Among the research gaps identified in this study, the need for a more detailed search on performance, including synonyms or related terms, stands out. Another gap would be focusing on specific I4.0 technologies, assessing which of them are receiving greater attention in projects and which have the most potential to drive the CE. Few references have addressed artificial intelligence or robotics, or even the use of augmented reality to enhance industrial projects that could expand CE and mitigate the risks of a linear process.

In conclusion, this study demonstrates that while the field is still developing, there is significant potential for future research that integrates sustainability and CE in the context of I4.0. Emerging technologies offer opportunities to expand the impact and application of these concepts, contributing to more sustainable and efficient industrial development.

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