The Integration of Industry 4.0 and Sustainable Development: Trends, Networks, and Future Research Directions

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Endüstri 4.0 ve Sürdürülebilir Kalkınmanın Entegrasyonu: Trendler, Ağlar ve Gelecekteki Araştırma Yönleri	The Integration of Industry 4.0 and Sustainable Development: Trends, Networks, and Future Research Directions

Öz

Bu araştırmanın temel amacı, Endüstri 4.0 ve sürdürülebilir kalkınma arasındaki ilişkiyi ele alan çalışmaların kapsamlı bir özetini sunmaktır. Çalışma, literatürün durumunu, coğrafi dağılımını, etkili çalışmaları, üretken yazarları, ana eğilimleri ve araştırma boşluklarını analiz etmektedir. Konunun entelektüel çerçevesini incelemek ve ortaya çıkan araştırma eğilimlerini belirlemek için kelime kümeleme analizi ve anahtar kelime eş zamanlılık analizi kullanılarak bir bilim haritalaması yapılmıştır. Veriler, 2017-2024 yılları arasında İngilizce olarak yayınlanmış 653 bilimsel makaleyi içeren Web of Science akademik veri tabanından toplanmıştır. Bu makale, büyük akademik ve toplumsal öneme sahip bir konunun durumunu özetlemekte ve gelecekteki araştırmalara rehberlik edecek değerli bir çerçeve sunmaktadır.

Abstract

The main purpose of this research is to provide a comprehensive summary of studies addressing the relationship between Industry 4.0 and sustainable development. The study analyzes the status of literature, its geographical distribution, influential studies, productive authors, main trends, and research gaps. A science mapping was carried out using word cluster analysis and keyword co-occurrence analysis to examine the intellectual framework of the subject and identify emerging research trends. Data were collected from the Web of Science academic database, encompassing 653 scientific articles published in English between 2017 and 2024. This article summarizes the status of a subject of great academic and societal importance and provides a valuable framework to guide future research.

1. Introduction

Industry 4.0 (I4.0) is a paradigm shift aimed at fundamentally changing production by digitizing all processes and increasing automation technology in manufacturing. This change has been a topic of significant discussion for over a decade among researchers in academia, practitioners in the industry, and policymakers. Recently, there have been views suggesting that profound changes in production directly and indirectly interact with sustainable development goals, complementing each other in many respects. Industry 4.0 has been observed to play a pivotal role in enabling the transition to sustainable development practices. Understanding the relationships between Industry 4.0 and

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regional sustainability, which benefits society, is quite significant for practitioners (Bai and Sarkis, 2017). The opportunities that Industry 4.0 offers for sustainable development are substantial; however, further theoretical and practical studies are needed to fully realize this potential.

The effects of Industry 4.0 technologies on social sustainability are being discussed in regional development processes, focusing on economic factors such as efficiency, environmental aspects like the effective use of natural resources, and the provision of social welfare. In the study by Stock and Seliger (2016), Industry 4.0 is acknowledged for its considerable ability to generate lasting value when viewed through the perspective of the triple bottom line (TBL). In the efficient use of digital technologies in Industry 4.0, it is essential to consider regional dynamics and sustainable development goals. Achieving a sustainable development process that encompasses the economic, environmental, and social dimensions of sustainability requires not only technological innovations but also strategic approaches that are tailored to regional characteristics (Silvestre and Ţîrcă, 2019). Although Industry 4.0 significantly impacts sustainable development, few studies evaluate this transformation from a sustainable development perspective (Sharma et al., 2021). Therefore, it is crucial to conduct further research on the impact of Industry 4.0 on sustainable development and the relationship between them and to transform the findings of these studies into applicable solutions in the field.

The existing literature indicates that a broader understanding of sustainable development and Industry 4.0 is needed regarding the significant connections and the magnitude of the effects in these areas (Birkel and Müller, 2021). Over the years, there has been curiosity about whether these findings are valid. One of the significant driving forces behind the preparation of this study is curiosity. There is a desire to determine whether similar themes are still being addressed in the literature or if there is a shift in the distribution of topics. Studying these issues is crucial from various perspectives, as this research area can be valuable for both industry professionals and policymakers (Lin et al., 2017). Although the literature addresses the relationship between sustainable development and various events and situations in many different contexts, there are gaps in certain mechanisms. Conducting new research in the relevant field will be significant in terms of examining the dissemination of practical knowledge, identifying limitations in theory, and providing recommendations for future directions.

This study aims to identify key research that incorporates the perspective of sustainable development within the context of Industry 4.0 and to map the broad area concerning the interoperability of the two topics. All articles published in English between January 1, 2017, and December 28, 2024, were downloaded from the Web of Science database, and the VOSviewer 1.6.20 program was used to analyze the dataset. The VOSviewer program was chosen for its capability to perform a systematic mapping review. In this paper, studies that demonstrate the relationship between Industry 4.0 and sustainable development, including the most cited articles, the most influential journals, the most productive countries and authors, and the most impactful documents, were analyzed using a bibliometric approach. Furthermore, scientific mapping was conducted, including word clustering analysis, frequency analysis, and co-occurrence analysis of keywords, to explore the intellectual structure of this field and investigate emerging areas.

Since 2020, no bibliometric analysis has been conducted on the combination of Industry 4.0 and sustainable development. The significance of this study lies in analyzing the most up-to-date dataset resulting from the accumulation of research in the relevant field and, in this context, revealing the gaps in the research area. The results of the study are expected to offer valuable insights for research or policies that approach the subject with the support of specialized groups. The motivation for this study is to understand this young literature field, which integrates Industry 4.0, which does not have a very long history, with the regionally emerging sustainable development in recent years.

This study is structured around several research questions:

1. How has the distribution of studies that combine Industry 4.0 and regional sustainable development topics changed over the years?

2. What is the citation effectiveness of the publications in the existing literature?

3. Which countries or regions have published the most in this field?

4. Who are the most influential researchers in the fields of Industry 4.0 and regional sustainable development?

5. In which academic journals is the number and distribution of publications in this field more concentrated?

6. What are the most effective studies in the synthesis of Industry 4.0 and regional sustainability?

7. Which keywords are frequently associated with sustainable development and Industry 4.0?

8. Which articles form the fundamental structures in the literature on Industry 4.0 and sustainable development and have the most citation connections?

This article is organized into three sections. Firstly, "Materials and Methodology," discusses the search query that defines the boundaries of the research topic and bibliometric analysis. The second section focuses on data analysis and presents the results. The last part discusses the findings and offers recommendations for subsequent research.

2. Materials and Methodology

Bibliometric analysis follows a transparent, objective method and a reproducible examination process to gather information about the researched topic and systematize this information (Grant and Booth, 2009). Through this analysis, researchers can easily explain the quantity and purpose of a research field by evaluating published studies on a specific topic. Bibliometric analysis is a quantitative method that assesses the literature on a subject by analyzing citations, authors, publication trends, and various data within a scientific field (Khatib et al., 2022). Researchers utilize bibliometric analysis to gain insights into countries, key topics, and collaborative networks related to emerging research within a scientific community (Block and Fisch, 2020).

To answer all the research questions presented in the introduction part, the relevant research area was first identified, followed by network visualization to demonstrate key concepts, themes, and collaborations in the flow of information. Some research questions in this study could only be answered through network visualization analysis. By the constraints identified on the network visualization screen, the size of each factor is determined by the frequency (occurrence) within that factor. In network visualization, the lines connecting the factors represent the connections, while the distance between two factors indicates the degree of their connections.

2.1. Research Scope

Obtaining a holistic picture of the actual structure of a subject, field, or discipline, identifying the research clusters that guide the field, and demonstrating the significant concepts within the field are achieved through bibliometric analyses (Oztürk and Güler, 2021). The most crucial stage in bibliometric analysis is identifying the key terms directly related to the topics being investigated. This is important because all search results will be based on these selected key terms.

It was planned to conduct searches using key terms in the "Title," "Subject," or "Author Keywords" groups through Web of Science. In this regard, two primary key terms were selected: "regional

sustainable development" and "Industry 4.0." A pilot search was conducted using these terms, which helped identify additional key terms for the subsequent search. In this study, the search query was executed using both exact concepts (e.g., "Industry 4.0") and expert-focused, semantically related terms (e.g., "regional development" or "regional growth") to define a collection of key terms.

The search query was designed as follows for title, subject, and keyword: ("sustainable development" or "regional sustainable development" or "regional development" or "regional growth") and ("I4.0" or "I 4.0" or "industry4" or "industry 4.0" or "industry 4" or "fourth industry revolution" or "industry revolution 4*"). To encompass multiple aspects of Industry 4.0 and regional sustainable development, the Boolean operator 'OR' was used to combine Title, Topic, Keyword, and Abstract, resulting in access to all outcomes. To maintain conceptual consistency within the search query, synonymous terms used in various ways in the literature were examined. Alternative expressions that replace or complement the concept of "Industry 4.0" ("I4.0" or "I 4.0" or "industry4" or "industry 4.0" or "industry 4" or "fourth industry revolution" or "industry revolution 4*") were scanned and compared. Two primary criteria were considered in the selection of these terms: keyword frequency and semantic relevance. Frequency was used by prioritizing the most frequently used terms in highly cited articles and leading journals in the field. Semantic relevance, on the other hand, was defined by the fact that each word used directly refers to Industry 4.0. For example, although the term "Smart Industry" is related to Industry 4.0, it was not used because it did not have the same meaning. As a result of this search, a dataset consisting of 927 articles was obtained. The resulting 927 records were reviewed at the title and abstract level to ensure no duplicates were found. Furthermore, because the Web of Science database systematically prevents duplicate records with the same DOI, no additional duplicate removal was required.

The last date for data collection in the obtained dataset for chronology is set as December 28, 2024, while January 1, 2017, was chosen for the first data point. Studies conducted before this date were excluded from the scope of the subject due to their irrelevance, resulting in a total of 8 studies being removed from the dataset. The third phase of the search restriction involved selecting English as the language of publication for the studies. As a result of this restriction, 21 studies were excluded from the dataset due to being published in languages other than English. Since the research focused on articles published in scientific journals and early-stage articles, a document type restriction was applied, leading to a final dataset of 653 articles. All these processes are illustrated in Figure 1.

Figure 1. Process of creating the study data set

2.2. Data Analysis

All studies for the relevant dataset have been downloaded in tab-delimited file format. To conduct a descriptive analysis on this subject and create a map with multiple items, the VOSviewer software tool was selected. VOSviewer features a robust visual interface that facilitates the effortless exploration of the created maps (Oztürk & Güler, 2021). The VOSviewer program supports the easy formation of scientific background on the subject by examining the articles in the dataset in terms of the journals in which they were published, the authors working on the topic, the scientific impacts of the studies, and the citations they received.

Additionally, the analysis aims to identify the most prominent word groups that appear together in article titles, keywords, and topics. This enables the determination of the main focuses of the subject and the identification of other less-studied areas, thereby enabling a clear insight into the subject's trajectory. It is also significant to apply co-citation analysis to see how a field has evolved by bringing together relevant studies and where new research connections have emerged. By determining the intellectual structure of the subject, the goal is to uncover the fundamental concepts, theoretical approaches, and key components within the research area.

3. Bibliometric Analysis Results

This section presents bibliometric analysis, including descriptive analysis of existing studies, citation analysis, source analysis, author analysis, document analysis, structural analysis, network analysis, and co-citation analysis.

3.1. Scientific Productivity by Year

Two of the most used indicators in bibliometric analyses are the count of publications and the count of citations. The general characterization of the 653 articles selected for the recent sample provides valuable insights into the state of the literature on the subject. The first question addressed was, "How is the distribution of studies combining Industry 4.0 and regional sustainable development over the years?" Figure 2 illustrates the annual scientific productivity related to this question.
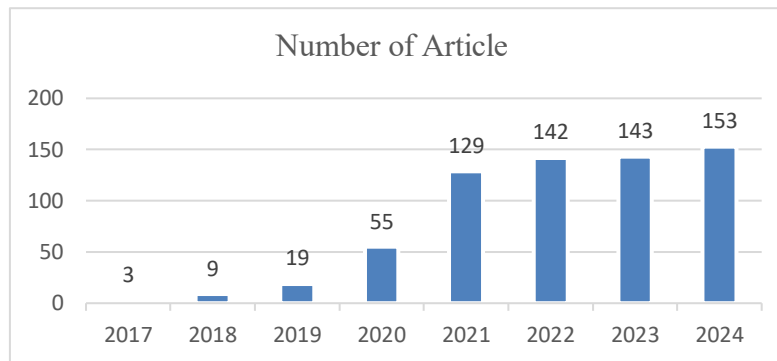

Figure 2. Annual frequency of article publications in the study period

In 2015, after the publication of the United Nations Sustainability Agenda, research began to be conducted within academic cultures. Until 2017, publications were mostly in the form of "news" in terms of introducing and adapting to the new goals. Almost all the literature belongs to the last eight years. In 2017, a total of three articles were published, and the number of articles increased each year, reaching 142 in 2022 and 143 in 2023. By the time of this study, the total had reached 153. This data showing the number of scientific articles by year is valuable in understanding the growth trend of the research area.

The productivity of scientific literature examining the relationship between Industry 4.0 and sustainable development is steadily rising each year, with the period from 2017 to 2020 marking a significant phase of discovery in this field. The last decade has seen significant research into Industry 4.0 applications, leading to a growing interest in sustainable development. New findings on the subject, technological developments and social needs may cause the integration of the two concepts to be more on the agenda. Data indicates that the issue has been subject to deeper examination since 2021. This is encouraging, especially for the production sector. In addition, although the number of articles reached significant levels after 2021, it was found that there was a slowdown in the growth rate, suggesting that conceptual research on this topic may be mostly complete.

3.2. Citation Analysis by Years

The second part of the bibliometric analysis focuses on article citations and examines reference lists to identify the most cited documents within a specific discipline (Ogutu, 2023). The number of citations is a crucial indicator of the academic importance of a topic. Citation analysis can often help to identify authors, literature, journals, source countries or institutions that have studied the topic. In this part of the research, the answer to the question "How is the effectiveness of publications in the existing literature in terms of citations?" is sought. The substantial number of citations of published articles indicates how much attention these articles receive in the academic community. Table 1 presents the total count of citations of all publications in the dataset by year.

Table 1. Number of citations in the topic by year

Year	Number of article (n)	Tot. Cit.	Tot. Cit./ n
2024	153	5212	34.06
2023	143	4128	28.86
2022	142	2787	19.63
2021	129	1364	10.57
2020	55	384	6.98
2019	19	130	6.84
2018	9	27	3.00
2017	3	1	0.33

In 2023, all articles in the dataset were cited a total of 4128 times, with an average of 28.86 citations per article. By the end of 2024, the number of citations reached 5212, with an average of 34 citations per article. Based on this increase, it can be said that synthesis studies on I4.0 and sustainable development are becoming more and more recognized and significant. The increase in citation counts over time indicates that the field is transitioning from its infancy to its maturation. It is also highly likely that the conceptual framework for the topic has begun to be addressed holistically across disciplines (e.g., industrial engineering, environmental management, regional development policies). Considering the total number of citations and the average number of citations per article, it is evident that the subject is attracting more attention. Conversely, growing interest in the topic has attracted more researchers, likely contributing to an increase in citations. In addition, studies on the effects of I4.0 applications on sustainable development form the basis for future research, and this contributes to an increase in the number of citations compared to the previous year.

Approximately 80% of the articles in the dataset were cited by other studies, highlighting the topic's significant impact.

3.3. Geographical Distribution of Publications

Identifying the countries where research is published can often provide information about the scientific research strategies and policies of those countries. This section addresses the question, "Which countries or regions have published the most in this field?" Answering this can help researchers forge scientific collaborations. Table 2 displays the data regarding the countries of origin for studies in this scientific area.

Table 2. The ten countries with the highest article publication counts

Countries-Regions	n	%
China	117	17.92%
India	89	13.63%
Poland	62	9.50%
Rusia	48	7.35%
England	45	6.89%
Brazil	44	6.74%
Italy	43	6.59%
U. S. A	35	5.36%
North Africa	34	5.01%
Malaysia	32	4.90%

Looking at the number and rates of publications, China stands out as the country having the greatest volume of publications in this area with a rate of 17.92%. China is followed by India with 13.63% and Poland with 9.50%. In the light of these data, when all publications are evaluated, 40% of the articles were directly performed by researchers in China, India and Poland.

The economic and social events faced by developing countries such as China and India may be behind the increased focus on sustainable development and production issues. China and India are among the fastest growing economies in the world. The adoption of industrial and technology-oriented growth strategies in these countries has brought to the fore the need to consider other factors to support regional development. The impact of economic growth on societies must be acknowledged. In China and India, two of the world's largest production centers, significant environmental issues, including pollution and water scarcity, are arising from their intense production activities. These events or situations may encourage researchers to work in these areas.

On the other hand, China (1,425,671,352) and India (1,428,627,663) (TurkStat, 2024) are the most populous countries in the world. As a result of their large populations, China and India are among the countries with the highest greenhouse gas emissions globally. This leads to environmental, economic and social impacts being felt on a wider scale. For example, in recent years, China and India have shown great interest in renewable energy sources. In line with this need, the capabilities of I4.0 technologies to provide innovative solutions to support large populations could be a crucial topic of interest for researchers. This awareness has led to a rapid increase in sustainable development-focused policies and academic research. It is also known that the number of higher education institutions, research funds and publication incentive mechanisms in both countries have increased significantly in the last 10 years.

Moreover, with the "Made in China 2025" program in China, I4.0 applications have come to the forefront and these technologies have assumed an encouraging role in terms of regional development goals. India's Make in India program, like China's Made in China 2025 program, is a significant initiative focused on digital transformation in industry and, consequently, technologies that support sustainable development. One of the strongest explanatory variables for the publication density of China and India in this field is government funding. For example, in China, the National Natural Science Foundation of China (NSFC) has allocated significant budgets in recent years to projects in sustainable production, green technology, and digital transformation. These efforts are directly impacting academic trends.

Projects carried out with this support also strengthen the visibility of countries like China and India in the global literature. For Poland, third on the list, problems such as air pollution caused by using coal in industry and the incentives and funds provided by the European Union may have an impact on researchers.

The results may provide a useful starting point for researchers working on this topic in different countries when choosing other researchers to collaborate with. This is because researchers aiming to publish international articles are sometimes uncertain about which researchers in which region to reach.

3.4. Author Analysis

This section seeks to answer the question "Who are the most influential researchers in the field of Industry 4.0 and regional sustainable development?". To answer this question, researchers who published on the combined topic were analyzed and evaluated. As a result of the analysis, it was found that a total of 2134 researchers wrote articles on sustainable development in the context of I4.0. This data indicates that numerous researchers have explored the intersection of I4.0 and sustainable development, highlighting its global significance. Regional sustainable development requires a great effort from researchers as it is a social need. The fact that the topic has a wide potential and requires a multidisciplinary approach contributes to more researchers working in this field.

Table 3 visually presents the performance of the most influential researchers in this field. At the same time, this performance also shows the scientific productivity of the authors. Table 3 lists 10 researchers who have published at least 5 articles on this topic. The inability of even the most dedicated researchers to exceed six articles indicates that the research topic is highly specialized. This also suggests that the area demands thorough analysis, which accounts for the limited number of studies.

Table 3. The ten most influential authors based on citation counts

Authors	n	Tot. Cit	Period Range
Singh, Rubee	6	85	2020-2024
Bai, Chunguang	5	660	2020-2024
Kumar, Saurabh	5	503	2021-2022
Govindan, Kannan	5	426	2020-2024
Yadav, Gunjan	5	358	2020-2024
Kazancoglu, Yigit	5	286	2020-2022
Jabbour, Charbel J.C.	5	232	2021-2024
Tseng, Ming-Lang	5	134	2019-2024
Gehlot, Anita	5	84	2022-2024
Singh, Rajesh Kumar	5	54	2022-2024

Each of the researchers in Table 3 is a pioneer in the knowledge production of this topic. Specialized researchers offer valuable insights for in-depth exploration of their field. Most studies were conducted after 2020, highlighting the topic's relevance and timeliness. In the future, different fields of study may emerge as research deepens. In addition, the volume of publications is an important metric, but the number of citations those publications receive is a key criterion. This significant factor motivates other

researchers in the field. C. Bai and S. Kumar each published five articles, collectively garnering over 500 citations. This indicates that the researchers have significantly contributed to publications.

3.5. Resource Analysis

For source analysis, the question "In which academic journals is the number and distribution of publications in this field more intense?" is sought to be answered. To answer this question, the analysis of 653 articles revealed their publication in 266 journals. A threshold of five articles per journal was established, resulting in twenty-one journals being included in the final list, with the top 10 journals for article publication tabulated. (See Table 4).

Table 4. Top ten journals based on publication and citation impact

Journal	Field	n	Tot. Cit.	Tot. Cit/ n
Sustainability	Business, Environment, Engineering.	114	2452	21.51
J. of Cleaner Production	Business, Environment	28	1543	55.11
Business Strategy and the Environment	Business, Environment	24	825	34.38
Sustainable Development of Modern Digital Economy	Business, Environment, Engineering.	20	13	0.65
Energies	Environment, Engineering	16	452	28.25
IEEE Transactions on Engineering Management	Engineering	12	156	13.00
IEEE Access	Engineering	11	254	23.09
Sustainable Production and Consumption	Business, Environment, Engineering	11	410	37.27
Heliyon	Business, Environment, Engineering	9	87	9.67
Environment Development and Sustainability	Business, Environment	9	57	6.33

3.6. Document Analysis

Identifying the most cited documents can provide a basis for understanding, analyzing and interpreting other studies. This section was prepared in response to the following questions:

"What are the most influential papers in the field of synthesis work on Industry 4.0 and regional sustainability?"

"What themes and issues do the most influential articles in this field focus on?"

 "In which years were the most influential studies on Industry 4.0 and regional sustainable development published?".

Table 5 lists the top 10 most cited studies in the relevant literature, along with a summary of each study's significance for accurate interpretation.

Table 5. The ten prominent scientific articles in the literature

	Document	Authors	Tot. Cit.
1	Industry 4.0 technologies assessment: A sustainability perspective	Bai et al. (2020)	1423
	This study aims to further examine the different impacts on sustainable development resulting from the adoption of Industry 4.0 technologies. Believing that the principles and goals of Industry 4.0 technologies will contribute to a more sustainable society, researchers emphasize that each technology should be carefully evaluated. In this context, hybrid multi-criteria decision-making approaches combining hesitant fuzzy set, cumulative expectation theory and VIKOR methods were used.		
2	The smart circular economy: A digital-enabled circular strategies framework for manufacturing companies	Kristoffersen et al. (2020)	687
	The aim of this study is to theoretically examine the circular economy framework to support the sustainable development goals of manufacturing companies. To this end, explanatory, diagnostic, exploratory, predictive and directive analyses are presented.		
3	Industry 4.0 based sustainable circular economy approach for smart waste management system to achieve sustainable development goals: A case study of Indonesia	Fatimah et al. (2020)	665
	This study aims to tackle Indonesia's waste management issues by developing a sustainable, smart national system that incorporates Industry 4.0 technologies. The study aims to improve economic, social and environmental performance by developing a multidimensional approach to make waste management processes more efficient. This study, backed by theoretical and empirical data, seeks to offer a comprehensive solution proposal.		
4	Industry 4.0 as enabler for a sustainable development: A qualitative assessment of its ecological and social potential	Stock et al. (2018)	578
	This study aims to examine how Industry 4.0 technologies contribute to sustainability and align with the United Nations' 2030 Sustainable Development Goals. It will analyze the positive and negative impacts of these technologies at both macro and micro levels, drawing on a combination of theoretical frameworks and empirical data.		
5	Industry 4.0 adoption and 10R advance manufacturing capabilities for sustainable development	Bag et al. (2021a)	576
	This study aims to analyze how Industry 4.0 technologies contribute to sustainability and their alignment with the United Nations' 2030 Sustainable Development Goals. By addressing the relationship between Industry 4.0 and sustainability, the study seeks to examine the positive and negative impacts of these technologies at both macro and micro levels, utilizing both theoretical and empirical methods.		
6	Industry 4.0 and Sustainability Implications: A Scenario-Based Analysis of the Impacts and Challenges	Bonilla et al. (2018)	545
	The aim of this study is to assess the potential impacts of Industry 4.0 technologies on environmental sustainability and discuss how these impacts can be aligned with sustainable development goals. The research offers both theoretical contributions and practical solutions.		
7	Blockchain-empowered sustainable manufacturing and product lifecycle management in industry 4.0: A survey	Leng et al. (2020)	492
	The aim of this study is to examine how blockchain technology can support sustainable production systems within the scope of Industry 4.0 and to evaluate the compatibility of this technology with sustainable development goals. The research is based on a theoretical approach.		
8	Key resources for Industry 4.0 adoption and its effect on sustainable production and circular economy: An empirical study	Bag et al. (2021b)	415

The aim of this study is to identify the resources required for the adoption of Industry 4.0 technologies and to examine their impact on sustainable production and circular economy capabilities. The study also aims to identify the challenges faced in the adoption of Industry 4.0 technologies through the case of South Africa.

9	Impact of technological innovation on energy efficiency in industry 4.0 era: Moderation of shadow economy in sustainable development	Chen et al. (2021)	354

The aim of this study is to examine the relationship between energy efficiency and technological innovation in the context of Industry 4.0 and to develop a framework to support MENA countries to achieve the goals of Affordable and Clean Energy, Decent Work and Economic Growth, Industry, Innovation and Infrastructure, and Quality Education. The study is based on an empirical approach.

10	Digitization, Digital Twins, Blockchain, and Industry 4.0 as Elements of Management Process in Enterprises in the Energy Sector	Borowski (2021)	349

The aim of this study is to analyze the relationship between Industry 4.0 solutions and other digital technologies and their consequences for the sustainable development and environmental impact of energy companies. The study is grounded in an empirical approach.

The aim of this study is to analyze the relationship between Industry 4.0 solutions and other digital technologies and their consequences for the sustainable development and environmental impact of energy companies. The study is grounded in an empirical approach.

Table 5 shows the top 10 most influential studies on the related topic. The study titled "Digitization, Digital Twins, Blockchain, and Industry 4.0 as Elements of Management Process in Enterprises in the Energy Sector" which ranks tenth on the list, received 349 citations and is the most recently published study among the articles. Two featured articles appeared in 2018, four in 2020, and four in 2021, with most studies employing both theoretical and empirical methods.

The most influential article on the list is "Industry 4.0 technologies assessment: A sustainability perspective" by Bai et al., published in 2020. This study deeply analyzes the relationship between Industry 4.0 technologies and sustainable development goals. The article was published in the Int. J. of Production Economics and was cited 1423 times until the end of 2024. The fact that Bai et al. (2020) have the highest number of citations in the field is thought to be effective in providing a general perspective on the subject. This study shows that it creates a knowledge network by referencing other studies to expand or deepen the scope of the subject. Second on the list is the study titled "The smart circular economy: A digital-enabled circular strategies framework for manufacturing companies". This article by Kristoffersen et al. was published in 2020 and received 687 citations. The study focuses on the relationship between digital technologies in Industry 4.0 and the circular economy for sustainable development. After the work of Bai et al. (2020), it had a major impact on the literature and stood out with a more specialized discipline of study.

The third most influential study (number of citations = 665) is an empirical study in Indonesia by Fatimah et al. Published in 2020 in the J. of Cleaner Production, this paper addresses the region's waste problems and proposes sustainable waste management by combining I4.0 technologies and circular economy tenets. These three articles, published in 2020, indicate that the issue began garnering more attention and awareness after that year. The fourth most influential article published on the subject is the study titled "Industry 4.0 as an enabler for sustainable development: A qualitative assessment of its ecological and social potential" by Stock et al. Published in 2018, this article received 578 citations by the end of 2024. The fact that the issue is examined from both macro (societal) and micro (institutional) perspectives suggests that this study is effective in its prominence.

3.7. Network Analysis

3.7.1. Co-occurrence Analysis

Co-occurrence analysis identifies the connections between items, which are established by the frequency of their joint appearance in documents (Van Eck & Waltman, 2010). In this analysis, the keywords used in the articles were selected as the unit of analysis, and the main research questions for the study were defined as follows:

Which keywords are frequently used for sustainable development and Industry 4.0?

What kind of connections do the relationships between these words reveal? created. The 65 synonyms (or close synonyms) were compiled in Excel and imported into the program. As a result of this process, it was determined that a total of 2,073 keywords were used across all studies. To analyze the words more efficiently, the minimum frequency for a keyword was set to 4, and under this condition, network visualization was generated for 74 distinct results (see Figure 3). The node sizes in the network represent the frequency of the words, while the positions of the terms on the map reflect the relative relationships between them.
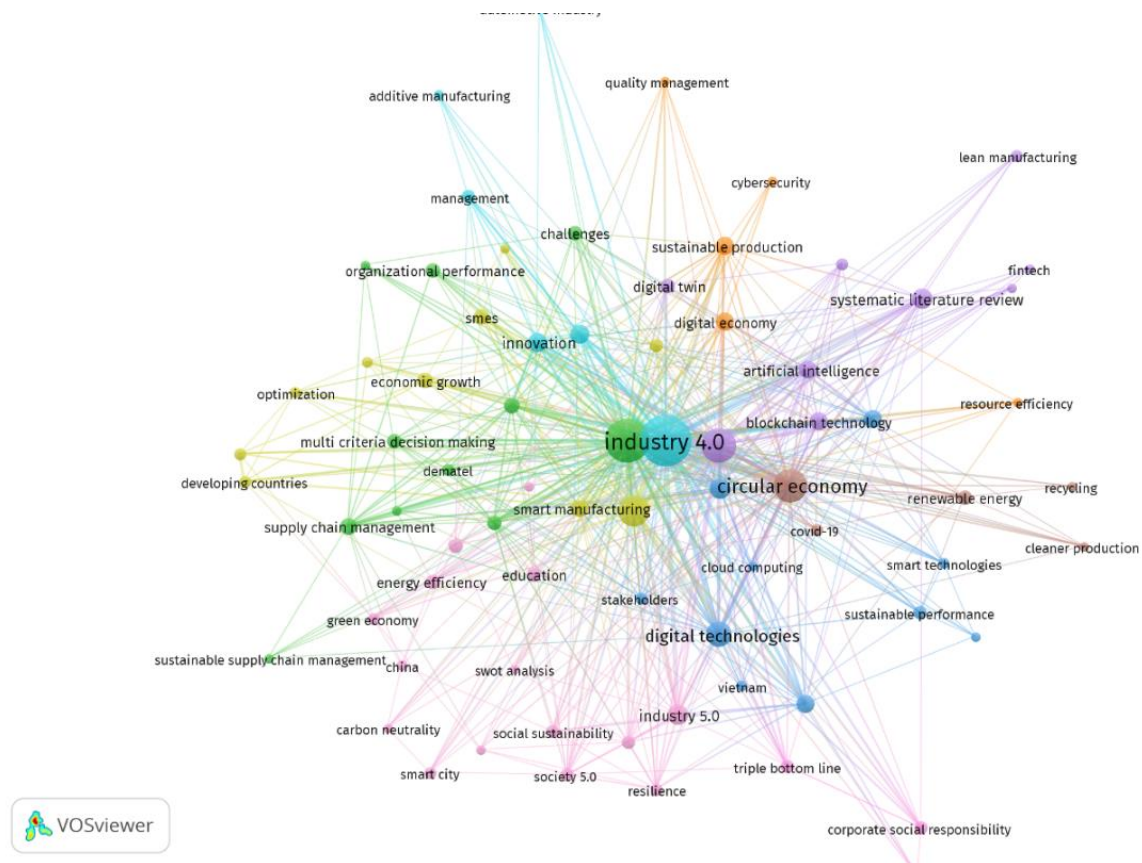

Figure 3. Visualization of common view analysis based on 2,073 keywords used across all studies

The "circular economy" is the most used phrase in conjunction with the concepts of sustainable development and Industry 4.0. The circular economy aims to use resources efficiently and minimize waste, directly aligning with sustainable development goals. On the other hand, innovative technologies in I4.0 have a significant impact in achieving the goals of the circular economy. Industry 4.0 and the circular economy converge towards a common goal of promoting resource reuse, recycling and shortening production cycles. Figure 3 also shows the use of the keyword "resource efficiency," which can be considered part of the circular economy. In addition, it is seen that the keywords

renewable energy, recycling, recycling, and cleaner production are used in the articles simultaneously with the circular economy.

Another group of words with the highest common appearance value is digital technologies. Due to digital technologies are often used only for I4.0, the concept has a strong connection with the concepts of Industry 4.0 and sustainable development. The literature on the relationship between I4.0 and sustainable development focuses on the potential of digital technologies to effectively realize regional development goals. Since I4.0 involves the incorporation of digital technologies into manufacturing processes, this concept is often used in conjunction with other concepts in related studies. Moreover, many countries and organizations are investing in industrial and technological revolutions to achieve sustainable development goals. In this context, it is emphasized that digital technologies have the potential to support the achievement of sustainable development goals.

Based on the overall network analysis, the Internet of Things (IoT) technology emerges as the largest purple node. The IoT is one of the core digital technologies of I4.0, enabling production processes to become more efficient by monitoring and analyzing them. The Internet of Things makes it possible to connect machines and equipment to production facilities. In this way, environmental factors in the production system, such as air pollution or energy consumption, can be continuously monitored, making it possible to develop strategies for sustainable development. This illustrates the relationship between concepts. The frequent use of this phrase by researchers paves the way for technology to be applied in various fields, such as smart cities, smart energy management, and more.

Other concepts with the largest nodes in the overall network analysis include artificial intelligence and blockchain technology. These also belong to the "purple cluster," which includes the keyword "Internet of Things." This suggests that these technologies are commonly featured as keywords in other studies. Both technologies play a critical role in improving production processes and sustainable development. Artificial intelligence, a key component of Industry 4.0, can optimize production lines, make resource use more efficient and reduce waste. These aspects have been frequently examined in the context of sustainable development. Blockchain technology is also addressed with the themes of making production processes more efficient, reducing environmental impacts and using resources more sustainably by providing key elements such as transparency, security and efficiency. These technologies have become a significant tool in achieving sustainable development goals through digitalization and innovative solutions, which is why both technologies are frequently researched and discussed in these fields. Based on this result, it can be concluded that many studies have been conducted to explore sustainable ways of adopting and implementing I4.0 technologies, such as artificial intelligence, blockchain, and especially the IoT. The use of the keyword Industry 5.0 in combination with other keywords was particularly prominent in the large green node. In this case, Industry 5.0 is considered to go beyond Industry 4.0 processes and adopt a human-centered, environmentally friendly and socially benefit-oriented production approach. Industry 5.0 is particularly prominent in studies on Industry 4.0 and sustainable development, as the fifth industrial revolution aligns closely with sustainable development goals. Common view analysis allows for the examination of other words associated with any concept by visualizing all keywords used together. Several themes stand out in the purple cluster, which includes Industry 5.0. The common cluster analysis reveals that these words are frequently used together. According to Figure 3, all keywords related to social sustainability and social themes are grouped in this cluster. Notably, themes such as corporate social responsibility, education, Society 5.0, and smart cities emerge prominently.

Another noteworthy cluster in Figure 3 is the green cluster. This cluster represents the methods used in the combined studies on Industry 4.0 and sustainable development. In these studies, "multi-

criteria decision making" and the DEMATEL (Decision Making Trial and Evaluation Laboratory) method are prominent.

3.7.2. Co-citation Analysis

Co-citation analysis, one of the significant analysis methods in bibliometric studies, occurs when two articles cite a common source (Aria & Cuccurullo, 2017). This relationship occurs when both articles cite the same third article. The more articles cite the same source, the higher the co-citation relationship of that source.

In this study, co-citation analysis was performed to better understand the connections between key themes and articles in the literature on Industry 4.0 and sustainable development. The main question of the study is, "Which articles form the foundational structures in the Industry 4.0 and sustainable development literature and have the most citation links?"

Only articles with a minimum of 30 citations were included to address this question. As a result, the network analysis was performed over 30 studies, and this network was visualized (Figure 4).
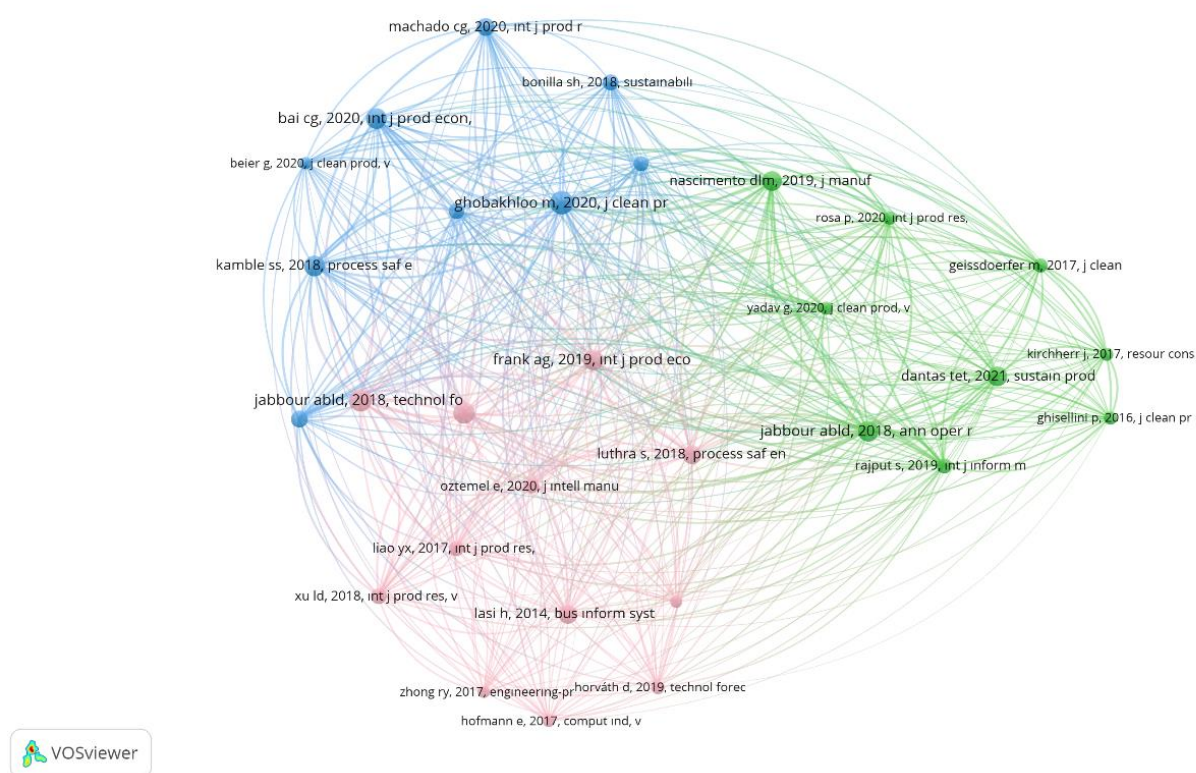

Figure 4. Louvain clustering-based co-citation network of 30 articles with a minimum of 30 citations

Co-citation analysis was used in this study to group sources according to their similarities. This study is crucial for comprehending the primary theoretical relationships and practical applications within the literature on Industry 4.0 and sustainable development. The clustering method helps to identify broader research themes by bringing together related sources. Three color clusters were formed in the network visualization resulting from the co-citation analysis. Each cluster represents key concepts or topics in the relevant research area.

Studies in the field of Industry 4.0 and sustainable development can be categorized into three main groups. In this context, it can be said that studies in this field are largely shaped around three different studies. These three main studies are shown in Figure 4, which was created to explain the basic concepts or events of the relevant scientific field. Studies such as those by Ghobakhloo (2020), Jabbour et al. (2018) and Frank et al. (2019) play a central role, and it can be easily stated that they have a wide interaction network.

There are a total of 9 articles in the blue cluster, and these studies are shaped around M. Ghobakhloo's (2020) study titled "Industry 4.0, Digitization, and Opportunities for Sustainability". The link strength value of the study, which shows the total relationship strength of the study with other studies, was 694. The articles in this cluster are formed by studies that examine the relationships between Industry 4.0 and sustainability, opportunities, challenges and how they are defined from a sociotechnical perspective. In general, these studies explored the impacts of Industry 4.0 on sustainable development and how these two concepts can be integrated.

There are 9 studies in the green cluster. The articles in the cluster are organized around the article "Industry 4.0 and the Circular Economy: A Proposed Research Agenda and Original Roadmap for Sustainable Operations" by Jabbour, A.B.L.D. (2018) published in Annals of Operation Research. The score indicating the strength of the link between this study and the other articles is 407. The common thread for the articles in this cluster is their focus on the relationship between Industry 4.0 and circular economy concepts. The articles have a common theme: How Industry 4.0 technologies can be integrated with circular economy goals and how this integration offers opportunities for sustainable development. In these studies, researchers examine the environmental and economic benefits of sustainable development and Industry 4.0 integration.

There are 12 articles in the pink cluster, and the articles are from Frank, A. G. (2019) "Industry 4.0 Technologies: Industry 4.0 Technologies: Industry 4.0 Technologies: Industry 4.0 Technologies: Industry 4.0 Technologies and Production Economics" published in Int. J. of Production Economics". The total link strength of this article reached 400. The common aspect of the studies in the cluster is that they examine the impact of I4.0 technologies on the manufacturing sector, their implementation patterns and their contribution to performance. These studies often focus on the implementation models of technologies, while sustainable development emerges as a complementary theme in relation to their environmental and social impacts. As a general comment, the studies in the pink cluster examined sustainable development as an indirect theme compared to the other two clusters. The role of I4.0 technologies in production processes was addressed by establishing an indirect relationship with sustainable development goals.

4. Evaluation and Discussion

I4.0 applications in sustainable development affect many economic, social and environmental developments. Talking about the radical changes in production processes and the digitalization of production with I4.0 would limit the great potential to a very narrow scope. With the realization of many promised results of Industry 4.0 technologies and processes, it has become crucial to reveal the direct or indirect effects on sustainable development, which is now the focus of the whole world, and the relationships between them. With the announcement of the Sustainable Development Goals in 2015, this synthesis literature is a relatively new area of research. The fact that literature has a history of eight years has raised research questions such as which researchers are in this field, what has been studied, the scientific productivity of the subject, and which themes are focused on. The fact that the last study on the subject was conducted in 2020 (Gajdzik et al., 2020) made it significant to reveal the literature of the past 4-5 years.

For this reason, a bibliometric analysis of studies on I4.0 and sustainable development was conducted. The distribution of the studies in the literature by years, the number of citations, the countries that have studied the topic the most geographically, the most influential articles, the most crucial journals, and the most productive authors were investigated. In addition, the themes that have emerged throughout its evolution and the theoretical and conceptual connections between the sources were also analyzed. Scientific background on the relevant topic was determined in the most up-to-date way, considering the journals in which the articles on I4.0 and sustainable development were published, the authors who studied the topic, the scientific impact of the studies, and the citations they received. For this purpose, different bibliometric methods were used to analyze 653 scientific articles on this topic between 2017 and 2024. In this context, we focused on articles published in WoS in English and analyzed them with VOSviewer software.

Initially, as the field has an eight-year history, there was a marked growth in scientific output when the subject was first examined. During this period, the topic grew rapidly as there was a process of discovery. It is observed that there is a decline in the growth rate due to the study of the subject for more specific areas. However, in terms of scientific productivity, the number of studies exceeded 150 in 2024. Depending on this increase in the number of studies, it is seen that the number of citations increases every year very much. This shows that there is an increase in the number of researchers interested in the field. It is also predicted that the increase in the number of citations will continue as the subject enters more specialized fields of study.

In terms of geographical distribution, researchers in China and India seem to be very interested in this topic. In general terms, four countries on the list: China, Malaysia, India and Russia (for the most part) are in Asia; three countries: Poland, the UK, and Italy are in Europe; two countries: America and Brazil are in the Americas; and North Africa is in Africa. Accordingly, while studies from Asia are said to dominate literature, Europe is also considered to have a significant contribution. The fact that the topic is studied especially by researchers in the Asian region may also be related to the fact that issues such as fast-growing economies, social transformations and state policies are more on the agenda. In the analysis of the sources, it was found that most studies on this topic were published in the Sustainability journal. However, despite the large number of articles published in this journal, it was observed that the impact levels of the articles were relatively low. For example, the high number of citations per article in the Journal of Cleaner Production highlights the quality and specificity of the articles published there.

One of the most striking points of this study is the common view analysis. According to the result obtained by visualizing the network analysis, some topics are not given enough importance and there is a lack of research in these areas. The outcomes may also offer valuable perspectives for researchers focused on the topic. According to the common view analysis, the most frequently used term in conjunction with the concepts of sustainable development and Industry 4.0 is the concept of circular economy. Other keywords frequently used in conjunction in these studies include renewable energy, recycling, and cleaner production. Another result relates to the excessive focus in the literature on the potential of digital technologies to contribute to regional development goals. Because Industry 4.0 refers to the integration of digital technologies into production processes, this concept has often been discussed alongside other fundamental concepts in related studies. The "Internet of Things," in particular, is the technology that stands out most in analyzing the relationships between these concepts, as it enables the development of strategies aimed at sustainable development goals.

In the common view analysis, while the focus of sustainable development is on economic, environmental, and social sustainability goals, the potential of I4.0 technologies to enhance

environmental sustainability has been more frequently emphasized. It has been found that areas such as economic inequality and social sustainability have not yet been explored in depth. Social sustainability is seen to be less prominent than other dimensions. According to this analysis, the keywords "social sustainability," which include social concepts, are grouped under the theme "Industry 5.0." At this point, it is seen that the words corporate social responsibility, education, Society 5.0 and smart city are used together in the studies. For sustainable development, themes such as social equality, which combines the social factor with the human factor, which is indispensable in industrial sectors, should also be studied. In particular, given that the social sustainability dimension is less well represented in the existing literature than the environmental and economic dimensions, it is crucial that future research address this gap by analyzing the societal impacts of Industry 4.0 applications. Furthermore, it is recommended that a theoretical discussion of social sustainability generates concrete implications linked to policy recommendations and implementation models.

A significant finding is that recent studies have focused on topics such as "smart city", "clean city" or "sustainable city". However, this topic is still at an exploratory stage. More studies should be planned on how potential applications in smart cities can shape regional sustainable development. Linking Industry 4.0 with waste management in the context of smart cities can fill a significant research gap. For example, recycling systems integrated with I4.0 technologies for waste management, one of the most critical elements of smart cities, will play a crucial role in sustainable development in cities.

In this part of the study, it would have been significant to find information about the methods in the relevant literature. Information about DEMATEL was found only when it emerged as a prominent element in network analysis. At this point, the absence of methods as keywords in the studies limited the ability to examine and analyze the methods used. Additionally, the lack of quantitative methods in the research is significant, as it points out a gap in this field. Furthermore, the absence of policy-related terms in the network visualization reveals another gap in the field. Given that sustainable development has a profound impact on society, it should be supported by policies in industrial practices. This area of study requires further attention.

Finally, one of the limitations of bibliometric studies also applies to this study. Although datasets were created from articles to go deeper into the subject, there are many databases that were not scanned. The global perspective can be improved by including other databases. This could be considered for future bibliometric studies on the two main keywords in the study.

Statement of Research and Publication Ethics

This study has been prepared in accordance with the principles of scientific research and publication ethics. The study does not require ethics committee approval.

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Extended Sumary

The Integration of Industry 4.0 and Sustainable Development: Trends, Networks, and Future Research Directions

This study aims to identify key research that incorporates the perspective of sustainable development within the context of Industry 4.0 and to map the broad area concerning the interoperability of the two topics. All articles published in English between January 1, 2017, and December 28, 2024, were downloaded from the Web of Science database, and the VOSviewer 1.6.20 program was used to analyze the dataset. The VOSviewer program was chosen for its capability to perform a systematic mapping review. In this paper, studies that demonstrate the relationship between Industry 4.0 and sustainable development, including the most cited articles, the most influential journals, the most productive countries and authors, and the most impactful documents, were analyzed using a bibliometric approach. Furthermore, scientific mapping was conducted, including word clustering analysis, frequency analysis, and co-occurrence analysis of keywords, to explore the intellectual structure of this field and investigate emerging areas.

This study is structured around several research questions:

1. How has the distribution of studies that combine Industry 4.0 and regional sustainable development topics changed over the years?

2. What is the citation effectiveness of the publications in the existing literature?

3. Which countries or regions have published the most in this field?

4. Who are the most influential researchers in the fields of Industry 4.0 and regional sustainable development?

5. In which academic journals is the number and distribution of publications in this field more concentrated?

6. What are the most effective studies in the synthesis of Industry 4.0 and regional sustainability?

7. Which keywords are frequently associated with sustainable development and Industry 4.0?

8. Which articles form the fundamental structures in the literature on Industry 4.0 and sustainable development and have the most citation connections?

To answer all the research questions presented in the introduction part, the relevant research area was first identified, followed by network visualization to demonstrate key concepts, themes, and collaborations in the flow of information. Some research questions in this study could only be answered through network visualization analysis. By the constraints identified on the network visualization screen, the size of each factor is determined by the frequency (occurrence) within that factor. In network visualization, the lines connecting the factors represent the connections, while the distance between two factors indicates the degree of their connections.

The search query was designed as follows for title, subject, and keyword: ("sustainable development" or "regional sustainable development" or "regional development" or "regional growth") and ("I4.0" or "I 4.0" or "industry4" or "industry 4.0" or "industry 4" or "fourth industry revolution" or "industry revolution 4*"). To encompass multiple aspects of Industry 4.0 and regional sustainable development, the Boolean operator 'OR' was used to combine Title, Topic, Keyword, and Abstract, resulting in access to all outcomes. As a result of this search, a dataset consisting of 927 articles was obtained. The last date for data collection in the obtained dataset for chronology is set as December 28, 2024, while January 1, 2017, was chosen for the first data point. The third phase of the search restriction involved selecting English as the language of publication for the studies. Since the research

focused on articles published in scientific journals and early-stage articles, a document type restriction was applied, leading to a final dataset of 653 articles.

According to scientific productivity results by year, the number of articles increased each year, reaching 142 in 2022, 143 in 2023, and 153 in 2024. This data showing the number of scientific articles by year is valuable in understanding the growth trend of the research area. According to a second analysis citiation analysis by year, all articles in the dataset were cited a total of 4128 times, with an average of 28.86 citations per article in 2023. By the end of 2024, the number of citations reached 5212, with an average of 34 citations per article. Based on this increase, it can be said that synthesis studies on I4.0 and sustainable development are becoming more and more recognized and significant. Considering the total number of citations and the average number of citations per article, it is evident that the subject is attracting more attention.

Looking at the number and rates of publications, China stands out as the country having the greatest volume of publications in this area with a rate of 17.92%. China is followed by India with 13.63% and Poland with 9.50%. In the light of these data, when all publications are evaluated, 40% of the articles were directly performed by researchers in China, India and Poland. The economic and social events faced by developing countries such as China and India may be behind the increased focus on sustainable development and production issues. China and India are among the fastest growing economies in the world. The adoption of industrial and technology-oriented growth strategies in these countries has brought to the fore the need to consider other factors to support regional development.

The most influential article on the list is "Industry 4.0 technologies assessment: A sustainability perspective" by Bai et al., published in 2020. This study deeply analyzes the relationship between Industry 4.0 technologies and sustainable development goals. The article was published in the Int. J. of Production Economics and was cited 1423 times until the end of 2024. The fact that Bai et al. (2020) have the highest number of citations in the field is thought to be effective in providing a general perspective on the subject. This study shows that it creates a knowledge network by referencing other studies to expand or deepen the scope of the subject.

In the study, co-occurence analysis was performed to answer the question "Which keywords are frequently used for sustainable development and Industry 4.0?".

The "circular economy" is the most used phrase in conjunction with the concepts of sustainable development and Industry 4.0. On the other hand, innovative technologies in I4.0 have a significant impact in achieving the goals of the circular economy. Industry 4.0 and the circular economy converge towards a common goal of promoting resource reuse, recycling and shortening production cycles. Figure 3 also shows the use of the keyword "resource efficiency," which can be considered part of the circular economy. In addition, it is seen that the keywords renewable energy, recycling, recycling, and cleaner production are used in the articles simultaneously with the circular economy. Another group of words with the highest common appearance value is digital technologies. Due to digital technologies are often used only for I4.0, the concept has a strong connection with the concepts of Industry 4.0 and sustainable development. The literature on the relationship between I4.0 and sustainable development focuses on the potential of digital technologies to effectively realize regional development goals.

Based on the overall network analysis, the Internet of Things (IoT) technology emerges as the largest purple node (see Figure 3). The IoT is one of the core digital technologies of I4.0, enabling production processes to become more efficient by monitoring and analyzing them. The Internet of Things makes it possible to connect machines and equipment to production facilities. Other concepts with the largest nodes in the overall network analysis include artificial intelligence and blockchain technology. These also belong to the "purple cluster," which includes the keyword "Internet of Things."

This suggests that these technologies are commonly featured as keywords in other studies. Both technologies play a critical role in improving production processes and sustainable development.

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Finally, one of the limitations of bibliometric studies also applies to this study. Although datasets were created from articles to go deeper into the subject, there are many databases that were not scanned. The global perspective can be improved by including other databases. This could be considered for future bibliometric studies on the two main keywords in the study.