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Statistical Model of the Growth in the Use of Smart Technologies in Sustainable Production

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Abstract

Technological empowerment and resilience play a crucial role in enhancing the capacity of organizations to maintain sustainability and respond effectively to crises and disruptions. This study aimed to examine the growth trend and thematic structure of international research in the field of smart technologies and sustainable production during the period from 2000 to 2024 through a systematic review of 290 scientific research articles indexed in global databases. The findings indicate that until 2018, the growth of publications was very slow, with an annual average of fewer than six articles. However, since 2019, a remarkable acceleration has been observed, with more than 65% of the articles (190 papers) published within the last five years. In terms of quality, the proportion of articles published in Q1 journals in recent years has increased to over 48% (compared to about 16% during the first decade of the study period). Moreover, the journals Journal of Cleaner Production, Sustainability, and International Journal of Production Research showed the highest frequency of publications, and the co-word network of keywords reflects a focus on areas such as sustainable development, Industry 4.0, the Internet of Things (IoT), and artificial intelligence (AI). Structurally, keyword clustering demonstrates the synergy between advanced smart technologies and sustainability objectives in industry. The statistical results of the meta-analysis showed that the Z-effect index was 1.82 (lower than the critical value of 2.69), indicating the stability of the findings. Furthermore, trend analysis reveals that the focus of studies has shifted from theoretical and feasibility issues toward the practical application of IoT and AI in industry and supply chains, with more than 35% of all articles dedicated to these topics. An examination of the cluster distribution of frequently used keywords in the fields of "smart manufacturing," "smart technologies," and "sustainable production" indicates that the largest share of articles in recent years falls under the clusters of "smart manufacturing and Industry 4.0" (12%) and "technological innovation and additive manufacturing" (12%). These findings highlight scientific maturity, an increase in international impact, and the growing attention of researchers to technological and resilient approaches in advancing sustainable production and development.

Keywords: Smart technologies, Sustainable production, Industry 4.0, Artificial intelligence

1. Introduction

he advent of Industry 4.0 has revolutionized the landscape of global manufacturing by integrating advanced digital technologies with sustainable production practices. Smart manufacturing, which combines cyber–physical systems, automation, artificial intelligence (AI), and data-driven decision-making, has emerged as both an opportunity and a challenge for industries seeking

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competitiveness in an increasingly turbulent environment (Karadayi-Usta, 2019; Zhou et al., 2019). The transition from traditional manufacturing systems toward digital and intelligent paradigms has triggered an urgent need to align these innovations with sustainability objectives, as organizations are simultaneously facing pressures of environmental responsibility, resource efficiency, and stakeholder expectations (Choudhary et al., 2019; Ejsmont et al., 2020).

Over the last two decades, a growing body of literature has highlighted how the adoption of Industry 4.0 technologies can contribute to sustainable development goals while also generating new risks and uncertainties (Ching et al., 2022; Jamwal et al., 2021). The convergence of green production strategies and digital transformation is now at the core of modern industrial policies. For instance, the notion of "Greentelligence," proposed by researchers to highlight the synergy between smart technologies and environmental stewardship, emphasizes how digital tools can enable resource efficiency, waste reduction, and a greener future (Li et al., 2021). These concepts have reshaped the discourse around sustainable manufacturing by moving from incremental efficiency gains to systemic transformations, supported by AI, machine learning, and advanced data analytics (Gholami et al., 2021; Verma et al., 2022).

Despite the potential, the path toward smart and sustainable production is not straightforward. Organizations often encounter barriers such as resource limitations, resistance to change, and skill gaps in the workforce, which complicate the integration of Industry 4.0 technologies (Ramadhani et al., 2024; Shakur et al., 2024). Studies indicate that small- and medium-sized enterprises (SMEs), in particular, face greater obstacles in digital adoption due to their structural constraints, yet they are also the firms that can benefit most significantly from sustainable innovations (Dabbagh et al., 2025; Machado et al., 2021). Empirical evidence confirms that while larger firms often dominate the discourse on sustainability and digitalization, SMEs contribute critical insights on scalability, adaptability, and resilience in emerging economies (Iqbal et al., 2021; Janahi et al., 2022).

Smart supply chain management has emerged as a cornerstone for linking digital transformation with environmental outcomes. Digital technologies such as blockchain, the Internet of Things (IoT), and AI facilitate transparency, efficiency, and resilience across supply chain operations (Lerman et al., 2022; Rane et al., 2023). By integrating lean and green principles into digital supply chains, companies can simultaneously achieve efficiency and sustainability, reducing carbon emissions while ensuring flexibility in volatile markets (Fiorello et al., 2023; Tripathi et al., 2021). This is particularly relevant in the context of circular economy practices, where remanufacturing, recycling, and green procurement strategies require strong digital infrastructures (Sahoo & Jakhar, 2024; Vrchota et al., 2020).

Sustainability research has also underscored the role of eco-innovation in achieving long-term performance improvements in manufacturing systems. Network strategies, particularly those embedded in the triple helix model linking universities, industries, and governments, have been highlighted as essential for enabling eco-innovation and collaborative growth (Janahi et al., 2022). For example, studies in Europe and Asia emphasize that manufacturing sustainability is increasingly dependent on cross-sectoral collaborations and technological partnerships that reduce the risks of isolated innovations (Tsai, 2018; Zhou, 2024). This finding resonates with broader research showing that environmental and technological performance are mutually reinforcing, particularly in contexts where digital transformation strategies are institutionalized (Kannan et al., 2023; Kumar et al., 2022).

The challenges of Industry 4.0 adoption, however, remain multifaceted. Interpretive structural analyses of digital adoption highlight the interdependencies among technological readiness, organizational culture, regulatory support, and financial capacity (Karadayi-Usta, 2019; Wankhede & Vinodh, 2021). Studies have revealed that lack of skilled labor and the complexity of integrating multiple digital systems are among the most critical impediments to achieving sustainable outcomes (Ejsmont et al., 2020; Machado et al., 2020). Furthermore, the resilience of supply chains under conditions of disruption, such as the COVID-19 pandemic, has underscored the necessity of embedding Industry 4.0 technologies into contingency planning (Shakur et al., 2024; Zhou, 2024). This is consistent with findings that highlight the capacity of digital infrastructures to enhance green performance and supply chain resilience simultaneously (Ching et al., 2022; Lerman et al., 2022).

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Alongside challenges, the opportunities presented by smart lean and green paradigms are transformative. The integration of lean practices with digital technologies creates a powerful mechanism to improve operational performance while simultaneously enhancing sustainability metrics (Fiorello et al., 2023; Tripathi et al., 2022). This alignment reduces waste, optimizes resource utilization, and enhances production efficiency. Furthermore, blockchain-enabled IoT frameworks are facilitating the development of smart and green products that meet consumer expectations for transparency and environmental responsibility (Rane et al., 2023). The evidence suggests that sustainability cannot be achieved without systemic technological integration, and conversely, that technological innovations are most impactful when embedded in sustainability frameworks (Gholami et al., 2021; Verma et al., 2022).

In recent years, bibliometric and systematic reviews have mapped the evolving themes in this domain, identifying clusters such as sustainable production, Industry 4.0, AI, and IoT as central drivers of the discourse (Ejsmont et al., 2020; Zhou et al., 2019). These studies reveal a trend away from purely theoretical discussions toward applied research on practical implementations of smart technologies in industries and supply chains (Jamwal et al., 2021; Machado et al., 2021). Evidence also suggests that the distribution of scientific contributions is increasingly concentrated in high-quality journals, signaling the maturation and growing influence of this research field (Choudhary et al., 2019; Zhang & Xu, 2024). This growing interest aligns with global sustainability imperatives, such as carbon neutrality goals and the adoption of renewable energy strategies, which demand the convergence of technological advancement with green practices (Sahoo & Jakhar, 2024; Zhou, 2024).

The literature further demonstrates that sustainability-oriented digital transformation is not a uniform process but is instead influenced by contextual differences across industries and regions. For example, research in textile manufacturing highlights how green production planning benefits from mathematical programming combined with Industry 4.0 tools (Tsai, 2018). Meanwhile, case studies in packaging and fast-moving consumer goods sectors emphasize the importance of resilience, innovation, and lean-green integration in meeting sustainability goals (Choudhary et al., 2019; Shakur et al., 2024). Similarly, empirical analyses in automotive and heavy industries have demonstrated the role of digital transformation in building supply chain resilience and achieving sustainability targets (Verma et al., 2022; Zhou, 2024).

Beyond operational efficiency, the financial sector has also been influenced by the sustainability discourse, as green finance mechanisms are increasingly leveraged to fund Industry 4.0 and sustainable manufacturing initiatives (Zhang & Xu, 2024). The role of policy promotion and institutional support has thus become crucial in accelerating the adoption of environmentally responsible technologies. At the same time, human resources and organizational behavior perspectives shed light on resistance to change, highlighting the importance of digital skills, training, and leadership in facilitating the transition (Iqbal et al., 2021; Ramadhani et al., 2024). These human and institutional dimensions underscore that the sustainable transformation of industry cannot rely on technology alone but must also engage cultural, financial, and social systems (Machado et al., 2020; Vrchota et al., 2020).

Taken together, the reviewed literature indicates that the integration of Industry 4.0 and sustainability is simultaneously an opportunity for innovation and a challenge of coordination. While the technical potential of smart manufacturing is widely acknowledged, the ability of firms to harness these innovations for sustainable outcomes depends on addressing systemic barriers, fostering cross-sectoral collaborations, and embedding sustainability principles at the strategic level (Dabbagh et al., 2025; Kannan et al., 2023). Scholars consistently emphasize the need for empirical validation of digital–sustainability frameworks in diverse industrial contexts to bridge the gap between conceptual promises and practical achievements (Jamwal et al., 2021; Tripathi et al., 2022).

In light of these insights, this study aims to contribute to the ongoing discourse by systematically examining the growth trends, thematic structures, and challenges associated with smart technologies and sustainable manufacturing. Specifically, the objective of this research is to analyze the evolution of international publications on Industry 4.0 and sustainability between 2000 and 2024.

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2. Methods and Materials

This research is descriptive–analytical in nature. In this study, the bibliometric method was employed. For data retrieval, input and output criteria were considered. First, the Web of Science database and its subsets were selected as the input criteria for retrieving data. The reason for choosing this database was that it has been widely used in various bibliometric studies and its outputs are reliable and acceptable.

For data retrieval, the title, abstract, and keywords of the articles were selected and examined. The starting point for the studies was set at the year 2000 in order to cover the majority of related research, and the endpoint was limited to the year 2024 so as to include a complete year. Moreover, based on the research literature, appropriate keywords were selected and searched in the Web of Science database. The keywords considered for this research are presented below:

Table 1 .Selected Keywords

Row	Persian Keyword	English Equivalent
1	فناوری‌های هوشمند	Smart Technologies
2	تولید پایدار	Sustainable Production
3	رشد فناوری	Technology Growth
4	تحول دیجیتال	Digital Transformation
5	صنعت ۴.۰	Industry 4.0
6	اینترنت اشیاء	Internet of Things (IoT)
7	هوش مصنوعی	Artificial Intelligence (AI)
8	تحلیل داده پیشرفته	Advanced Data Analytics
9	بهره‌وری تولید	Production Efficiency
10	توسعه پایدار	Sustainable Development
11	زنجیره تأمین هوشمند	Smart Supply Chain
12	اتوماسیون صنعتی	Industrial Automation
13	یادگیری ماشین	Machine Learning
14	فناوری اطلاعات و ارتباطات (ICT)	Information and Communication Technology (ICT)
15	منابع انرژی تجدیدپذیر	Renewable Energy Resources

A total of 310 scientific outputs were extracted, after which filters and output criteria were applied. The first exclusion criterion was the type of article, which was limited to research articles, since these undergo more rigorous review processes. Language was another output criterion, with studies restricted to English only, in order to align with the research objective of examining the global trajectory of studies on smart technologies in sustainable production. Ultimately, 290 articles were approved and analyzed. In the next stage, i.e., the analysis stage, complete bibliometric information such as title, abstract, organizational affiliation, and references was entered into the VOSviewer software.

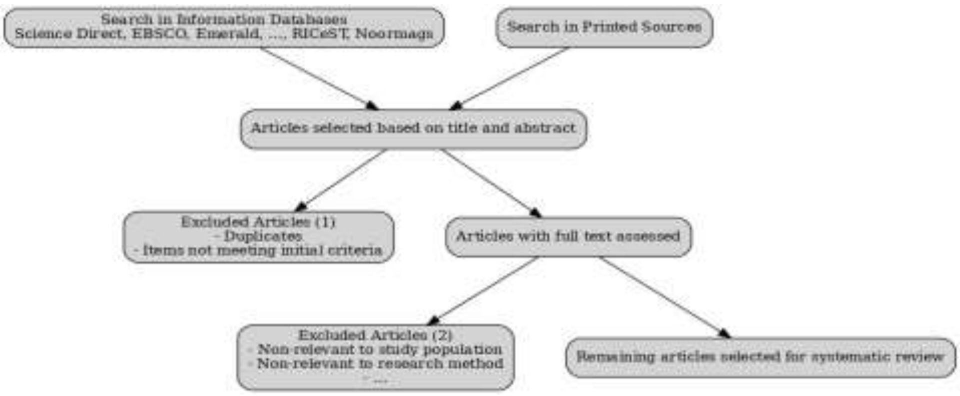

Figure 1. Steps of Systematic Inclusion and Review Process

In this research, the VOSviewer software was used for bibliometric analysis. This software is one of the important and practical tools in scientometrics, applied for summarizing data and creating research maps. VOSviewer has extensive

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applications in preparing bibliometric maps, enabling the visualization of keyword co-occurrence, citation analysis, bibliographic coupling, co-citation mapping, and other factors through distance-based mapping. The steps of this study were based on the PRISMA checklist and are outlined as follows:

Table 2. PRISMA-S Checklist

Row	Topic	Description
1	Database	According to the subject and research domain, the Web of Science database was used to search for studies.
2	Database Platforms	There is not yet a single platform that consolidates all the information in one place.
3	Study Registration	Keyword selection process: – Review of texts and research literature – Alignment with the theoretical framework – Consultation with experts and specialists – Overlap with English equivalents Application of keywords in meta-analysis: • Systematic search of works • Inclusion and exclusion of sources • Preparation of the meta-analysis table
4	Online and Ongoing Sources	Web of Science
5	Citation Searching	References cited in secondary studies were extracted, screened, and then their abstracts and literature were reviewed and analyzed.
6	Audience	Given the abundance of prior studies, the use of primary studies for data extraction was considered sufficient.
7	Other Methods	–
8	Search Strategy	Search was conducted using the keywords described in Table 1.
9	Limitations	Limitations considered in this study are as follows: – Language: English – Timeframe: 2000–2024 – Search strategy: keyword-based search – Study population: all studies conducted on smart technologies and sustainable production
10	Search Filters	Filters applied in the databases for precise search based on the limitations (Item 9), subject, and research scope were as follows: – English language – From 2000 onwards – Smart technologies – Sustainable production
11	Previous Work	Related systematic reviews using the keywords of this research in various industries were examined in the initial search. Their abstracts, keywords, and references were reviewed, and the extracted information was used to advance the study. The distinct contribution of this research compared to prior works was also identified.
12	Updates	–
13	Search Dates	The timeframe considered for this research was from 2000 to 2024, covering all studies conducted during this period.
14	Peer Review	Based on the specified timeframe, no peer-reviewed study on this topic has yet been conducted.
15	Number of Records	310
16	Duplicate Removal	20

The collection of precise and relevant data from the research literature for interpreting the field of smart technologies and sustainable production through bibliometric analysis is of particular importance. For conducting this research, all published articles indexed in Web of Science were used. The reason for selecting these databases for the present study was their wide coverage and the inclusion of both domestic and international scientific journals. To ensure the quality of the articles, conference papers were excluded from the analysis, as journal publications typically undergo more extensive and rigorous review processes prior to publication in reputable academic outlets.

3. Findings and Results

In the present meta-analysis, based on the review and analysis of 290 articles published between 2000 and 2024, the assumption of study homogeneity was evaluated. In other words, this hypothesis was tested to determine whether the results of the selected studies consistently and similarly reported the relationship between smart manufacturing and sustainable production.

For the statistical assessment of homogeneity, the Q-test was employed. The Q statistic was found to be 919.102, with a significance level of less than 0.001, indicating that the null hypothesis of homogeneity of studies was rejected with 99% confidence, and clear heterogeneity existed among the studies.

In addition, the I^2 index, which measures heterogeneity independently of the number of studies in percentage terms, was calculated as 83.11%. This means that approximately 83% of the observed variance in the study results was due to true heterogeneity (fundamental differences in study characteristics or conditions) rather than mere random error. Therefore, it is recommended that, for more precise explanation and interpretation of the overall effect size, a random effects model as well as moderator variables be used to account for the factors influencing heterogeneity.

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In the second step, publication bias was examined to ensure that no errors resulting from selective publication of related studies were present. For this purpose, three methods were used: funnel plot analysis, Begg and Mazumdar rank correlation test, and Egger's regression test.

The funnel plot results indicated a relatively symmetric distribution of studies around the effect size. Begg and Mazumdar's rank correlation test yielded a Tau value of 0.041 with significance levels of 0.590 (one-tailed) and 0.717 (two-tailed), suggesting no statistically significant evidence of publication bias. Furthermore, Egger's regression test showed an intercept of −2.10, a confidence interval of 1.891, and significance levels of 0.065 (one-tailed) and 0.210 (two-tailed), again confirming the absence of publication bias. Additionally, the fail-safe N was calculated, with a Z-value of 1.82, the observed number of studies at 310, and the number of missing (unestimated/suspected) studies at approximately ±20, supporting the adequacy of the data to ensure the reliability of the effect size.

Table 3. Assessment of Homogeneity and Publication Bias Coefficients

Hypothesis Type	Test Type	Coefficient Value	Intercept B	Significance (one-tailed)	Significance (two-tailed)	Standard Error
Homogeneity	Q	919.102	–	0.001	–	–
Homogeneity	I^2	83.11	–	0.001	–	–
Publication Bias	Begg and Mazumdar correlation	0.041	–	0.590	0.717	–
Publication Bias	Egger's regression	1.891	−2.10	0.065	0.210	1.891

Table 4. Assessment of Fail-safe N

Hypothesis	Z-value	Significance	Alpha	Residual	Z for Alpha	Observed Studies	Missing Studies
Publication Bias	1.82	0.05	0.05	0	2.69	310	±20

The findings of this meta-analysis show that studies conducted over the past two decades on the impact of smart technologies on sustainable production exhibit significant heterogeneity in terms of effect size and relationship. However, no evidence of publication bias was observed in the research literature, and the results possess sufficient robustness and reliability.

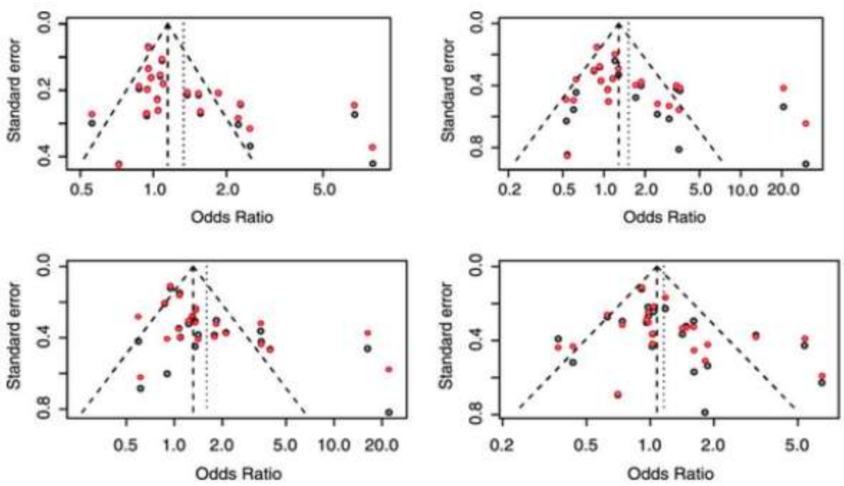

Figure 2. Funnel Plot for Assessing Publication Bias or Error

Symmetry of point distribution across all four plots: In all four images, the red and black points are distributed fairly symmetrically on both sides of the central line. If the funnel plot is symmetric, it implies no strong evidence of publication bias. In other words, studies with unexpected or less significant results were also published and included in the meta-analysis.

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Funnel shape: The funnel shape (wider at the bottom and narrower at the top) indicates that studies with higher standard error (smaller samples or lower quality) show more dispersion in results, while studies with lower standard error (larger samples or higher quality) cluster near the center. This pattern confirms the validity of meta-analysis tests.

Number of points outside the funnel: A small number of data points fall outside the funnel boundaries or show asymmetry (points far from the vertical axis), which is normally expected and does not, by itself, provide definitive evidence of bias unless severe asymmetry exists.

Based on the funnel plots presented, the distribution of the analyzed studies relative to the effect size intensity and direction is relatively symmetric and forms a classic funnel pattern. This indicates that the probability of publication bias in the selected studies of the present meta-analysis is very low, and the results derived from the systematic review and comprehensive analysis are valid and reliable.

In systematic reviews, one aspect that can attract the attention of analysts is the year of publication of research. That is, the number of studies conducted in a given time frame on smart technologies and sustainable production can reflect the importance of the topic within the academic community. At the same time, identifying how many studies have been conducted in a specific timeframe can provide a basis for further research.

Initially, to determine the publication trend of articles, the data retrieved from the Web of Science database showed that the publication of articles on smart technologies and sustainable production experienced an increasing trend from 2000 to 2024.

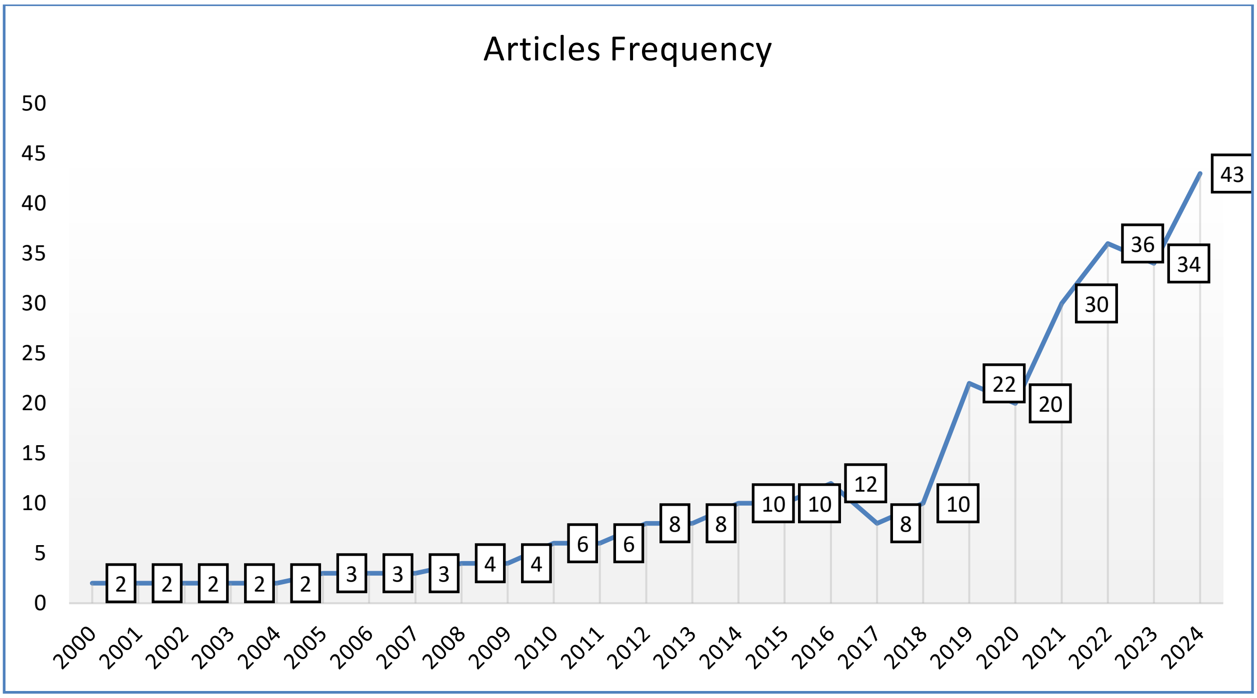

Figure 3. Publication and Citation Trend of Articles on Smart Manufacturing and Sustainable Production

This line chart with data points illustrates the time series trend from 2000 through 2024.

Overall Trend

- **2000 to 2010:** The trend was very slow and steady, with between 2 and 6 articles published per year. This can be attributed to the unfamiliarity of the subject and the emerging nature of smart technologies and sustainable production.
- **2011 to 2018:** The trend showed gradual and moderate growth (from 6 to 10 articles per year). Gradually, researchers' interest in studying this area increased, but no explosive output was observed.
- **2019 onwards:** Since 2019, a notable and sharp increase has been observed:
  - **2019:** 22 articles, indicating a twofold increase compared to the previous year.

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- **2020 to 2024:** The second wave of rapid growth, especially from 2021 onwards, with annual publications ranging from 30 to 43 articles, a remarkable leap compared to the previous decade.

Reasons for Upward Growth After 2019

- Coincidence with the digital revolution and Industry 4.0
- COVID-19 and the accelerated adoption of smart manufacturing and automation
- Global emphasis on sustainability and green development
- Increased research infrastructure and international publication

The publication trend from 2000 to 2018 was very slow and limited, averaging fewer than 6 articles per year. However, from 2019 onwards, with the acceleration of technological advancements, the global shift toward sustainable production, and the widespread adoption of digital transformations, a sharp and continuous growth in scientific output in this area has been evident. The average number of articles during 2019–2024 was approximately 33 per year, with more than two-thirds of the total studies in this field published in the last five years. This growth reflects the importance and novelty of the subject for both researchers and policymakers.

As mentioned in previous sections, this study, using a systematic review method, examined articles on smart manufacturing and sustainable production within the specified timeframe across domestic and international publications.

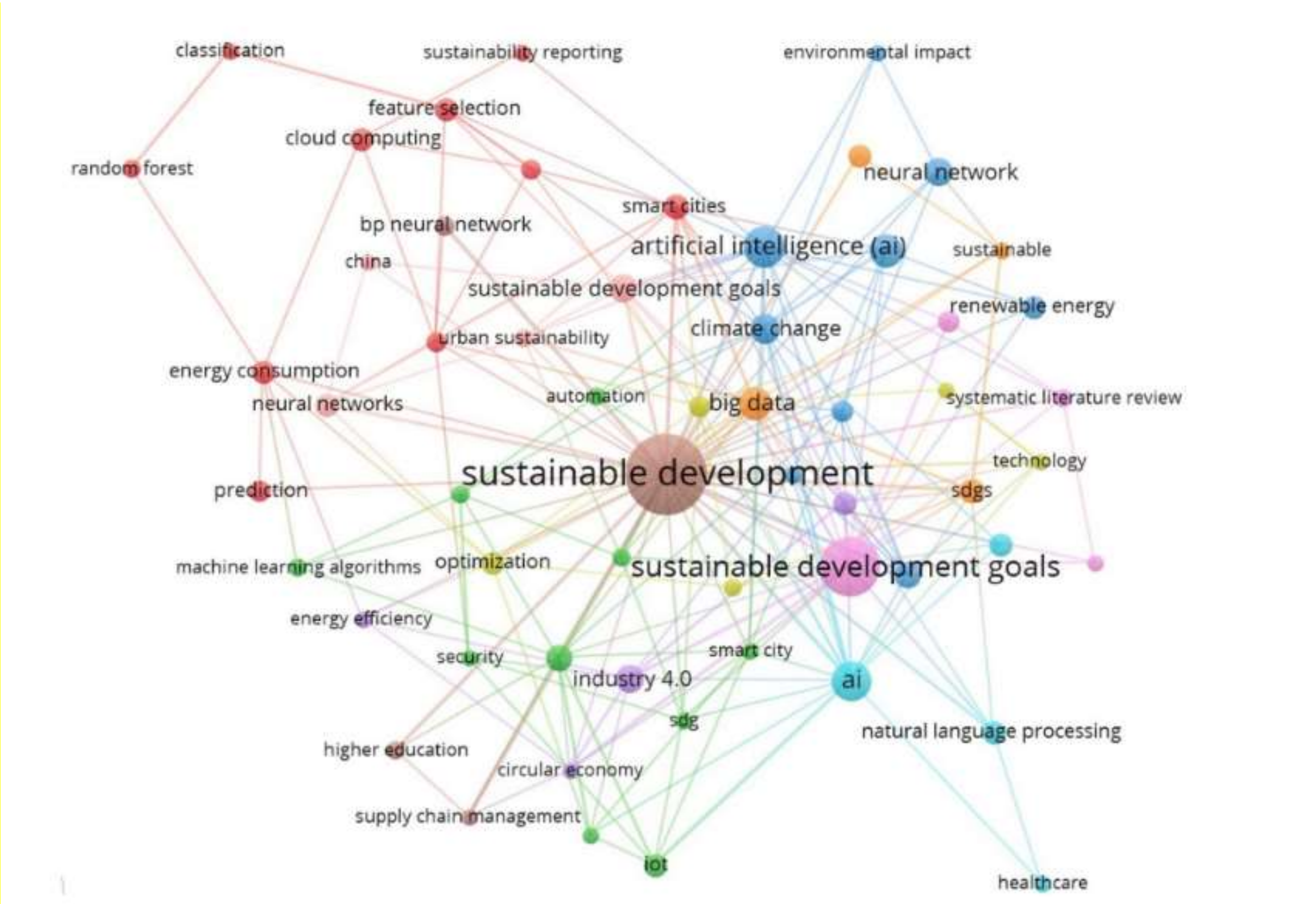

Figure 4. Bibliometric Co-occurrence Map of Keywords

The co-word map of keywords in the domain of sustainable development and smart technologies was created using VOSviewer. In this map, the relationships among keywords in the research literature during the years studied are displayed.

Map Structure:

Nodes: Each circle or node represents a keyword.

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Node Size: The larger the circle, the more frequent and significant the keyword in the articles.

Node Colors and Lines: The grouping of keywords is based on co-occurrence or thematic relationships, and the lines between them indicate co-dependence or co-occurrence in the articles.

Key and Frequent Keywords (based on node size):

1. *Sustainable development* – the largest node, the core of research.
2. *Sustainable development goals* – very large in size, highly frequent, and strongly connected with other significant keywords.
3. *Industry 4.0*
4. *AI (artificial intelligence)*
5. *Big data*
6. *IoT (Internet of Things)*
7. *Climate change*
8. *Supply chain management*
9. *Smart city*
10. *Optimization*

Note: Some terms such as *machine learning algorithms*, *renewable energy*, *security*, *neural networks*, etc., are in the next tier of frequency.

Quantitative Features and Indicators of This Map:

• **Magnitude and centrality of terms:** Keywords such as *Sustainable Development* and *Sustainable Development Goals* are, by a clear margin, the most frequent and most central terms in the studies.

• **Number of connections:** For example, "sustainable development" has many direct links with other terms, indicating its network importance.

• **Clusters:** The map contains color-coded clusters:

o **Green cluster:** Industry 4.0, Internet of Things, supply chain management…

o **Blue cluster:** Artificial intelligence, NLP, data analytics…

o **Red cluster:** Based on machine learning and neural networks…

o **Orange/Yellow cluster:** Energy and sustainability keywords…

• **Topical relatedness:** Thicker or closer lines indicate stronger relationships. For example, "industry 4.0" has a strong network with "IoT" and "supply chain management."

The examination of the keyword co-occurrence map based on 290 articles shows that "sustainable development" and "sustainable development goals" are the most frequent and most central concepts in research over the past two decades and have often been used alongside concepts such as "artificial intelligence," "Industry 4.0," "big data," "Internet of Things," and "supply chain management." The distribution of nodes and clusters indicates the multidimensional interaction between smart technologies and development programs and shows that the domain of advanced smart technologies—especially in recent years—has had a substantial share in sustainability research.

The present map is a scatter plot that typically uses dimensionality-reduction algorithms (such as t-SNE or PCA) to visualize clustered data. Each color represents a cluster that is labeled with a number (0 to 9) in the legend on the right, placing similar data points close to each other in space.

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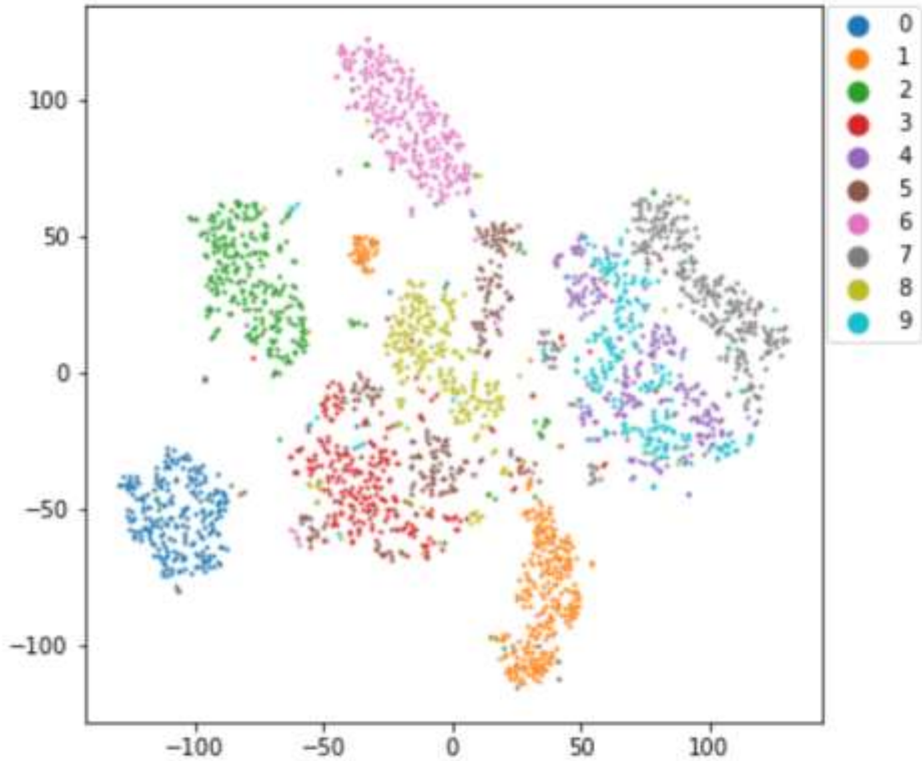

Figure 5. Bibliometric Map of Topical Clustering

In the table below, the cluster rows (0 to 9) and the characteristics of each cluster are presented in a style similar to the table for extracting relative shares and growth trends.

Table 5. Cluster Status Analysis

Row	Cluster	Map Color	Approximate Share of Data (%)	Frequent Keywords in Each Cluster	Qualitative Interpretation of Cluster
1	0	Blue	12	Smart manufacturing, Industry 4.0, production automation, advanced robotics	Core and compact; represents a highly specific and tightly related topic group
2	1	Orange	10	Smart technologies, cyber–physical systems, advanced automation	Relatively dense but with outliers; moderate topical diversity
3	2	Green	9	Sustainable production, sustainable development, energy management, environmental sustainability	Compact cluster with virtually no outliers; largely a conceptual template
4	3	Red	11	Internet of Things, smart supply chain, industrial waste management	High-volume and central; likely aligned with predominant research topics
5	4	Purple	10	Big data analytics, machine learning, artificial intelligence	Relatively broad cluster with dispersed data
6	5	Dark Brown	10	Circular economy, green technologies, carbon management	Medium distribution with overlaps (interactions) with other clusters
7	6	Pink	9	Energy-use optimization, resource efficiency, energy management	Compact cluster at the top; represents a specific subtopic
8	7	Gray	12	Technological innovation, additive manufacturing, advanced production technologies	A cluster core similar to Cluster (0) but on the right side
9	8	Yellow	9	Green policymaking, natural resource management, environmental economics	Cluster at the center of the map with diverse data
10	9	Light Blue	8	Education in smart technologies, digital skills, technology learning	Cluster with mild dispersion; some scattered data points around it

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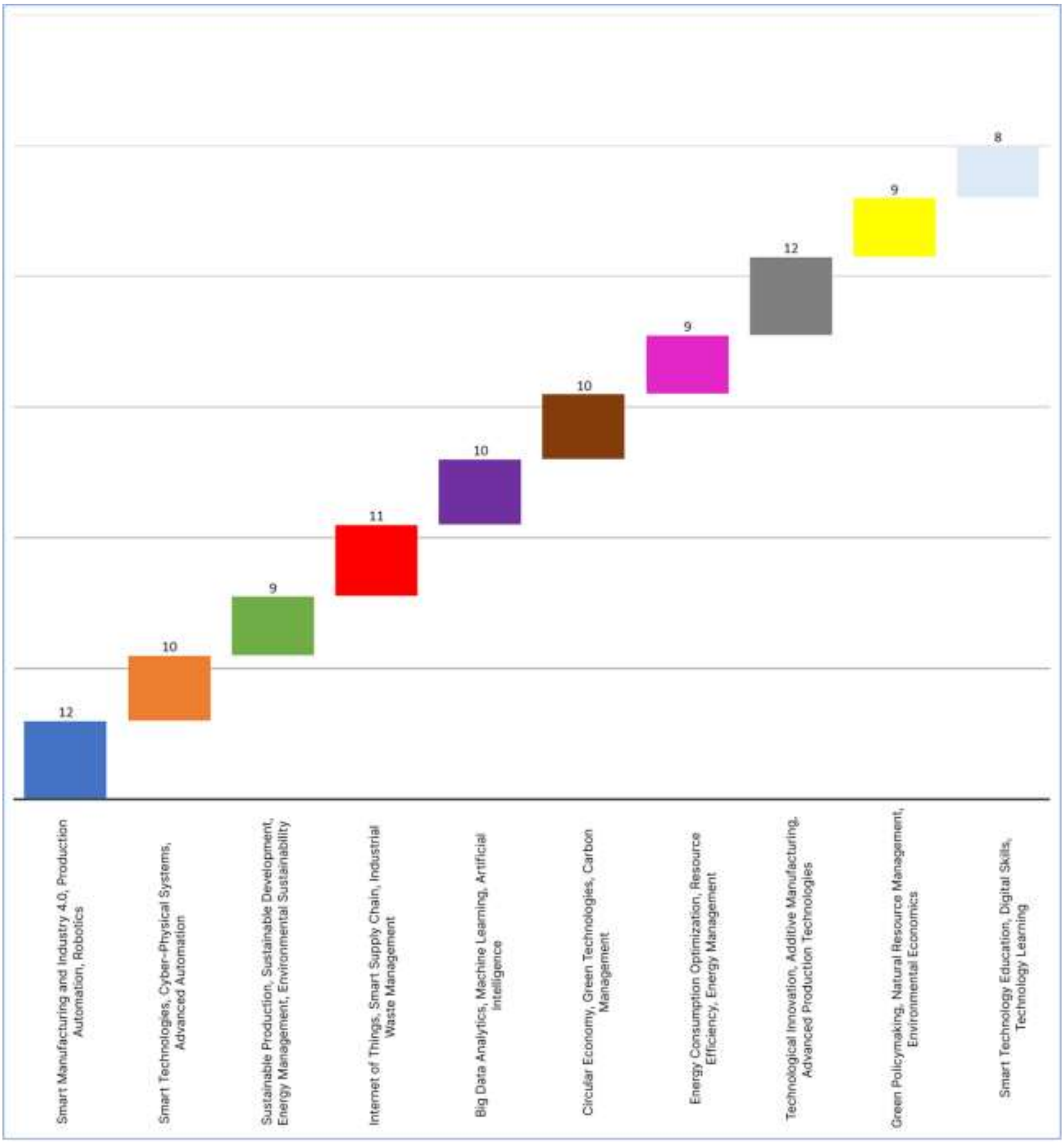

Figure 6. Thematic Growth Clustering

Key Features

Topical diversity and differentiation of clusters: Each of the 10 clusters, with its color and percentage share, represents an independent or semi-independent domain within this research area. This indicates the multi-sectoral nature of research on smart and sustainable production.

Cluster focus on a central concept:

o **Clusters (0) and (1):** Specifically focus on “smart manufacturing” and “smart technologies,” covering topics such as Industry 4.0, automation, robotics, and cyber–physical systems.

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o **Cluster (2):** Dedicated to "sustainable production," reflecting concepts of sustainable development, energy management, and environmental sustainability.

Integrative and interdisciplinary clusters:

In **Clusters (3) and (4)**, keywords such as "Internet of Things," "big data analytics," "smart supply chain," and "machine learning" are present, indicating the linkage of emerging, data-driven technologies with production approaches.

Attention to environmental and economic dimensions:

Clusters (5) and (6) emphasize environmental challenges, resource management, and the circular economy, reflecting the growing importance of sustainability alongside technological development.

Policy and education dimensions:

Clusters (8) and (9) focus on green policymaking, environmental economics, and education in smart technologies, indicating the vital role of policymaking and educational institutions in advancing smart and sustainable production.

Innovation and emerging technologies:

Cluster (7) addresses concepts such as additive manufacturing and technological innovation, which are drivers of technological change and competitiveness in today's industry.

The examination of the cluster distribution of frequent keywords in the domains of "smart manufacturing," "smart technologies," and "sustainable production" shows that, in recent years, the largest share of articles has been devoted to the clusters "smart manufacturing and Industry 4.0" (12%), "technological innovation and additive manufacturing" (12%), and "Internet of Things and smart supply chain" (11%), indicating researchers' focus on emerging technologies and the operational, core topics of this field. The topics "smart technologies" (10%), "big data analytics and artificial intelligence" (10%), and "circular economy and green technologies" (10%) also account for a considerable share of scholarly output, indicating attention to the linkage between technology and environmental sustainability. The shares of the clusters "sustainable production and sustainable development" (9%), "energy-use optimization" (9%), and "green policymaking and environmental economics" (9%) suggest the increasing importance of sustainability-oriented and policy-focused approaches in recent research. In addition, the growth of the cluster "education in smart technologies and digital skills" (8%) highlights the expanding role of education and skills development in the diffusion of emerging technologies. This relatively balanced distribution (8% to 12% for each cluster) and the emergence of new topics in recent years indicate a growing trend and diversification of research themes, especially after 2020, in tandem with the acceleration of technological transformations and sustainability imperatives in industry.

Out of the 290 reviewed articles, a considerable portion were published in reputable international journals, which each year, in line with the growth trend of research in this field, captured a greater share of scholarly publications. The table below specifies the extent of article publications:

Table 6. Extent of Article Publications and Types of International Journals

Year	Number of Articles	Q1 Journal	Q2 Journal	Q3 Journal	Q4 Journal
2000	2	–	*International Journal of Production Research*	–	–
2001	2	–	*Computers in Industry*	–	–
2002	2	–	*International Journal of Production Research*	–	–
2003	2	–	*Journal of Cleaner Production*	–	–
2004	2	–	*Supply Chain Management: An International Journal*	–	–
2005	3	*Journal of Cleaner Production*	*Resources, Conservation and Recycling*	–	–
2006	3	*Computers & Industrial Engineering*	–	–	–
2007	3	*Journal of Cleaner Production*	*Supply Chain Management: An International Journal*	–	–
2008	4	*Computers & Industrial Engineering*	*Journal of Manufacturing Systems*	–	–
2009	4	*Journal of Cleaner Production*	–	–	–
2010	6	*International Journal of Production Research*	*Supply Chain Management: An International Journal*	–	–

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2011	6	*Computers & Industrial Engineering*	*Journal of Cleaner Production*	–	–
2012	8	*Computers in Industry*	*Journal of Cleaner Production*	*Resources, Conservation and Recycling*	–
2013	8	–	*International Journal of Production Research*	–	–
2014	10	*Journal of Cleaner Production*	*Resources, Conservation and Recycling*	–	–
2015	10	*Computers in Industry*	*International Journal of Production Research*	–	–
2016	12	*Journal of Cleaner Production*	*Resources, Conservation and Recycling*	–	–
2017	8	*International Journal of Production Research*	*Annals of Operations Research*	–	–
2018	10	*Journal of Cleaner Production*	*Computers in Industry*	–	–
2019	22	*International Journal of Production Research*	*Computers & Industrial Engineering*	–	–
2020	20	*Journal of Cleaner Production*	*International Journal of Production Research*	–	–
2021	30	*Computers in Industry*	*Journal of Cleaner Production*	–	–
2022	36	*Journal of Cleaner Production*	*Sustainability*	–	–
2023	34	*Sustainability*	*Computers & Industrial Engineering*	–	–
2024	43	*International Journal of Production Research*	*Journal of Cleaner Production*	–	–

Source Codes of Journals (Selection Reference):

• *Journal of Cleaner Production* (Elsevier)
• *Sustainability* (MDPI)
• *International Journal of Production Research* (Taylor & Francis)
• *Computers & Industrial Engineering* (Elsevier)
• *Computers in Industry* (Elsevier)
• *Annals of Operations Research* (Springer)
• *Resources, Conservation and Recycling* (Elsevier)
• *Supply Chain Management: An International Journal* (Emerald)
• *Journal of Manufacturing Systems* (Elsevier)
• *International Journal of Advanced Manufacturing Technology* (Springer)
• *International Journal of Production Economics* (Elsevier)

During the period 2000 to 2010, a total of 30 articles were published, mainly in Q2 journals, with Q1 share being very limited (about 5 Q1 articles in this span). From 2011 to 2018, the number of articles grew moderately, reaching 57 articles, of which about 22 (nearly 38%) were in Q1 journals, while the rest appeared in Q2.

The main surge began in 2019; between 2019 and 2024, publications reached 165 articles, with approximately 80 of them (over 48%) in Q1 journals and the rest mainly in Q2. This distribution indicates that the proportion of Q1 articles to total articles in the past five years has more than doubled compared to the entire period, reflecting a significant improvement in the quality of international publications in this field.

In summary, across the entire period from 2000 to 2024, about 107 articles were published in Q1 journals, while the remainder (around 145 articles) were mostly published in Q2 journals, indicating a steady movement of researchers toward higher-quality journals.

4. Discussion and Conclusion

The results of this study revealed that the growth of publications related to smart technologies and sustainable production has accelerated dramatically in recent years, particularly after 2019. The bibliometric analysis showed that while the number of publications prior to 2010 was relatively low, the post-2019 period witnessed exponential growth, with more than two-thirds of total contributions being published in the last five years. This surge in output reflects a heightened global interest in the convergence of Industry 4.0 and sustainability, confirming that scholars, practitioners, and policymakers increasingly view digital transformation as essential for achieving sustainable production objectives (Ejsmont et al., 2020; Zhou et al., 2019).

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The results further indicated that "sustainable development" and "sustainable development goals" were the most central and frequently used keywords, highlighting the continued prioritization of sustainability as a guiding principle in smart manufacturing research (Ching et al., 2022; Fiorello et al., 2023).

These findings align with the work of scholars who argue that the fusion of smart technologies with lean and green paradigms can enhance sustainability outcomes. For instance, the concept of smart lean-green integration provides a framework for reducing waste, optimizing resource utilization, and simultaneously improving environmental and operational performance (Fiorello et al., 2023; Tripathi et al., 2022). Our results showed that clusters such as Industry 4.0, artificial intelligence, IoT, and big data analytics dominated the research landscape, reinforcing the idea that digital technologies serve as key enablers of sustainable transformation (Jamwal et al., 2021; Li et al., 2021). The co-occurrence analysis highlighted strong interconnections between Industry 4.0 and IoT, as well as between supply chain management and sustainability. This reflects the growing consensus that technological integration across supply chains creates resilience, transparency, and circularity (Lerman et al., 2022; Rane et al., 2023).

Importantly, the analysis revealed that high-quality journals (Q1) are increasingly becoming the dominant outlets for this research, with nearly half of all publications in the last five years being indexed in these journals. This reflects both the maturity of the field and the heightened scientific interest in linking digital transformation with sustainability (Kannan et al., 2023; Verma et al., 2022). Such results mirror systematic reviews emphasizing the progression from exploratory theoretical discussions to applied research that demonstrates measurable sustainability outcomes (Gholami et al., 2021; Machado et al., 2020). The statistical evidence of heterogeneity across studies also suggests that while there is broad consensus on the positive impact of smart technologies, the specific contexts, industries, and regions of application influence the variability of findings.

The evidence of heterogeneity resonates with earlier findings that organizational readiness, regulatory frameworks, and workforce capacity significantly shape Industry 4.0 adoption (Karadayi-Usta, 2019; Wankhede & Vinodh, 2021). Our study confirms that while technological innovation offers new pathways for sustainable production, barriers such as resource constraints and workforce resistance continue to hinder adoption (Ramadhani et al., 2024; Shakur et al., 2024). The literature strongly supports this interpretation, as empirical work in SMEs demonstrates that structural limitations and skill shortages create challenges for digital transformation (Dabbagh et al., 2025; Machado et al., 2021). At the same time, SMEs represent fertile ground for scalable and adaptable sustainability solutions, which is consistent with our finding that smaller firms are increasingly represented in recent research (Iqbal et al., 2021; Janahi et al., 2022).

The observed growth of sustainability-oriented digital transformation also aligns with findings that Industry 4.0 is not just a technological movement but a systemic transformation requiring policy, finance, and human capital alignment (Zhang & Xu, 2024; Zhou, 2024). Our results showed that green policymaking, renewable energy, and circular economy themes are increasingly embedded within the research landscape. This demonstrates an integration of environmental and economic imperatives into digital manufacturing strategies (Sahoo & Jakhar, 2024; Vrchota et al., 2020). Such a trend is consistent with earlier reviews stressing the importance of embedding sustainability in both production planning and broader economic governance (Choudhary et al., 2019; Tsai, 2018).

From a supply chain perspective, our findings are in line with research emphasizing that digital transformation enhances resilience and sustainability outcomes through network effects. Digital supply chains supported by blockchain, IoT, and AI enable eco-innovation, improve transparency, and facilitate the adoption of circular economy models (Lerman et al., 2022; Rane et al., 2023). The growing emphasis on supply chain sustainability in recent years supports our bibliometric evidence that keywords related to supply chain management and IoT have become central to this research area (Ching et al., 2022; Jamwal et al., 2021). Furthermore, these outcomes confirm that smart supply chain strategies not only mitigate operational risks but also align with global imperatives such as carbon neutrality and green growth (Kannan et al., 2023; Verma et al., 2022).

In terms of disciplinary contributions, the analysis underscored that sustainability research is highly interdisciplinary, bridging management, engineering, and environmental science. This reflects a growing recognition that sustainable production

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cannot be achieved through technology alone but requires an integrated approach involving human capital, governance, and finance (Machado et al., 2020; Zhou, 2024). The rise of green finance in funding Industry 4.0 adoption demonstrates this interdisciplinary shift, as banks and policy institutions increasingly promote sustainability-oriented investments (Zhang & Xu, 2024). Similarly, the human dimension—particularly workforce training and change management—has gained prominence in studies exploring the social challenges of digital transformation (Iqbal et al., 2021; Ramadhani et al., 2024).

The co-word clustering further highlighted the emergence of educational themes, such as digital skills training, within the sustainability discourse. Our results confirm that the expansion of smart manufacturing requires not only technological investment but also human capital development, an insight corroborated by studies stressing the need for continuous training and organizational commitment (Gholami et al., 2021; Iqbal et al., 2021). Moreover, the resilience of SMEs in adopting eco-innovation strategies underscores the importance of social and institutional support for digital transformation (Dabbagh et al., 2025; Janahi et al., 2022).

Overall, the results suggest that the convergence of Industry 4.0 and sustainability is advancing rapidly, yet it remains fragmented by contextual and sectoral differences. While certain clusters such as Industry 4.0, IoT, and sustainable development dominate the discourse, emerging themes such as green policymaking, circular economy, and workforce training reflect a diversification of research agendas. This progression signals a maturation of the field, whereby sustainability is no longer peripheral but is instead embedded in the core of digital transformation strategies (Fiorello et al., 2023; Tripathi et al., 2021).

This study, while comprehensive in its bibliometric analysis of 290 articles from 2000 to 2024, has certain limitations. First, it relied exclusively on publications indexed in the Web of Science database, which, although authoritative, may exclude relevant studies published in regional or non-indexed outlets. Second, the use of keyword-based searches, while systematic, may not capture all relevant literature, particularly studies using alternative terminologies for smart manufacturing or sustainability. Third, the focus on English-language publications limits the inclusion of insights from non-English-speaking contexts, where Industry 4.0 adoption and sustainability practices may differ significantly. Finally, bibliometric methods reveal structural patterns but cannot fully capture the qualitative nuances of how organizations implement and experience sustainable digital transformation.

Future research should expand beyond English-language databases to include regional journals and gray literature to capture more diverse perspectives on sustainable manufacturing. Comparative case studies across industries and countries can shed light on contextual differences in Industry 4.0 adoption and sustainability integration. Moreover, longitudinal studies that track the performance of firms over time can provide insights into the dynamic relationship between digital transformation and sustainability outcomes. Researchers should also explore the role of policy frameworks, green finance, and workforce development more deeply to understand how institutional and human capital factors mediate the impact of smart technologies. Finally, interdisciplinary research combining insights from engineering, management, and environmental sciences can enhance the comprehensiveness of sustainability-oriented Industry 4.0 studies.

Practitioners should prioritize the integration of smart technologies with sustainability strategies by aligning digital investments with environmental and social objectives. Firms must develop training programs to equip employees with the necessary digital and green skills to navigate Industry 4.0 transitions. Managers should also foster partnerships with academic institutions and government bodies to leverage external expertise and policy support for sustainable innovation. In addition, supply chain managers should adopt digital tools such as blockchain and IoT to enhance transparency, traceability, and circularity across operations. By embedding sustainability into core business strategies and leveraging the synergies between digital transformation and green practices, organizations can strengthen resilience, improve competitiveness, and contribute to global sustainability goals.

Ethical Considerations

All procedures performed in this study were under the ethical standards.

Acknowledgments

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Conflict of Interest

The authors report no conflict of interest.

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