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Toward Industry 5.0: Mapping technologies, competencies, and research opportunities

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Abstract

PURPOSE: *The goal of this study is to map the current state of academic knowledge on Industry 5.0 by identifying key technologies, required competencies, and emerging thematic areas through a systematic literature review. Based on this analysis, the study proposes a conceptual framework that synthesizes these findings to support future research and enhance understanding of this evolving industrial paradigm—particularly by identifying critical capabilities for implementing human-centric, sustainable, and resilient strategies aligned with the Sustainable Development Goals (SDGs).* ***METHODOLOGY:*** *A systematic literature review was conducted by querying the Scopus and Web of Science databases. This comprised eight steps designed to comprehensively understand existing literature on I5.0. In total, 470 papers were assessed, 112 of which qualified for subsequent data extraction and analysis.* ***FINDINGS:*** *The study organizes existing literature into five key thematic domains that structure current academic knowledge and guide future research on Industry 5.0: (1) Technologies and Digital Development; (2) Education, Skills, and Knowledge, alongside People, Ethics, Health, and Safety; (3) Society, Laws, and Government; (4) Benefits, Challenges, and General Factors, in conjunction with Organizational Strategy and Management; and (5) Sustainability. These domains offer a comprehensive perspective on the core components and interdependencies that characterize the Industry 5.0 paradigm. The findings also indicate that future research should prioritize empirical studies that examine how human-centricity, resilience, and sustainability are being operationalized within real-world industrial contexts.* ***IMPLICATIONS:*** *This study highlights specific gaps for future research, particularly the need to explore how human-centricity, sustainability, and resilience are integrated in practice. For organizations, the findings provide clarity on key technologies, competencies, and strategic priorities, helping guide transitions aligned with the SDGs.* ***ORIGINALITY:*** *While grounded in a systematic literature review, this study offers originality by structuring dispersed academic knowledge into five thematic domains that reflect the evolving nature of Industry 5.0. The resulting framework does not claim to be a new theoretical model but adds value by connecting concepts, technologies, competencies, and implementation challenges in a coherent and actionable structure. This contribution helps scholars frame future research and offers organizations a clearer path to navigating the Industry 5.0 landscape.*

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INTRODUCTION

Industry 5.0 (I5.0) refers to the use of technology not only to drive economic growth and job creation but also to support sustainability and place a strong emphasis on worker well-being (Breque et al., 2021). In line with this vision, the World Economic Forum introduced a new multidimensional framework in 2024 to evaluate national progress beyond GDP. This framework is built on four pillars: Innovation, Inclusion, Sustainability, and Resilience (WEF, 2024). The topic is gaining increasing attention in both academic and industrial circles (Madsen & Berg, 2021; Ghobakhloo et al., 2023). Indeed, several authors, including Xu et al. (2021), Cillo et al. (2022), and Madsen and Slåtten (2023), argue that the COVID-19 pandemic underscored the fragility of global supply chains and highlighted the need to rethink business models and work practices. The aim is to build industries that are better equipped for the future: more resilient, human-centric, and sustainable.

Most Industry 5.0 (I5.0) technologies have evolved from the advancements made during Industry 4.0 (I4.0), which primarily focused on digital transformation and the use of AI-driven technologies to enhance production flexibility and efficiency (Atif, 2023). While I4.0 emphasized process optimization, it often overlooked the human costs associated with these improvements. In this context, Nahavandi (2019) notes that I4.0 may encounter challenges and resistance, particularly due to concerns over job displacement and environmental impact. Joseph Schumpeter's theory of technological change helps explain how paradigms such as Industry 4.0 and Industry 5.0 emerge through innovation and "creative destruction," replacing old technologies and redefining production, work, and consumption models.

Although many Industry 4.0 (I4.0) technologies can also be applied within Industry 5.0 (I5.0), their implementation must now prioritize essential social needs, values, and responsibilities as core objectives. Several studies (Xu et al., 2021; Saniuk et al., 2022; Grabowska et al., 2022; Narkehede et al., 2024) suggest the emergence of a new techno-social revolution, in which technology serves as an enabler and social needs become the primary focus. This shift represents a fusion of two paradigms: the technology-driven approach of I4.0 and the value-driven perspective of I5.0 (Xu et al., 2021).

Nahavandi (2019) argues that I5.0 may offer a solution to the limitations of I4.0 by fostering a collaboration between humans and machines, allowing for greater use of human creativity and intellect to enhance both process efficiency and sustainability through the integration of intelligent systems into workflows. Similarly, Daoud et al. (2025) contend that I5.0 has the potential to drive innovation aligned with the Sustainable Development Goals (SDGs), promoting a more sustainable and human-centered model of development.

One key distinction between Industry 4.0 (I4.0) and Industry 5.0 (I5.0) lies in their core focus: while I4.0 emphasizes digitization and customization, I5.0 shifts toward personalization (Javaid & Haleem, 2020). The advancements made under I4.0 provide a foundation for the I5.0 framework, which is built on three main pillars: human-centricity, sustainability, and resilience (Nahavandi, 2019; Jafari et al., 2022; Ghobakhloo et al., 2022; Atif, 2023). The human-centric approach prioritizes individuals' interests, needs, and expectations, placing them at the heart of the production process. Rather than asking what can be done with new technologies, the guiding question becomes: what can these technologies do for humans? Furthermore, an exclusive focus on profit has proven to be unsustainable. It is now crucial—and increasingly urgent—to integrate social and environmental concerns in order to maximize not only efficiency and profit, but also long-term prosperity for all stakeholders, including shareholders, employees, customers, and society as a whole. This perspective also resonates with the Society 5.0 (Fukuyama, 2018), which emphasizes a human-centered technological evolution aimed at addressing societal challenges and enhancing overall well-being. In terms of resilience, Industry 5.0 emphasizes building greater robustness in industrial production, aiming to prevent disruptions and enable faster recovery from crises—specifically, events that could lead to process underperformance (Fonda & Meneghetti, 2022; Lu et al., 2022a; Atif, 2023; Madsen & Slåtten, 2023).

The European Commission has taken proactive steps to promote this vision through initiatives such as the Industry 5.0 Community of Practice (CoP 5.0), which supports the implementation of the New European Innovation Agenda (NEIA). This community brings together stakeholders to exchange ideas and advance innovation efforts aligned with I5.0 principles (European Commission, 2023a). However, Madsen and Berg (2021) and Ben Youssef and Mejri (2023) highlight the ongoing need for clearer and more consistent definitions of I5.0. To date, much of the existing literature offers only a broad overview, focusing on publication trends and identifying key documents, authors, sources, and countries—without delving deeply into the conceptual and practical dimensions of Industry 5.0.

Given the significance of the issues at stake—for academia, the business sector, and society at large—this paper aims to address the following research question (RQ):

RQ: What are the key issues that must be addressed in future research on Industry 5.0?

The main goal of this study is to map the current state of academic knowledge on Industry 5.0 by identifying key technologies, required competencies, and emerging thematic areas through a systematic literature review. Therefore, we propose a framework that organizes the core concepts and thematic trends found in the I5.0 literature, while also highlighting the central challenges that may shape future research directions.

To support this goal, a Systematic Literature Review (SLR) was conducted based on the methodology proposed by Tranfield et al. (2003). This structured approach allows researchers to "locate existing studies, select and evaluate contributions, analyze and synthesize data, and report the evidence in such a way which allows reasonably clear conclusions to be reached about what is already known" on a particular subject (Denyer & Tranfield, 2009, p. 671).

This article is organized into five sections. The first introduces and contextualizes the research problem, followed by a statement of the study's purpose. The second provides the theoretical background necessary to understand the central topic of Industry 5.0 (I5.0). The third outlines the entire Systematic Literature Review (SLR) process and highlights the study's main contributions and originality. The fourth section presents the key definitions, tools, skills, and capabilities associated with I5.0 identified in the literature, which are then analyzed within a theoretical framework and used to propose a research agenda. Finally, the fifth section summarizes the main findings and discusses the study's limitations and opportunities for future research.

LITERATURE REVIEW

It is important to raise certain questions and clarify key concepts related to Industry 4.0 (I4.0), Industry 5.0 (I5.0), the Fifth Industrial Revolution, and Society 5.0, as these terms are often sources of confusion and are sometimes used interchangeably or even merged. Pessôa and Becker (2020) draw a distinction between I4.0 and the Fourth Industrial Revolution, noting that I4.0 is specifically focused on the industrial environment, while the Fourth Industrial Revolution extends the I4.0 concept beyond the factory floor to encompass broader societal impacts. The authors also emphasize that the term "Industry 4.0" was introduced and formally defined at the Hannover Fair in 2011, whereas the Fourth Industrial Revolution—like its predecessors—does not have a fixed starting point and is typically viewed as a gradual and evolving process.

Breque et al. (2021) explain that the concept of Industry 5.0 (I5.0) originated from a 2020 meeting that brought together European research institutions, technology organizations, and funding agencies. This meeting resulted in a European Commission document titled "Industry 5.0: Towards a sustainable, human-centric and resilient European industry." However, the exact timing of when the concept first emerged is still debated. Breque et al. (2021) also note that the idea of Society 5.0 was introduced earlier, in 2016, by an industrial federation in Japan. Furthermore, the way people secure their livelihoods is closely tied to how they shape society, with the numbering of societies (such as Society 5.0) following a different timeline than that of Industry 5.0. The first two societies correspond to pre-industrial eras. Society 3.0 roughly overlaps with the first, second, and part of the third industrial revolutions. Society 4.0 represents a highly digitized stage that spans the third industrial revolution up to the present day. According to this model, the upcoming Society 5.0 aims to balance solutions to environmental and social challenges alongside economic growth.

Although the European Commission has played a significant role in advancing Industry 5.0, research on the topic is clearly spreading well beyond Europe. Martins et al. (2022) identify India, Italy, and the USA as the three leading countries in conducting and publishing research on I5.0. Similarly, Slavic (2023) points to China, India, and Italy as the most productive countries in terms of publication volume. Rejeb et al. (2025) also highlight China, India, and Italy as the top contributors to the literature. While Italy consistently appears as a key player in all three studies, the other leading countries are outside Europe. This demonstrates that, from a scientific standpoint, knowledge about Industry 5.0 is increasingly expanding across regions worldwide.

Kraaijenbrink (2022) argues that the core of Industry 5.0 (I5.0) marks a shift in focus from economic value to social value. Integrating social and environmental concerns into industry is not entirely new—it echoes concepts like Corporate Social Responsibility, ESG, and the Triple Bottom Line. Ghobakhloo et al. (2023b) also emphasize that many sustainable manufacturing practices discussed are not unique to I5.0. In fact, Piccarozzi et al. (2023) note that Industry 4.0 (I4.0)

offers technologies that can advance sustainability but require a systemic perspective combined with innovative business models. Kraaijenbrink (2022) points out that while many ideas within I5.0 have been explored before, the proposal to prioritize the planet and people over profits and growth as the defining goals of industry is unprecedented. This represents a fundamental rethinking of the industry's core objectives. This paradigm shift also aligns with broader policy efforts, such as those supported by the European Structural and Investment Funds (ESIF), which seek to foster economic, social, and territorial cohesion through inclusive and sustainable growth initiatives (Veiga, 2025).

Along these lines, Nahavandi (2019) suggests that, unlike Industry 4.0 (I4.0), which focuses on improving process efficiency through automation often without considering the human cost, Industry 5.0 (I5.0) aims to use automation to enhance the work experience for employees. Its goal is to bring people back into the workplace and improve process efficiency by supporting collaboration. In fact, while Industry 5.0 emphasizes human-centricity, ethics, and societal well-being, the ethical foundations of its implementation remain insufficiently developed. There is a notable gap between the aspirational discourse on ethical industrial transformation and the concrete mechanisms by which ethical principles are operationalized in practice.

Moreover, Potoczek (2021) points out that the digitalization driven primarily by Industry 4.0 has been influenced not only by technological innovation but also by customer demands and various social, environmental, political, and health factors that have contributed to the rise of Industry 5.0. According to Vacchi, Siligardi, and Settembre-Blundo (2024), the shift from Industry 4.0 to Industry 5.0 represents a paradigm change—from automation and data collection to smart manufacturing and human-centered automation. Nahavandi (2019) argues that I5.0 offers a solution by integrating humans and machines, harnessing human creativity and intellectual capacity to boost process efficiency through the combination of workflows and intelligent systems.

According to Pathak et al. (2019), the core principles of Industry 5.0 (I5.0) include mass customization (tailoring products or services to individual needs), cultural collaboration (breaking down borders between countries and regions to foster new ideas that improve products), customer centricity (placing customer aspirations at the center), cyber-physical systems (developing intelligent systems that help meet customer needs), and green computing (emphasizing the use of renewable energy sources). Bettiol et al. (2023) further explain that knowledge creation and innovation rely not only on technology but also on the relationships a company builds both within and beyond its organizational boundaries. Therefore, since I5.0 emphasizes human-centricity, prioritizing the quality of relationships inside and between organizations is crucial for effective knowledge and innovation management.

METHODOLOGY

This article presents a systematic literature review (SLR), which is defined as a method for searching and analyzing scientific articles in a specific area of interest to ensure greater rigor and more reliable results (Denyer & Tranfield, 2009). Following the approach outlined by Tranfield et al. (2003), the SLR was carried out in eight steps, organized into three phases: planning, conducting, and reporting (see Figure 1).

By examining the current research landscape on Industry 5.0 (I5.0) and reviewing the existing literature (step 1), the main gap identified was the lack of in-depth investigation into this emerging topic. Therefore, this systematic literature review (SLR) aims to establish a foundation for identifying and organizing key concepts and themes related to I5.0, and proposes a framework to guide future research efforts.

To explore this literature, four review questions were formulated, derived from the overall research question:

RQ1: What are the definitions and foundational concepts surrounding Industry 5.0?
RQ2: What are the most relevant technologies and tools for implementing Industry 5.0?
RQ3: What skills and capabilities are required for implementing Industry 5.0?
RQ4: What gaps and research opportunities exist within Industry 5.0?

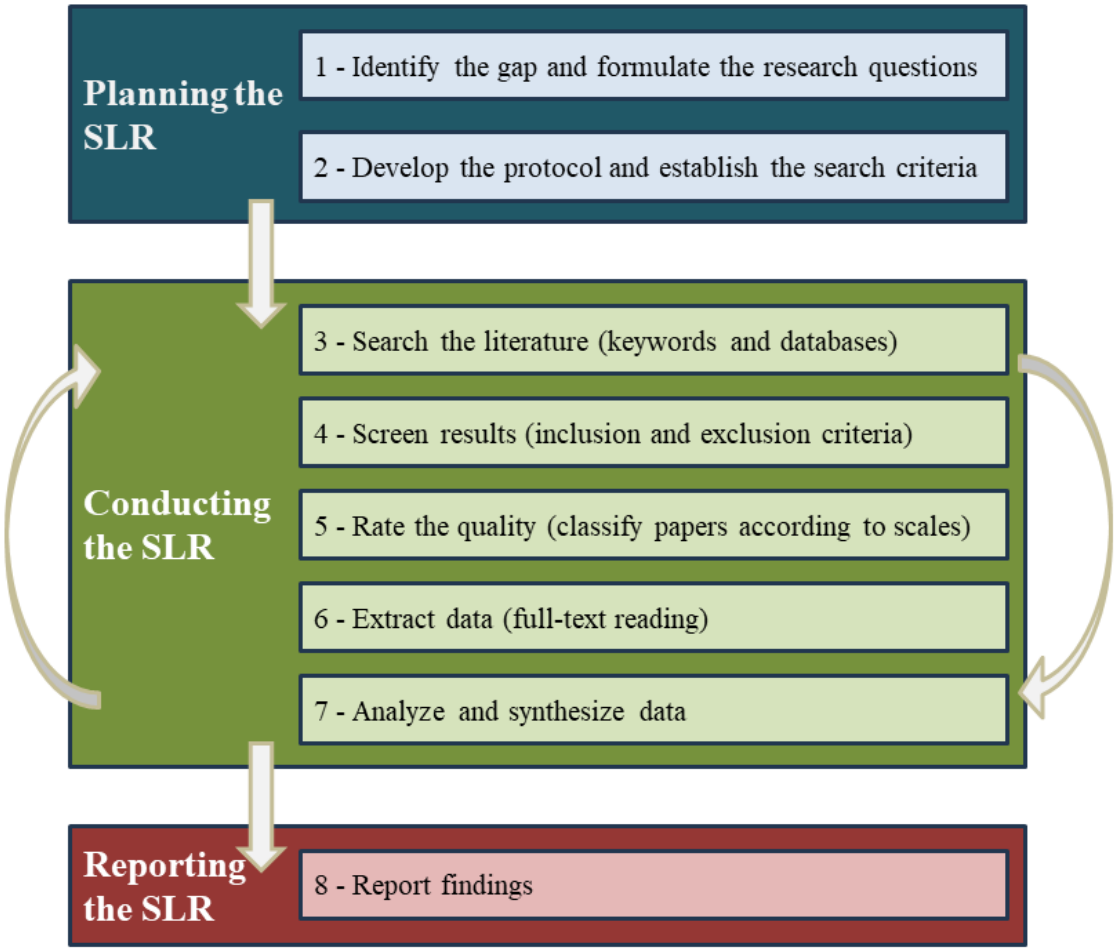

Figure 1. SLR process.
Source: Adapted from Tranfield et al. (2003).

The following criteria were established to develop the research protocol (step 2). Scopus and Web of Science were chosen as the primary databases due to their extensive coverage and accessibility of relevant articles. Initially, the authors considered other databases, such as ScienceDirect, EBSCO, and PubMed. However, most of the relevant articles were already identified through searches in Scopus and Web of Science. Since both are well-established and comprehensive databases (Mongeon & Paul-Hus, 2016; Li et al., 2016), the search was focused on these two. In research areas that are relatively new or specialized, broader database coverage is especially important for capturing a wider range of relevant studies (Balstad & Berg, 2020; Zupic & Cater, 2014).

After testing various terms, "Industry 5.0" was selected as the search string for the title, keywords, and abstract fields, as the goal of this review is to gather broad and up-to-date information on this emerging topic (step 3). The authors decided not to include specific keywords directly related to I5.0, since existing systematic literature reviews already cover those aspects. For example, Alves et al. (2023) focused on the human-centricity of I5.0, Ghobakhloo et al. (2023) discussed I5.0 in relation to sustainability, and Borchardt et al. (2022) examined resilience from the perspective of education and training.

No time frame was applied to capture the earliest appearance of this topic in academic literature. After the initial search results, duplicate papers were removed. Two inclusion criteria were then applied in the first screening: language—excluding any articles not written in English, Spanish, or Portuguese—and accessibility—excluding articles lacking access information such as a DOI (step 4). These criteria were set to ensure that the selected articles are in languages familiar to the researchers and are readily accessible, thereby supporting the replicability of the study.

The results presented here were obtained by following the research protocol outlined in Figure 1 and detailed in Figure 2. The initial database search was conducted in December 2021, yielding 105 papers that were analyzed and

categorized according to the established criteria (step 5). The search was then updated twice: first in August 2022, covering papers published between December 2021 and August 2022, which added 169 new articles; and again in May 2023, covering August 2022 to May 2023, which added 196 more articles. Out of a total of 1,419 documents identified, 470 were screened, and 112 were selected for data extraction.

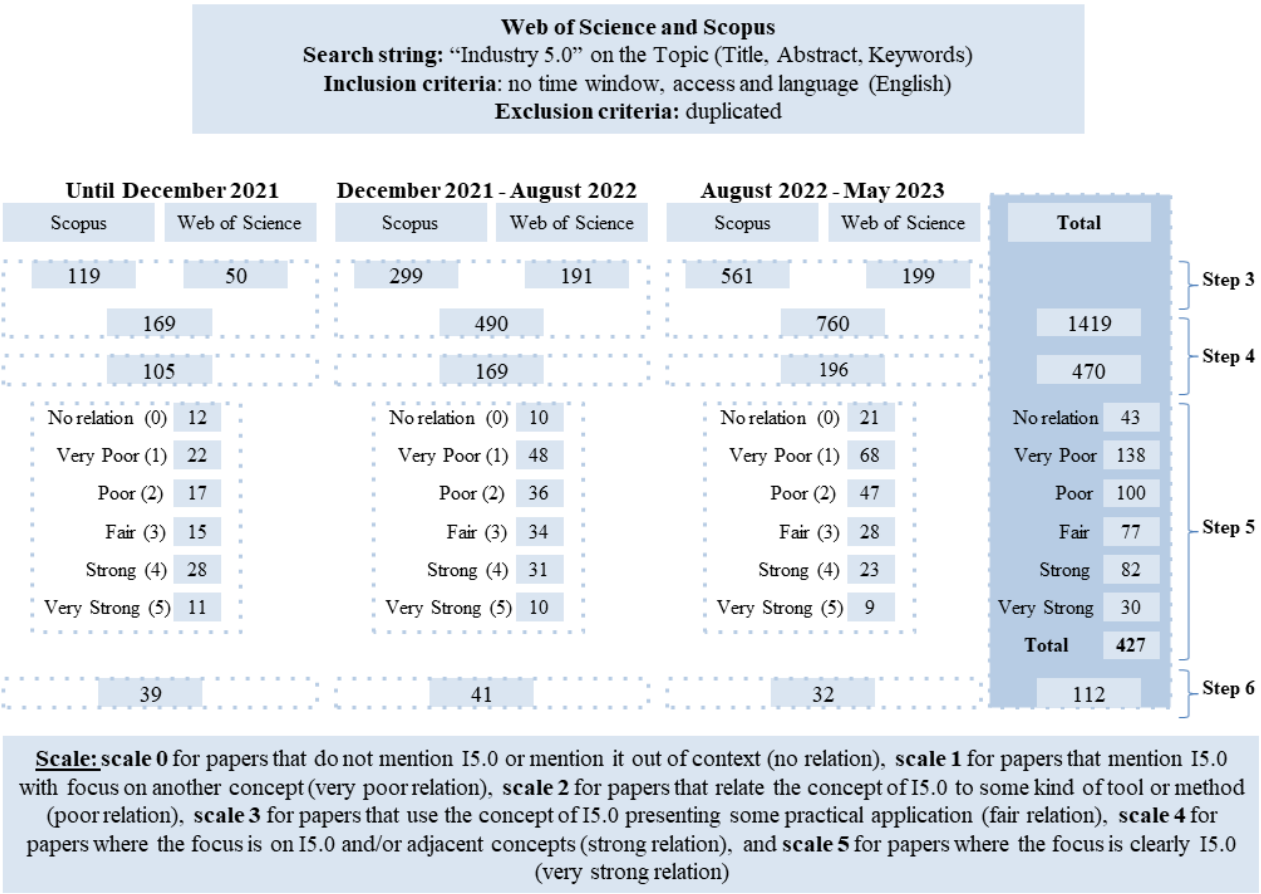

Figure 2. Overview of the SLR

Before analysis, the papers were classified according to their relevance to Industry 5.0 (I5.0) using the scale proposed by Martins et al. (2022) (step 5). Only those rated as "strong" or "very strong" were included for data extraction and analysis, as they were considered most relevant to addressing the review questions (steps 6 and 7). The results of the systematic literature review (SLR) are presented in the results and discussion section (step 8).

Out of the 470 papers assessed during the quality rating process (step 5), 82 were rated as strong (4) and 30 as very strong (5) in their relation to I5.0, and were thus selected for full-text data extraction (see Figure 2). The SLR team consisted of four researchers working in pairs to conduct the classification rounds, with each pair reviewing the other's work to ensure consistency and quality.

The 82 papers rated as strong (4) and the 30 rated as very strong (5)—a total of 112 documents—were selected for data extraction through full-text reading. Their content formed the basis for reporting the results. Figure 3 illustrates the publication trends over the years: out of 427 selected papers (excluding those rated 0, meaning no relation to I5.0), 222 were published in 2022 and 88 in 2023 (up to May), representing over 70 percent of the total.

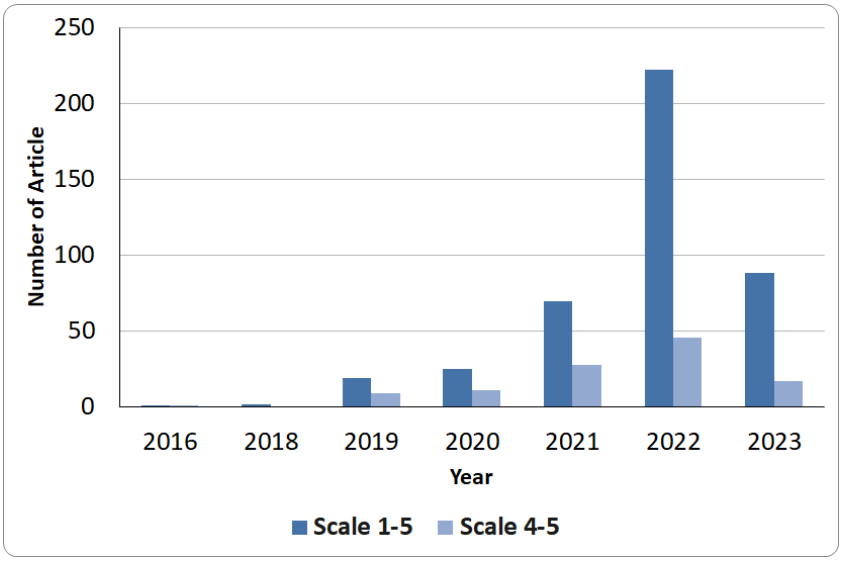

Figure 3. Number of publications by year

Finally, Figure 4 provides a summary of the research steps. The data extraction process involved a thorough reading of each of the 112 selected articles, followed by systematic recording of information using spreadsheet software. Basic bibliographic details were collected, including authorship, publication source, research method, and keywords. Additionally, the following elements were manually coded: the definition of Industry 5.0 used, references to Society 5.0, cited technologies and applications, the main contributions of each study, as well as identified research gaps and emerging trends.

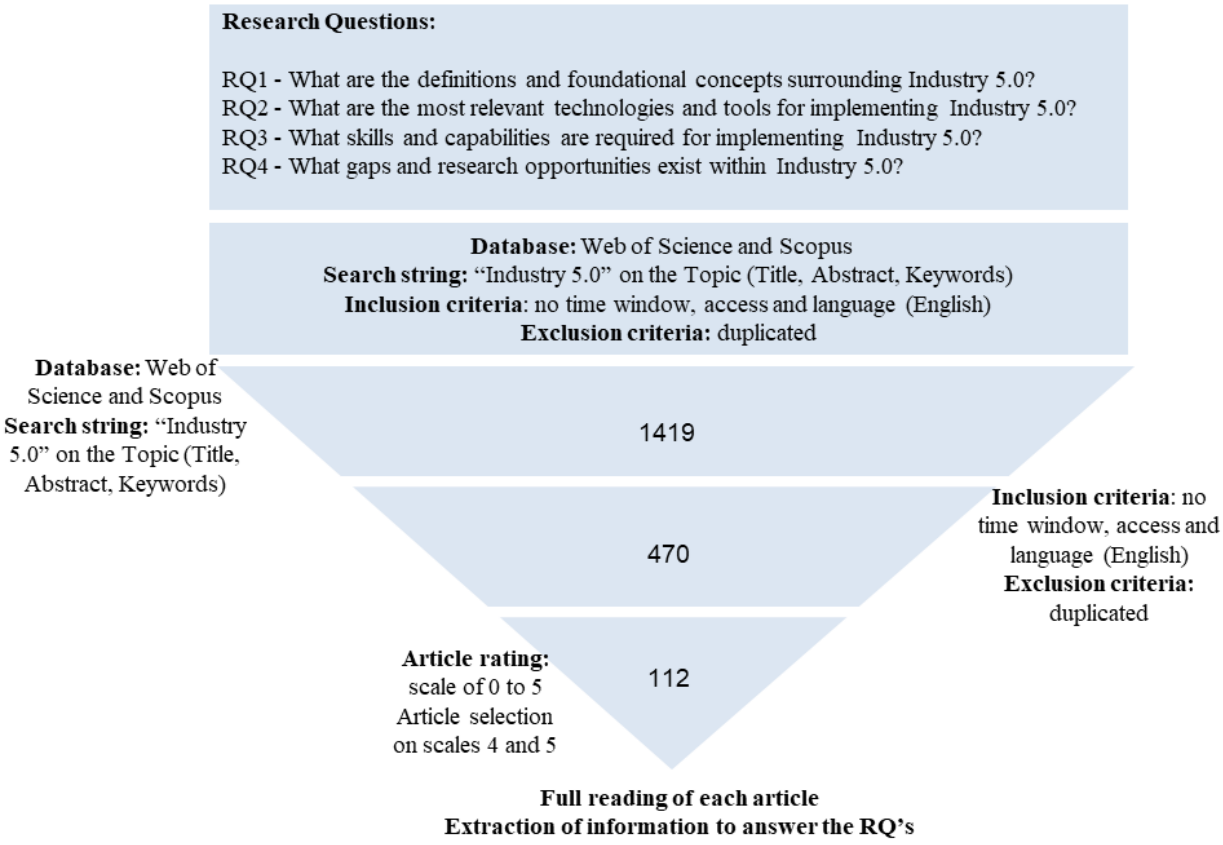

Figure 4. Research stages

While this approach (Figure 4) helped maintain clarity in the scope of the review, it may not have captured studies that address related ideas using alternative terminology—such as "fifth industrial revolution," "human-centric manufacturing," or "Society 5.0". Additionally, the review was limited to two databases (Scopus and Web of Science), publications in English, Spanish, or Portuguese, and access was restricted to institutional affiliations in Brazil and Portugal.

RESULTS AND DISCUSSION

The findings (step 8 of the SLR process) are presented in the following sections, organized around this article's four research questions. The analysis includes articles selected across the three data collection stages (Figure 2) and covers publications up to May 2023. Notably, among the 112 articles identified, the three countries with the highest number of publications are India (17), Italy (11), and the USA (7). This finding aligns with those from other studies, such as Martins et al. (2022), Slavic (2023), and Rejeb et al. (2025). Beyond these leading countries, the research also incorporates publications from a diverse range of regions worldwide. The top 12 countries by number of publications are: Ireland (5), the United Kingdom (5), Russia (5), Greece (4), Germany (3), China (3), Indonesia (3), Norway (3), and Poland (3).

The research methods identified during data extraction are summarized in Table 1, with the studies grouped as follows: The "reviews" category includes various literature review methods classified differently by authors, such as bibliometric analysis (BA), literature review (LR), constructive research methodology (CRM), integrative literature review (ILR), and systematic literature review (SLR). The "theoretical" group comprises papers that are neither reviews nor applied studies but offer discussions or descriptive approaches—sometimes labeled as theoretical studies—or editorial articles. The "qualitative" group includes case studies, action research, grounded theory, and interviews. The "quantitative" group encompasses studies that utilize statistical, modeling, or experimental analyses, as well as decision-making methods such as the Analytic Hierarchy Process (AHP), simulations, and surveys. Finally, the "mixed" group refers to articles combining qualitative or review methods with quantitative approaches, often considered applied studies related to I5.0. While some papers in the mixed methods group address applications related to digital technologies in I5.0, none report actual cases of I5.0 implementation. This highlights the need for more empirical research on this emerging topic.

Table 1. Distribution of publications by research methods

Research method	Total publications (n)
Theoretical	49
Reviews	30
Mixed	12
Quantitative	12
Qualitative	9
Total	**112**

Given the novelty of the concept, the authors anticipated that many papers from the SLR would be theoretical or focus on various types of literature reviews. This was taken into account during data analysis and synthesis (step 7) to identify the objectives of each review paper and to compare their goals with those of this study. Among the 30 review papers identified, 9 used bibliometric analysis, 12 were literature reviews, 1 applied constructive research methodology, 1 conducted an integrative literature review, and 7 performed systematic literature reviews.

Theoretical data were examined using content analysis, focusing on the keywords and research questions addressed in each review, which helped clarify the aims of each study. This approach revealed which aspects of each article were relevant to the present study. Notably, most authors (16 out of 30) conducted reviews on topics related to, but not directly focused on, Industry 5.0, often linking it to related concepts such as Society 5.0 and Employment 5.0, as summarized in Table 2.

Table 2. Review papers from SLR with no focus on Industry 5.0

Subjects only related to Industry 5.0	Review papers
Circular economy	Atif (2023)
Construction industry	Marinelli (2023)
Industry 4.0	Grabowska et al. (2022), Roblek et al. (2021), Mourtiz et al. (2022a), Kolade and Owoseni (2022), Dhirani et al. (2023), Marinelli (2022), Madhavan et al. (2022)
Innovation management	Aslam et al. (2020)
Lean manufacturing	Mladineo et al. (2021)
Maritime industry	Shahbakhsh et al. (2021)
Supply chain and smart logistics	Frederico (2021), Jafari et al. (2022)
Technological competitiveness	Alvarez-Aros and Bernal-Torres (2021)
Trauma and orthopaedics	Iyengar et al. (2022)

The remaining 14 articles are more focused on I5.0 itself and, consequently, show more similarities to this SLR as described in Table 3 and discussed as follows. Same database: Agarwal and Chauhan (2022), Borchardt et al. (2022), and Pizon and Gola (2023) also conducted their searches using the Scopus and Web of Science databases. However, their reviews were more targeted in scope, focusing respectively on: e-commerce and cobots; Industry 5.0 in the context of business and management operations; and human–machine interaction. Same keyword: Akundi et al. (2022) and Madsen and Berg (2021) chose to use "Industry 5.0" as their sole search term. Despite this similarity, their research methods and selected databases differ from those used in this SLR. Additionally, Akundi et al. (2022) limit their discussion to five major themes related to Industry 5.0 found in the literature, while Madsen and Berg (2021) explore the main differences between Industries 4.0 and 5.0, with a focus on bibliometric data. Same research method: Alves et al. (2023), Borchardt et al. (2022), Ghobakhloo et al. (2023), Hein-Pensel et al. (2023), and Tavares et al. (2022) also conducted systematic literature reviews (SLRs). However, as shown in Table 3, their approaches were more narrowly focused on specific aspects related to Industry 5.0, rather than the concept as a whole.

Table 3. Description of review papers from this SLR

Author (year)	Method	Search criteria	Main goals and discussions
Agarwal and Chauhan (2022)	Literature Review	Database: Scopus and Web of Science Keywords: „E-commerce industry" + „cobots" (and related terms)	This study focuses on the essential employability skills needed to work with cobots in the e-commerce industry, emphasizing that effective collaboration between cobots and humans relies on three key drivers: Human Resources acting as change agents, employees' skills, and organizational support.
Akundi et al. (2022)	Literature Review	Database: IEEE, Science Direct and MDPI Keywords: „Industry 5.0"	The authors analyze the current state of Industry 5.0 and identify five major themes: supply chain, enterprise innovation, smart and sustainable manufacturing, transformation driven by Industry 4.0 technologies, and human-machine coexistence.
Alves et al. (2023)	Systematic Literature Review	Database: Science Direct, Scopus, and Web of Science Keywords: "Industry 5.0" + "Human-centricity"	Given the novelty of Industry 5.0, the authors center their discussion on its human-centric nature after presenting bibliometric data, raising the question: "If Industry 5.0 is human-oriented, will Industry 6.0 focus on environmental concerns?"
Ben Youssef and Mejri (2023)	Bibliometric Analysis	Database: Scopus Keywords: "Industry 5.0" + terms of I4.0 technologies + "smart sustainability"	The authors provide a general bibliometric analysis on Industry 5.0, highlighting that while the results cover a broad spectrum, there is still a need for more literature on the topic.
Borchardt et al. (2022)	Systematic Literature Review	Database: Scopus and Web of Science Keywords: "Industry 5.0" + filter of subject area "business and management operations"	The primary goal of the study is to analyze and understand Industry 5.0 from the perspective of business and operations management, identifying four main themes: technological applications, human resources and workers, education, and business and operations management.

Author (year)	Method	Search criteria	Main goals and discussions
Espina- Romero et al. (2023)	Bibliometric Analysis	Database: Scopus Keywords: „Industry 5.0" + „human-centered Industry 4.0"	The study aims to assess the current state of Industry 5.0 through bibliometrics, discussing the most influential industries and key topics for future research, such as sustainability, cobots, bioeconomy, smart cities, and sentiment analysis.
Ghobakhloo et al. (2023)	Systematic Literature Review	Database: Scopus, Web of Science, and Google Scholar Keywords: „Industry 5.0" + „Society 5.0"	This paper explains how Industry 5.0 transformation supports sustainable development. After reviewing previous research and outlining its main characteristics, the authors propose a roadmap of 11 critical enablers for sustainable industrial growth and recommend extending this work in future studies.
Hein-Pensel et al. (2023)	Systematic Literature Review	Database: SpringerLink, ScienceDirect, and ResearchGate Keywords: terms related to manufacturing, Industry 4.0, human-centricity, and maturity models	This study investigates whether existing maturity models for Industry 4.0 are suitable for evaluating digital transformation processes in the context of Industry 5.0, particularly emphasizing the human-centered perspective in small and medium-sized enterprises (SMEs).
Humayun (2021)	Literature Review	No search criteria were provided in the paper	Another author discusses general aspects of Industry 5.0, including concepts, applications, enabling technologies, opportunities, and challenges within the Fifth Industrial Revolution.
Madsen and Berg (2021)	Bibliometric Analysis	Database: Scopus Keyword: "Industry 5.0"	Through exploratory bibliometric analysis, authors compare Industry 4.0 and 5.0, examining publication trends in citations, countries, authors, and sources, while suggesting future research should include more in-depth review studies.
Pizon and Gola (2023)	Literature Review	Database: Scopus and Web of Science Keywords: terms related to human-machine + Industry 5.0	The authors explore the human–machine relationship within Industry 5.0, asking: "How is the perspective on human–machine relationships changing, and what developmental path accompanies these changes?"
Proia et al. (2022)	Literature Review	Database: IEEE Keyword: "cobots" (and related terms)	This study focuses on critical aspects of human-robot collaboration (HRC), identifying safety, ergonomics, and efficiency as the main priorities, alongside control techniques used in collaborative robotics.
Raja Santhi and Muthuswamy (2023)	Literature Review	Database: Google Scholar, Scopus, and Web of Science Keywords: combinations of "Industry 4.0" + "Industry 5.0" + various technologies	The authors identify and describe enabling technologies of Industry 4.0, their application across manufacturing functions, and discuss Industry 5.0's sustainability aspects, suggesting it might be called "Industry 4.0S."
Tavares et al. (2022)	Systematic Literature Review	Database: Scopus and Google Scholar Keywords: "Industry 4.0" + "Industry 5.0" + "Society 5.0" + "Education 5.0"	The authors highlight the paradigm of a new era they term "Era 5.0," encompassing Society, Education, and Industry 5.0. They present discussions on each topic and on Industry 4.0, pointing out the most promising applications to develop a more humanistic and sustainable society.

None of the reviewed articles adopts the same methodological procedures and research criteria as those used in the present study. While some papers share a similar structure, the authors emphasize the following limitations and suggestions for future research: the need for more in-depth review studies that extend beyond bibliometric analysis and cover different timeframes, particularly using both Scopus and Web of Science databases, given the rapid emergence of the I5.0 topic (Madsen & Berg, 2021); and the necessity of expanding the literature on the definition and conceptual framing of Industry 5.0 (Ben Youssef & Mejri, 2023; Ghobakhloo et al., 2023).

To achieve the main goal of this study, which is to map the current state of academic knowledge on Industry 5.0 by identifying key technologies, required competencies, and emerging thematic areas through a systematic literature review, this SLR is guided by the four research questions outlined in the previous section. Addressing these questions is essential not only to understand the current state of the literature but also to consolidate existing knowledge and provide clear, precise definitions of Industry 5.0. In doing so, the study aims to identify and highlight real gaps in the field, which are subsequently incorporated into a proposed research agenda.

RQ1 – What are the definitions and foundational concepts surrounding Industry 5.0?

Although Industry 5.0 has gained increasing attention in academic and industrial discourse, the concept remains poorly defined. The absence of a unified and operationalized definition contributes to theoretical fragmentation and impedes the consolidation of a coherent research agenda. This ambiguity hinders the clear differentiation of Industry 5.0 from its predecessor, Industry 4.0, and impedes the development of robust frameworks for analysis and implementation.

According to Demir et al. (2019), the industrial revolutions were driven by the aim of separating "human work" from "machine work." The term refers to technological advancements that have transformed society (Taj & Jhanjhi, 2022). Since 1784, it is evident that technological innovations have disrupted traditional production models, subsequently influencing societal development. Industry 1.0 harnessed the power of water and steam to perform mechanical work. Industry 2.0 introduced electricity as the key enabler of new production methods. The emergence of information technology in production processes led to the era of Industry 3.0, characterized by the automation of systems. Industry 4.0 (I4.0) emphasizes productivity enhancement through cutting-edge technologies, including the Internet of Things (IoT), robotics, artificial intelligence (AI), big data, and cloud computing (Javaid & Haleem, 2020; Mourtzis et al., 2022a).

According to Madsen and Slåtten (2023), unlike the well-documented onset of Industry 4.0 (I4.0), it is challenging to determine when Industry 5.0 (I5.0) began precisely. These authors suggest that the concept was first introduced by Michael Rada in 2015 via social media platforms. Since then, discussions surrounding I5.0 have grown steadily in both academic literature and on social media. In contrast, Breque et al. (2021) argue that I5.0 originated from a 2020 meeting involving European research institutions, technology organizations, and funding agencies.

Some of the earliest academic publications to reference I5.0 include works by Sachsenmeier (2016), Özdemir and Hekim (2018), Nahavandi (2019), and Alvarez-Aros and Bernal-Torres (2021). These studies began to address the challenges and societal impacts of I4.0 technologies, marking a shift toward the human-centric perspective now associated with I5.0. These early contributions can be considered seminal, as they highlight the need for a paradigm shift in the direction of industrial development. Figure 5 shows how frequently these foundational papers are cited across the 112 articles analyzed in this study, along with their key contributions to the conceptualization of Industry 5.0.

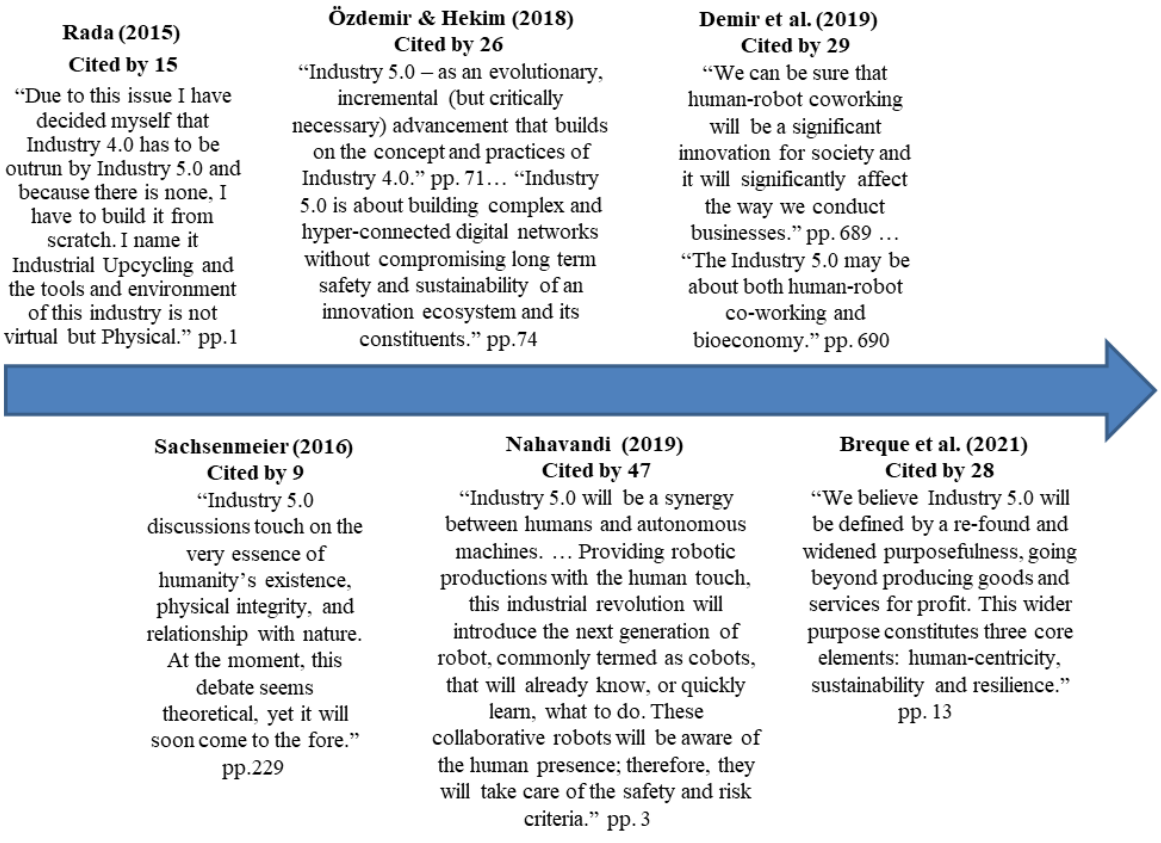

Figure 5. Industry 5.0 concepts identified in the analyzed articles

Although it is difficult to pinpoint the exact starting point of Industry 5.0 (I5.0), the concept has quickly gained traction among academic researchers, as illustrated in Figure 3. Despite the growing dissemination of ideas summarized in Table 1, Ghobakhloo et al. (2023a) argue that I5.0 remains an emerging and underdeveloped concept, with no consensus yet established around its definition. For example, echoing the perspectives of Rada (2015) and Sachsenmeier (2016), Østergaard (2020) describes I5.0 as the return of the "human touch" to the factory floor. In comparing Industry 4.0 and 5.0, Johansson (2017) explains that while I4.0 is primarily focused on interconnecting devices, I5.0 emphasizes collaboration between humans and machines in industrial environments. Similarly, Bednar and Welch (2020) note that I4.0 aimed to accelerate technological performance, whereas I5.0 emphasizes the need for synergy between technological and social systems to enable the mass customization of goods and services. Thus, rather than replacing human workers, I5.0 is centered on optimizing human–robot collaboration—leveraging each other's strengths and compensating for their respective limitations (Welfare et al., 2019).

Several of the analyzed papers emphasize collaboration between humans and machines. For example, Nahavandi (2019), Javaid and Haleem (2020), Madsen and Berg (2021), Kumar et al. (2021), Shahbakhsh et al. (2022), Javaid et al. (2020), and Chin (2020) highlight the importance of human–machine synergy through the use of autonomous systems, collaborative robots, and other digital technologies. These technologies are applied to reduce waste, lower final manufacturing costs, and enable the production of more personalized products and services. As a result, it is expected that intelligent robots and systems will play a significant role in shaping the future of supply chains (Frederico, 2021).

Although Pathak et al. (2019) suggest that the primary goal of Industry 5.0 (I5.0) is to represent an evolutionary and incremental advancement of Industry 4.0 (I4.0), Xu et al. (2021) and Mourtzis et al. (2022a) emphasize that I5.0 should not be seen as a chronological continuation of I4.0. The European Commission (EC) instead proposes a paradigm shift, aiming to transform industry into a resilient engine of prosperity—one that respects planetary boundaries while placing the well-being of industrial workers at its core (Breque et al., 2021). As Xu et al. (2021) note, the COVID-19 pandemic highlighted the limitations of purely evolutionary approaches and underscored the need for a new industrial paradigm centered on resilience, human-centricity, and sustainability.

Breque et al. (2021) also highlight a growing synergy in Industry 5.0 (I5.0) between key technological drivers and societal development, organized into six main categories: human–machine interaction, bio-inspired technologies and smart materials, digital twins and simulation, big data analytics, artificial intelligence, and energy efficiency. While many of these technologies were already central to Industry 4.0 (I4.0), I5.0 emphasizes the importance of the human–machine interface in their application. In this regard, I5.0 does not introduce entirely new technologies or breakthroughs. Instead, this new industrial paradigm encourages companies to redefine their roles—not only as engines of job creation and economic growth, but also as contributors to broader environmental and social values (Lattanzio et al., 2022).

Pramanik et al. (2020) and Mladineo et al. (2021) describe Industry 5.0 (I5.0) as a natural evolution of Industry 4.0 (I4.0), emphasizing the European Commission's concept, which frames I5.0 as the fusion of human creativity with the speed, productivity, and precision of robots. Similarly, other scholars—including Gürdür Broo et al. (2022), Akundi et al. (2022), Romero and Stahre (2021), Taj and Jhanjhi (2022), Bitsch (2022), and Mourtzis et al. (2022a)—present a shared understanding of I5.0 built on three core pillars: human-centricity, resilience, and sustainability. However, there is still a lack of consensus across the literature regarding these defining characteristics.

Figure 6 shows that most of the analyzed articles highlight human-machine interaction as the defining feature of Industry 5.0, with 41 articles emphasizing this aspect. This relationship—often referred to as "cobots"—suggests that collaborative robots working alongside humans can generate more creative solutions and enable customer-centric or personalized products (Doyle & Kopacek, 2021). The themes of human-centered design and sustainability also appear frequently, featured in 40 and 33 articles, respectively. Although resilience appears less often, the concept introduced by Breque et al. (2021) aligns well with the understanding of I5.0 found in the analyzed literature. Specifically, these results support Pramanik et al. (2020), who describe I5.0 as centered on human-machine collaboration with a focus on customized manufacturing. However, these authors view I5.0 not as a completely new paradigm but rather as an evolution of I4.0.

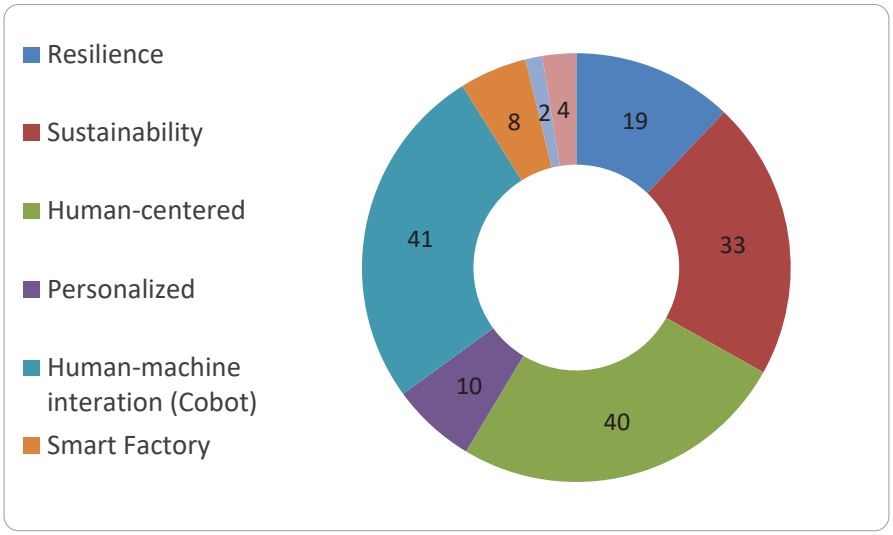

Figure 6. Elements of I5.0 cited in the analyzed articles (number of citations)

Babkin et al. (2022), Lattanzio et al. (2022), and Borchardt et al. (2022) emphasize that Industry 5.0 is not a new industrial revolution but rather an evolutionary extension of Industry 4.0 technologies, aimed at enhancing collaboration between humans and robots (Pizon & Gola, 2023; Alves et al., 2023). Industry 5.0 sets a forward-looking agenda that builds on the unique features of Industry 4.0 by placing sustainability at the heart of digital industrial transformation. Despite ongoing discussions, this concept must move beyond academic circles and be applied in practice. Industries must adopt a human-centric approach, prioritize sustainability, and foster resilience to become the driving force behind a new society (Xu et al., 2021). In short, while buzzwords like 'Industry 6.0' or 'Industry 7.0' might inspire academic papers or funding proposals, if they fail to translate into concrete business actions or technological solutions, they risk remaining mere theoretical ideas with little real impact on industrial progress or societal development.

RQ2 – What are the most relevant technologies and tools for implementing Industry 5.0?

Many authors note that while digital technologies from Industry 4.0 remain important in Industry 5.0, certain technologies will require greater focus (Xu et al., 2021). This is especially true for those related to sustainability, which is widely discussed today in contexts such as Environmental, Social, and Corporate Governance (ESG), as well as technologies aimed at energy efficiency, storage, renewable energy, and bio-inspired solutions. Demir et al. (2019) similarly highlight renewable resources, sustainable agricultural production, and bionics as key Industry 5.0 technologies.

From the SLR papers discussing technologies and tools in the context of Industry 5.0, two main groups emerge: those that identify Industry 4.0 technologies as the foundation for Industry 5.0, and those that emphasize novel tools and technologies more specifically aligned with the core pillars of Industry 5.0. Technologies linked to human-centricity tend to focus on collaborative robots and human–machine interaction, while those related to sustainability typically address production and operational contexts tied to resilience. These sustainability-related technologies are also closely connected to human factors such as training and education.

Table 4 summarizes the aforementioned tools, grouped by technology category, along with the authors who identified them as being relevant to Industry 5.0.

Table 4. Technologies and tools discussed by the SLR papers

Technologies and tools related		References that mention or suggest them
Human- centricity	Cobots/Collaborative Robots, Individualized human-machine interaction, Worker-friendly ergonomic design	Aceta et al. (2022), Agarwal and Chauhan (2022), Al Mubarak (2022), Alves et al. (2023), Bednar and Welch (2020), Cimini et al. (2022), Demir et al. (2019), Doyle-Kent and Kopacek (2021), Duggal et al. (2021), Emma-Ikata and Doyle-Kent (2022), Frederico (2021), Gervasi et al. (2023), Haleem and Javaid (2019), Javaid and Haleem (2020), Javaid et al. (2020), John et al. (2020), Kemendi et al. (2022), Kukreja and Kumar (2020), Kumar Singh and Sobti (2022), Lu et al. (2022b), Lykov and Razumowsky (2023), Madsen and Slåtten (2023), Marinelli (2022), Nahavandi (2019), Pathak et al. (2019), Pizon and Gola (2023), Prassida and Asfari (2021), Raja Santhi and Muthuswamy (2023), Taj and Jhanjhi (2022), Xu et al. (2021)
Sustainability	Bioengineering, Bio-inspired technologies, Smart Materials, Renewable Resources, Sustainable Agricultural Production, Bionics, Advanced Materials, Nanotechnology, Sustainable Manufacturing, Smart grids	Demir et al. (2019), Duggal et al. (2021), Ghobakhloo et al. (2023a), Habash (2022), Möller et al. (2022), Xu et al. (2021)
Resilience	Biological transformation, Virtual training, Worker Assistance Systems	Cimini et al. (2022), Nahavandi (2019), Rauch (2020)
Industry 4.0	Big data, Smart sensors, Internet of Things (IoT), Internet of Everything (IoE), Artificial Intelligence (IA) and emerging artificial intelligence, Blockchain, Multi-agent systems and technologies, Digital Ecosystem, Digital twins, Smart manufacturing/Smart factory, Smart cities, Complex adaptive systems, 3D printing, 4D printing, 5D printing, 3D scanning, Holography, Virtual Reality (VR), Augmented Reality (AR), Mixed Reality (MR), Extended Reality (XR), Cyber-Physical Systems (CPS), Information and Communication Technology (ICT), machine learning, 6G communications	Adel (2022), Al Mubarak (2022), Alvarez-Aros and Bernal-Torres (2021), Alves et al. (2023), Atif (2023), Boschetti et al. (2023), Bitsch (2022), Demir and Cicibaş (2019), Emma-Ikata and Doyle-Kent (2022), Frederico (2021), Garcia Rivera et al. (2022), Ghobakhloo et al. (2023b), Humayun (2021), Javaid and Haleem (2020), Javaid et al. (2020), John et al. (2020), Johri et al. (2021), Kemendi et al. (2022), Khaimovich et al. (2020), Khan et al. (2022), Kolade and Owoseni (2022), Kukreja and Kumar (2020), Kumar Singh and Sobti (2022), Lykov and Razumowsky (2023), Maddikunta et al. (2021), Marinelli (2022), Martynov et al. (2019), Mladineo et al. (2021), Möller et al. (2022), Mourtzis et al. (2022a), Pathak et al. (2019), Raja Santhi and Muthuswamy (2023), Romero and Stahre (2021), Rožanec et al. (2022), Sharma et al. (2022), Taj and Jhanjhi (2022)

In fact, the intensification of advanced technologies applied at I5.0—such as artificial intelligence, robotics, and smart systems—raises concerns about overreliance on digital infrastructures and the potential for labor displacement. While Industry 5.0 promotes human-machine collaboration, the growing automation of industrial processes may lead to job loss, increased skills gaps, and a widening digital divide, particularly in regions with limited technological capacity or workforce training.

RQ3 – What skills and capabilities are required to implement Industry 5.0?

From an organizational perspective, the authors identified studies within the SLR that discuss practices companies adopt to enable the implementation of Industry 5.0. For example, Mladineo et al. (2021) suggest that implementing lean manufacturing can support I5.0, especially for small and medium-sized enterprises. They highlight key success factors in lean manufacturing that align with I5.0 principles, such as respect for people, education, communication, leadership, customer value, personal experience, empowerment, continuous improvement, waste elimination, organization, lead time reduction, and systems thinking.

Choi et al. (2022) describe Industry 5.0 as "human-centered" rather than "system-centered." In this context, Mondal and Samaddar (2023) highlight that effective collaboration between humans and smart systems demands new skills, competencies, knowledge, and abilities. Raja Santhi and Muthuswamy (2023) explain that collaborative robots, or cobots, are flexible robots designed to enable the 3Cs: coexistence, cooperation, and collaboration. Their main purpose is "to mainly carry out routine tasks and work hand-in-hand with humans" (Emma-Ikata & Doyle-Kent, 2022, p. 420). However, the skills and competencies required to program and automate cobots remain a limiting factor. Other authors

addressing skills related to cobots include Proia et al. (2022), Welfare et al. (2019), and Nahavandi (2019). Supporting this discussion, Agarwal and Chauhan (2022) emphasize the importance of assessing the employability skills needed to work effectively with cobots.

All aforementioned points converge on the worker's perspective. Al Mubarak (2022) focuses on the emerging skills gaps in Industry 5.0, stressing the need for digital literacy, leadership, problem-solving, and self-management skills. Likewise, Suciu et al. (2023) explore the skillsets necessary for a truly sustainable, resilient, and inclusive Industry 5.0, emphasizing both technical and non-technical competencies. These include proficiency with technological tools, analytical and innovative thinking, programming, creativity, originality, initiative, emotional intelligence, leadership, and the ability to tackle complex problems.

In a study focusing on India, Kukreja and Kumar (2020) emphasize that adopting innovative management practices, investing in human capital, and improving workers' qualifications are key factors for implementing Industry 5.0. They highlight the education sector as playing a crucial role in developing the skills needed for these new industrial revolutions. Similarly, Emma-Ikata and Doyle-Kent (2022) stress the importance of educating "future modern workers," arguing that I5.0 and its related tools, technologies, and approaches should be integrated into students' curricula so they gain the skills required to work with these innovations. Gürdür Broo et al. (2022) propose that to prepare engineers for Industry 5.0, education must follow four strategies: lifelong learning and transdisciplinary education; modules on sustainability, resilience, and human-centered design; practical courses on data fluency and management; and hands-on experience with human-machine interaction. Additionally, Tavares et al. (2022, p. 17) underscore that educators and educational institutions, as foundational pillars for improving human capital and driving societal progress, hold significant responsibility in this process of change and transformation.

A new concept has emerged from this literature review, capturing the competencies needed for successful Industry 5.0 implementation: Operator 5.0. Mourtzis et al. (2022b) highlight the key skills and attributes associated with this role, including strong communication abilities, proficiency in working with artificial intelligence and IT systems across different interfaces and platforms, and a willingness to embrace continuous change. Other important competencies include creative problem-solving, the ability to work safely and effectively—both physically and mentally—with emerging technologies, and strong intercultural and interdisciplinary collaboration skills. Additionally, the Operator 5.0 must be aware of cybersecurity, privacy, and data protection concerns, be able to manage increasing complexity and multitasking demands, and combine cognitive, physical, sensory, and interactive capabilities. Meanwhile, Romero and Stahre (2021) discuss Operator 5.0, focusing on intelligent and resilient systems, and emphasize anticipation skills and resilience as key characteristics, enabling adaptation to unexpected changes and recovery from new situations.

Table 5 provides an overview of the key skills and capabilities required for Industry 5.0, along with the related aspects discussed earlier and their respective references.

Table 5. Main skills and capabilities required for Industry 5.0

Worker's main skills and capabilities		**Related aspects and respective references**
Non-technical	Leadership, problem-solving, self-management, creativity, originality, initiative, emotional intelligence, communication, open-mindedness towards constant change, anticipation ability and resilience to adapt and recover from new situations, inter-cultural and disciplinary skills, attributes such as cognitive, physical, sensorial, and interaction capabilities, ability to handle increasing complexity of many requirements and simultaneous tasks	Organizational practices (Mladineo et al., 2021; Kukreja & Kumar, 2020) Education/qualification (Emma-Ikata & Doyle-Kent, 2022; Gürdür Broo et al., 2022; Al Mubarak, 2022; Suciu et al., 2023) Operator 5.0 (Mourtzis et al. 2022b; Romero & Stahre, 2021)
Technical	Programming and automating cobots, analytical and innovative thinking, knowledge to work with artificial intelligence and information technology systems through different interfaces and platforms, digital and technological devices, cybersecurity, privacy, and data mindfulness	Cobots/training (Mondal & Samaddar, 2023; Welfare et al., 2019; Nahavandi, 2019; Proia et al., 2022) Education/qualification (Emma-Ikata & Doyle-Kent, 2022; Gürdür Broo et al., 2022; Al Mubarak, 2022; Suciu et al., 2023) Operator 5.0 (Mourtzis et al. 2022b; Romero & Stahre, 2021)

In sum, Industry 5.0 represents a sociotechnical transformation that extends beyond technological innovation to include human and societal dimensions. It aspires to integrate human-centricity, sustainability, and resilience into industrial systems. However, balancing these goals with productivity and efficiency presents significant practical and conceptual challenges. The integration of ethical considerations, worker well-being, and social responsibility into industrial design remains insufficiently addressed in both scholarly and practical discussions.

RQ4 – What gaps and research opportunities exist within Industry 5.0?

Based on the analysis, the authors propose a future research agenda outlined in Table 6. They suggest that most of these questions should be addressed through practical research rather than theoretical studies alone. This conclusion is supported by the data in Table 1, which shows that practical studies (quantitative, qualitative, and mixed methods) account for less than 30% of the existing literature. Table 6 organizes eight thematic areas identified as most relevant based on the authors' judgment and the findings from the Systematic Literature Review. The first column lists these thematic areas, the second presents research questions developed through a synthesis of relevant literature and the authors' insights, and the last column credits the authors who inspired each thematic area and the corresponding research questions. For example, Sharma et al. (2022) and Frederico (2021) highlight the need for studies exploring the benefits and challenges of Industry 5.0. Sharma et al. (2022) examined barriers to implementing Industry 5.0 in the pharmaceutical sector and recommended conducting similar analyses in other industries. Frederico (2021) proposed research on the benefits and challenges involved in transitioning to Supply Chain 5.0. Building on their work, several research questions were formulated to explore previously unexplored aspects, including the benefits and challenges across different sectors, as well as the potential influence of an organization's size and age.

Crucially, future research should focus on education, skills, and knowledge in the context of Industry 5.0. Doyle-Kent and Kopacek (2021), Borchardt et al. (2022), and Taj and Jhanjhi (2022) emphasize the need to evaluate how educational systems are adapting to these changes. Lattanzio et al. (2022) emphasize the importance of examining the profile of the next generation of workers and their implications for education. Kolade and Owoseni (2022) call for research on interventions aimed at addressing inequalities caused by disruptive digital transformation. Additionally, Demir et al. (2019), Nahavandi (2019), Al Mubarak (2022), Borchardt et al. (2022), Mondal and Samaddar (2023), and Suciu et al. (2023) suggest investigating new skills, capabilities, and competencies, along with methods for their development. Future studies should also investigate how different generations will adapt to these changes and which skills may be more or less accessible to them.

Organizational strategy and management also require further attention. Future research could explore strategies and their impact on Industry 5.0 (Frederico, 2021); the implications of I5.0 for business outcomes and operations management (Borchardt et al., 2022); studies focused specifically on small and medium-sized enterprises (Madhavan et al., 2022); and the effects of organizational culture (Suciu et al., 2023). Several authors, including Duggal et al. (2021), Durmaz and Kitapcı (2021), Borchardt et al. (2022), and Ben Youssef and Mejri (2023), emphasize the need for research on new business models tailored to the demands of Industry 5.0. Borchardt et al. (2022) emphasize the importance of focusing on innovative business models. Overall, management and organizational strategy play a crucial role in guiding change. Future studies should delve deeper into aspects such as culture, leadership, innovation management, and lean manufacturing.

Another crucial area for research is the role of laws and government. Demir et al. (2019), Dhirani et al. (2023), and Atif (2023) emphasize the need to study legal, regulatory, and policy constraints. Ghobakhloo et al. (2022) emphasize the importance of examining how public-private partnerships can influence the development of policies, initiatives, and regulatory frameworks to support Industry 5.0. It is essential to investigate the impact of these changes on legal matters and how governments and legal systems are adapting to such rapid and significant transformations. In this sense, research in this direction must incorporate concepts from stakeholder theory and institutional theory, taking into account the holistic perspective of I5.0.

It is also important to study the impact on people and related ethical issues. Several authors recommend research on human-robot interaction (Demir et al., 2019; Cimini et al., 2022; Emma-Ikata & Doyle–Kent, 2022; Espina-Romero et al., 2023; Gervasi et al., 2023; Ghobakhloo et al., 2023a; Pizon & Gola, 2023), as well as evaluations of the technologies that support this interaction to promote human-centeredness (Ghobakhloo et al., 2023a) and investigations into people's main fears and insecurities (Nahavandi, 2019). There is a clear need for more research on the psychological impact, social implications, and effects on organizational climates (Demir et al., 2019). Doyle-Kent and Kopacek (2021) argue that research should explore how Industry 5.0 can contribute to creating higher-value, more comfortable, and safer jobs.

Studies on ethics are also crucial (Nahavandi, 2019; Welfare et al., 2019; Long, 2020; Borchardt et al., 2022; Alves et al., 2023; Ben Youssef & Mejri, 2023), along with investigations into the health impacts of I5.0 (Rožanec et al., 2022; Taj & Jhanjhi, 2022) and its effect on workers' quality of life (Longo, 2020). Research on health and safety issues is equally important (Welfare et al., 2019; Longo, 2020; Lattanzio et al., 2022; Alves et al., 2023; Marinelli, 2023). Overall, it is crucial to understand how organizations maintain a human-centric approach to their decision-making processes.

The topic of technologies and digital development has already attracted significant interest from researchers who have proposed studies on various aspects, including the role of technologies in Industry 5.0 (Humayun, 2021; Ghobakhloo et al., 2022; Taj & Jhanjhi, 2022); Industry 4.0 technologies that can support Industry 5.0 (Frederico, 2021); the impacts of digital development on the transition from Industry 4.0 to 5.0 (Babkin et al., 2022); resilience and antifragility implications (Ghobakhloo et al., 2023a); and cybersecurity concerns (Ghobakhloo et al., 2022; Kemendi et al., 2022; Atif, 2023; Ben Youssef & Mejri, 2023). Research focusing on new technologies and digital development across different countries, as well as the primary technologies adopted by organizations according to sector and size, is essential, including cybersecurity.

Some authors also suggest exploring societal issues in the era of Industry 5.0 (Frederico, 2021; Borchardt et al., 2022; Mourtzis et al., 2022a; Taj & Jhanjhi, 2022; Tavares et al., 2022), smart cities (Espina-Romero et al., 2023), and bioeconomics (Borchardt et al., 2022; Espina-Romero et al., 2023). Studies examining the transition across different continents and countries, considering their economic contexts, are equally essential.

Sustainability has also attracted significant attention and is considered a central focus of Industry 5.0. Some authors emphasize the need for studies that demonstrate how Industry 5.0 contributes to achieving climate goals and promoting the circular economy (Frederico, 2021; Borchardt et al., 2022). Others emphasize the importance of research on Industry 5.0 in relation to the Sustainable Development Goals (SDGs) (Borchardt et al., 2022; Tavares et al., 2022); social dimensions (Atif, 2023; Espina-Romero et al., 2023; Ghobakhloo et al., 2023a; Raja Santhi & Muthuswamy, 2023); environmental factors (Espina-Romero et al., 2023; Ghobakhloo et al., 2023a); corporate governance (Ghobakhloo et al., 2022); sustainable business models (Borchardt et al., 2022); and greener production processes (Ben Youssef & Mejri, 2023). Consequently, it is crucial to conduct research that evaluates the practical contributions of Industry 5.0 to sustainability.

Most articles have focused on theoretical studies, leaving the question of how actually to implement Industry 5.0 unanswered. Initiatives like the European Commission's (2023a) call for participation in the Industry 5.0 Community of Practice (CoP 5.0) play a crucial role, providing strong incentives to put Industry 5.0 into practice. At the same time, case studies, action research, surveys, and interviews with employees in organizations that have adopted Industry 5.0 are vital. Future research must address the three key aspects most authors emphasize: human-centricity, resilience, and sustainability. Echoing the European Commission's intentions, new business models will need to emerge to enable the successful adoption of Industry 5.0.

Table 6. Proposed agenda for future research

Area	Research question	Authors
Benefits, challenges and general factors	What benefits are organizations experiencing from implementing Industry 5.0? How do sector and company size influence these benefits? Does a company's age affect its adoption of Industry 5.0? What role do startups play in this transition? What are the main barriers organizations face when transitioning to Industry 5.0, and how have they overcome them? How is Industry 5.0 being implemented across different departments within organizations and between organizations? For example: Quality 5.0, Logistics 5.0, Supply Chain 5.0, Project Management 5.0, Purchasing 5.0, Sales 5.0, Production Planning and Control 5.0, People Management 5.0, etc. How has Industry 5.0 impacted various sectors, such as healthcare, transportation, tourism, and construction?	Sharma et al. (2022); Frederico (2021)
Education, skills and knowledge	How are educational institutions responding and adapting to the changes brought by Industry 5.0? What are the key hard and soft skills people need to develop to adapt to Industry 5.0, and how are they acquiring them? What challenges do different generations (Baby Boomers, Generation X, Millennials (Y), Generation Z, Alpha) face in adapting to Industry 5.0?	Demir et al. (2019); Nahavandi (2019); Doyle-Kent and Kopacek (2021); Al Mubarak (2022); Borchardt et al. (2022); Borchardt et al. (2022); Kolade and Owoseni (2022); Lattanzio et al. (2022); Taj and Jhanjhi (2022); Mondal and Samaddar (2023); Suciu et al. (2023)

Area	Research question	Authors
Organizational strategy and management	What strategies have companies successfully transitioning to Industry 5.0 employed? How do leadership styles and organizational culture influence the transition to Industry 5.0? Are certain leadership types or cultures more conducive to this shift? Are organizations migrating to Industry 5.0 seeing better financial and non-financial results? How significant is Industry 5.0's impact on organizational performance? What new business models have emerged with Industry 5.0, and how will it affect existing models? Are companies with Lean practices finding it easier to implement Industry 5.0? How can knowledge and innovation management support the transition to Industry 5.0?	Duggal et al. (2021); Durmaz and Kitapcı (2021); Frederico (2021); Borchardt et al. (2022); Madhavan et al. (2022); Suciu et al. (2023); Ben Youssef and Mejri (2023)
Law and government	How has Industry 5.0 influenced legal and regulatory issues, especially concerning AI and collaborative robots (cobots)? How might delays in legislation affect people's lives amid the rise of Industry 5.0? In what ways can public-private partnerships facilitate the transition to Industry 5.0?	Demir et al. (2019); Ghobakhloo et al. (2022); Dhirani et al. (2023); Atif (2023)
People, ethics, health and safety	How have labor relations evolved with the adoption of Industry 5.0? What effects do new technologies have on workers' physical and mental health, as well as social interactions? Within organizations, who decides which technologies to adopt, and how are decisions made considering their impact on workers' well-being? How secure are the new technologies being introduced? What roles do organizations, research institutions, and governments play in assessing security? How are organizations and governments addressing ethical issues related to new technologies? Are organizations genuinely placing humans at the center of decision-making? How is this being achieved?	Demir et al. (2019); Nahavandi (2019); Welfare et al. (2019); Longo (2020); Doyle-Kent and Kopacek (2021); Borchardt et al. (2022); Cimini et al. (2022); Emma-Ikata and Doyle–Kent (2022); Lattanzio et al. (2022); Rožanec et al. (2022); Taj and Jhanjhi (2022); Alves et al. (2023); Ben Youssef and Mejri (2023); Espina-Romero et al. (2023); Gervasi et al. (2023); Ghobakhloo et al. (2023a); Marinelli (2023); Pizon and Gola (2023)
Technologies and digital development	How has the development and adoption of new technologies and digital advancements varied across countries and regions? What impact will this have on financially disadvantaged countries? What are the leading technologies currently used by organizations, and how do these vary by sector, company size, and location?	Frederico (2021); Humayun (2021); Babkin et al. (2022); Kemendi et al. (2022); Ghobakhloo et al. (2022); Taj and Jhanjhi (2022); Atif (2023); Ben Youssef and Mejri (2023); Ghobakhloo et al. (2023a)
Society	What are the main societal impacts of Industry 5.0? How will the transition to Industry 5.0 unfold, considering the economic conditions of different countries and regions? How can organizations and governments support this transition, ensuring people remain central not only within organizations but also across society? How can society and the labor market be prepared for the changes brought by Industry 5.0? What steps have already been taken?	Frederico (2021); Borchardt et al. (2022); Mourtzis et al. (2022b); Taj and Jhanjhi (2022); Tavares et al. (2022); Espina-Romero et al, (2023)
Sustainability	What social and environmental impacts are resulting from the adoption of Industry 5.0? Is Industry 5.0 contributing effectively to sustainable development? How has Industry 5.0 supported the achievement of the Sustainable Development Goals (SDGs), considering different societal sectors? What impact has Industry 5.0 had on organizations recognized for their ESG performance? How has Industry 5.0 contributed to advancing the circular economy?	Frederico (2021); Borchardt et al. (2022); Ghobakhloo et al. (2022); Tavares et al. (2022); Atif (2023); Ben Youssef and Mejri (2023); Espina-Romero et al. (2023); Ghobakhloo et al. (2023a); Raja Santhi and Muthuswamy (2023)

Framework proposal

To achieve the objectives of this study, a framework was developed based on the findings of the systematic literature review (Figure 7). This framework aims to support companies in their transition to Industry 5.0 by highlighting essential technologies and the required competencies, thereby aiding the effective pursuit of the Sustainable Development Goals. From an academic perspective, it identifies key concepts, thematic areas, and future research directions to promote a deeper understanding and further exploration of this emerging paradigm. Introducing Industry 5.0 requires a clear understanding of its core elements and an evaluation of how these elements interact in practice. Additionally, it is crucial to have skilled personnel who can effectively use the wide range of technologies and tools available. Beyond this, a human-centered approach calls for a new style of management. Regarding technologies and tools (detailed in section 4.2), these include both Industry 4.0 innovations focused on automation, additive manufacturing, and smart factories, as well as those specifically linked to Industry 5.0. These technologies have been grouped following the classifications used by the European Commission and other key studies.

The analyses give rise to potential future areas of research. Future studies should focus on how Industry 5.0 changes are being implemented in practice. Conducting surveys, case studies, and action research would be especially valuable.

The research themes were grouped according to the areas outlined in Table 6. Notably, the themes of "Education, skills, and knowledge" and "People, ethics, health, and safety" share significant overlap, as any progress toward Industry 5.0 directly impacts these areas. Research centered on these topics, in turn, supports advancements across other domains. Here, it is interesting to note that human participation becomes limited to supervisory or adaptive functions, rather than being meaningfully integrated into design and decision-making processes. This may marginalize the social, emotional, and ethical aspects of labor, undermining the very values that Industry 5.0 purports to prioritize.

"Technologies and digital development" represent a crucial aspect of Industry 5.0, and ethical considerations must always be taken into account when evaluating existing or emerging technologies. For instance, questions regarding data privacy, algorithmic bias, workplace surveillance, and the unequal distribution of technological benefits. Since sustainability is a central focus of Industry 5.0, it is essential to understand how technologies can support this goal, how knowledge is generated and shared, and how widely recognized concepts like the Sustainable Development Goals (SDGs), Environmental, Social, and Governance (ESG) criteria, and the circular economy are being addressed within the Industry 5.0 context.

Other groups focus on the areas of "Benefits, challenges, and general factors" and "Organizational strategy and management." Research in these areas should not only explore the benefits and challenges of Industry 5.0 but also examine how organizations are managing these changes and what strategies they are employing. Finally, the groups "Society" and "Laws and government" remind us that all the changes discussed in the other areas will directly impact society. Therefore, legislation and government policies must keep pace to ensure decisions align with ethical standards, environmental protection, and the well-being of people. In fact, considering the results from this SRL, the integration of ethical concerns into design processes and strategic decision-making is often superficial, lacking frameworks that ensure accountability, inclusivity, and transparency.

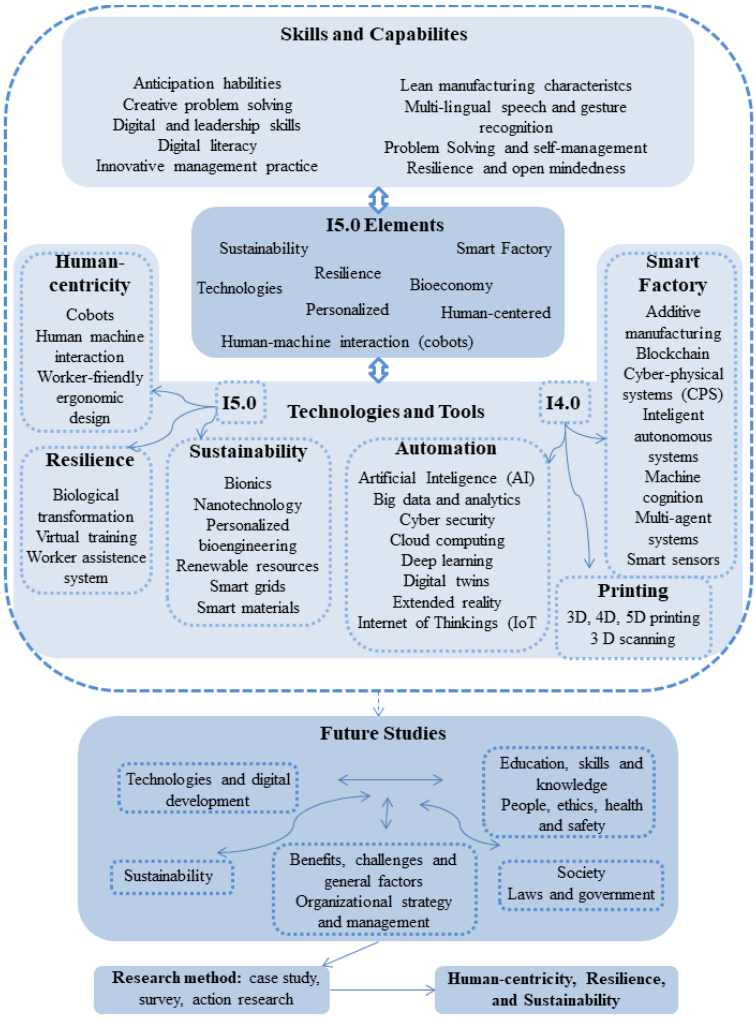

Figure 7. Theoretical framework for Industry 5.0

From a business perspective, the framework provides strategic insights into how organizations can align technological innovation with human-centered values, ethical considerations, and sustainability goals. By outlining the competencies required for implementing Industry 5.0, companies can identify skill gaps, guide workforce development, and foster leadership models that promote collaboration between humans and intelligent systems. Moreover, integrating emerging technologies—such as human-robot collaboration tools, AI-driven decision support, and smart manufacturing systems—requires not only technical adoption but also organizational change. This involves rethinking business models, redefining performance metrics, and nurturing a culture that embraces continuous learning, resilience, and social responsibility.

The proposed framework aligns with the Sustainable Development Goals (SDGs) by guiding organizations in their transition to Industry 5.0 in a human-centered, technologically advanced, and sustainable manner. It supports SDG 8 (Decent Work and Economic Growth) by promoting people-focused work environments; SDG 9 (Industry, Innovation, and Infrastructure) by encouraging the responsible adoption of advanced technologies; and SDG 12 (Responsible Consumption and Production) by fostering more circular and efficient production practices. Additionally, by addressing skills development, education, and workplace well-being, the framework also contributes to SDGs 3, 4, 5, and 13, emphasizing the strategic role businesses play in advancing global sustainability goals.

CONCLUSION

With growing academic and institutional interest in Industry 5.0, this study aims to address the following research question: What are the key issues that future research on Industry 5.0 should focus on? This article provides a comprehensive review of the recent and emerging literature on I5.0. The number of publications on this topic rose significantly—from 25 in 2020 to 70 in 2021, and then to 222 in 2022 (Figure 3)—highlighting its increasing relevance. The European Commission has played a major role in advancing Industry 5.0, alongside growing academic interest, by launching initiatives such as the Industry 5.0 Award (European Commission, 2023b) to recognize EU-funded projects that promote a more human-centered, resilient, and sustainable industry. According to Ghobakhloo et al. (2023b), I5.0 is expected to spread rapidly beyond Europe, just as I4.0 did. The authors note that significant contributions to Industry 4.0 came from both emerging and developed economies outside Europe—including Brazil, China, the USA, and Australia—and a similar trend is anticipated for Industry 5.0.

This article presents the main current definitions of Industry 5.0. However, the concept still requires a clearer definition in the literature, as there is no consensus on its key elements or when exactly I5.0 emerged—most articles mention the term only superficially. Another important topic discussed in the literature concerns the technologies used in Industry 5.0: many authors note that numerous Industry 5.0 technologies originated from Industry 4.0. Still, some researchers question the need for new, specific technologies for this era, especially those focused on sustainability. Additionally, many emphasize the importance of developing and enhancing the competencies and skills required for I5.0—particularly individuals who are psychologically, physically, and intellectually prepared to operate within its three core pillars: human-centricity, sustainability, and resilience. Finally, this article proposes a framework based on the insights gathered from the systematic literature review, highlighting key factors for the transition to I5.0 and directions for future research.

Moreover, while the article rightly highlights the need for new skills and competencies, the literature still lacks detailed guidance on the educational and organizational strategies needed to develop these capacities in practice. Therefore, although this study helps organize and frame the current state of research, it also underscores the conceptual, technological, and practical uncertainties that must be addressed to advance both academic understanding and the industrial implementation of Industry 5.0.

Based on the findings, future research on Industry 5.0 should focus on several key gaps to help establish it as both a solid theoretical framework and a practical guide for industrial transformation. First, it is crucial to develop a clear and consistent definition of Industry 5.0 that clearly distinguishes its principles and scope from earlier industrial paradigms. Second, research should identify and validate technological enablers that truly align with the core values of human-centricity, sustainability, and resilience. Third, since human skills are central to this new industrial era, future studies need to explore educational strategies and organizational models that support the development of these competencies. Additionally, there is a pressing need to create metrics and indicators to measure the performance and impact of Industry 5.0 initiatives. Further research should also investigate how Industry 5.0 integrates with broader sustainability agendas and ESG frameworks across different regions and industrial sectors. Finally, the ethical, social, and legal aspects—especially those related to the evolving role of humans within increasingly automated systems—require a deeper interdisciplinary

exploration. Addressing these challenges will be crucial to realizing the promise of Industry 5.0 and deriving tangible, measurable benefits for both industry and society.

In conclusion, this study contributes to Industry 5.0 research by clarifying its core principles, distinguishing it from related concepts, and proposing an integrative framework that links definitions, technologies, competencies, and research gaps, while also outlining a research agenda. Methodologically, it employs a structured and systematic literature review process, supported by relevance scales that guided the selection of articles. From a practical perspective, it offers a starting point for organizations transitioning toward more sustainable, resilient, and human-centric industrial models, in alignment with the Sustainable Development Goals.

Practical and theoretical implications

The proposed framework contributes to the ongoing discussion around Industry 5.0 by going beyond simply organizing existing literature. It synthesizes findings from the systematic literature review into an integrated structure that links conceptual definitions, enabling technologies, and necessary competencies with the identified research gaps and practical challenges. This comprehensive approach makes the framework valuable both as an academic resource, facilitating further theoretical research, and as a strategic guide for organizations navigating the shift toward a more human-centered, sustainable, and resilient industrial model. In this way, it provides a forward-looking roadmap to tackle unresolved issues and align academic work with industrial practice as Industry 5.0 continues to evolve.

From an academic standpoint, this work highlights several directions for future research, emphasizing the need to deepen understanding of the interfaces and integration among key elements of Industry 5.0, such as the connections between process technologies and people, as well as the interaction between these technologies, people, and sustainability. Additionally, it stresses the importance of field research to gain clearer insights into what companies are actually implementing in practice and the challenges they encounter in adopting Industry 5.0.

From an organizational perspective, the article provides an overview to help clarify the nature of Industry 5.0. It aims to address common misunderstandings between Industry 5.0, Industry 4.0, the Fifth Industrial Revolution, and Society 5.0. The literature reveals a lack of consensus on the definition of Industry 5.0, with some authors using the terms interchangeably with Industry 4.0 or Society 5.0. While Industry 5.0 builds upon Industry 4.0, sometimes referred to as Industry 4.0+, 4.5, or 4.0S, it places distinct emphasis on human-centricity, sustainability, and resilience. Unlike Industry 4.0, which focuses mainly on automation and efficiency, Industry 5.0 prioritizes integrating human and environmental values into industrial systems. Society 5.0, in contrast, represents a broader societal vision that goes beyond the industrial context. The key difference lies in Industry 5.0's goal to transform industry through values-driven innovation, leveraging both existing and emerging technologies to promote social and environmental well-being. Additionally, the article outlines the main technologies currently in use and the skills and capabilities required from workers, providing organizations with the knowledge needed to begin their transition into this new era.

In conclusion, the proposed framework advances the Sustainable Development Goals (SDGs) by providing a clear, structured approach for organizations transitioning to Industry 5.0. It supports SDG 8 (Decent Work and Economic Growth) by promoting human-centered, resilient work environments; SDG 9 (Industry, Innovation, and Infrastructure) through the responsible integration of technology; and SDG 12 (Responsible Consumption and Production) by encouraging more efficient and sustainable production methods. Additionally, by addressing education, skills development, workplace well-being, and ethical considerations, the framework also contributes to SDG 3 (Good Health and Well-being), SDG 4 (Quality Education), SDG 5 (Gender Equality), and SDG 13 (Climate Action). This highlights the strategic role Industry 5.0 plays in promoting inclusive, innovative, and sustainable development.

Future studies

Future research could benefit from expanding the search strategy to include variations from the term "Industry 5.0", thereby encompassing a broader range of perspectives on the topic. Additionally, as a suggestion for future work, this article proposes a research agenda (framework) based on the literature review and the authors' personal experiences. At this stage, we have not established hierarchical relationships or causal assumptions between the analyzed elements. Our intention was to map and connect the key concepts, technologies, and competencies associated with Industry 5.0. The resulting framework reflects this approach and has the potential to guide future theoretical or empirical research, which may build upon it to explore deeper relationships or propose more specific models. For instance, the Industry 5.0

approach presupposes the human-centered use of advanced technologies, with the expectation that its implementation may foster job satisfaction, engagement, and social well-being. However, validating such cause-and-effect relationships requires further research focused on defining and consolidating measurement items and scales for this construct, enabling its assessment through quantitative methods in specific empirical contexts. Furthermore, future research should focus on the practical applications of Industry 5.0, utilizing methods such as case studies, surveys, action research, and expert and academic interviews. Additionally, research should focus on real-world cases that allow for the analysis of human-centricity, resilience, and sustainability within practical settings, exploring the interactions and cause-and-effect relationships among these three pillars of Industry 5.0 and their potential impacts on desired outcomes.

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Conflicts of interest

The authors declare no competing interests.

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