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Review

A Bibliometric Analysis of Industry 4.0 and Occupational Health and Safety: Research Trends and Gaps

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Abstract

Industry 4.0 (I4.0) is transforming industrial systems through interconnected, data-driven technologies, raising questions about how these developments affect Occupational Health and Safety (OHS). This study investigates research trends, thematic structures, and knowledge gaps at the intersection of I4.0 and OHS using a multilevel bibliometric framework applied to Scopus records published from 2011 to 2025. The analysis moves from a broad overview of the I4.0 landscape to more focused examinations of specific I4.0–OHS publications, prevention-oriented studies, and emerging-risk research. The results show that OHS has limited visibility in the general I4.0 literature and is more prominent mainly in targeted subsets, where digital sensing, artificial intelligence, machine learning, and immersive technologies drive prevention-focused research. Conversely, emerging risks such as cognitive load, psychosocial stressors, and human–autonomy interaction appear in smaller, more dispersed clusters. Overall, the findings suggest that the relationship between I4.0 and OHS is unevenly developed, with established prevention mechanisms and early-stage conceptualization of new risks. Strengthening this field will require integrating human factors with digital indicators, better characterizing emerging risks, and ensuring that digital transformation supports SDG 8 by fostering safe and healthy working environments.

Keywords: industry 4.0; OHS; prevention mechanisms; emerging risks; SDG 8; bibliometric analysis

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1. Introduction

1.1. Digital Transformation and the Rise of Industry 4.0

The constant impetus to integrate new digital technology into industrial practice transformed manufacturing models, leading to the fourth industrial revolution, or Industry 4.0 (I4.0), in 2011 [1,2]. Nine pillars have facilitated the adoption of I4.0. These include simulation, the Internet of Things (IoT), horizontal and vertical systems integration, autonomous

and collaborative robots, 3D additive manufacturing, cybersecurity, cloud computing, augmented reality (AR), and big data [3]. When combined with existing physical infrastructure, these nine technologies can transform traditional production tasks into innovative, autonomous, systematized, and interconnected processes [4,5], making their implementation within companies essential for economic growth, innovation, and competitiveness [6].

The digital transformation of industrial settings is not occurring at the periphery of economic activity; rather, it is unfolding within a variety of factors related to production, employment, and value creation [7,8]. Industrial sectors are a major contributor to the global economy, accounting for 20.9 percent of the world's gross domestic product (GDP) and, through the combined manufacturing, mining, and utilities sectors, generating about one-fifth of global economic output [9]. More specifically, industry remains an important employer, as manufacturing shows a strong employment multiplier: one manufacturing job creates more than 2 additional jobs in other sectors of the economy [10]. In addition, manufacturing contributes roughly 16–17% of global GDP in terms of manufacturing value added (MVA) and accounts for more than half of business investment in research and development, underscoring its role as a key driver of innovation and productivity [11].

1.2. Environmental Pressures and the Role of Digital Technologies

Beyond economic and productivity considerations, environmental pressures have emerged as a second major driver shaping the digital transformation of industrial work environments [12,13]. Industrial firms face an environmental stigma because of their significant environmental footprint: industrial processes account for 9% of global greenhouse gas emissions, approximately 6.5 $GtCO_2e$ of CO_2, or 11% of the emissions of the energy sector [14]. Furthermore, 19% of the world's freshwater use is due to industry and energy [15], with the EU (49%) and Asian regions (47%), especially India and China, accounting for the largest industrial water consumption. Adding to these issues, around 19.9 gigatons of waste were generated globally from 2019 to 2020, and at least 70% of end-of-life materials have not been reused or recycled [16].

In response to increasing criticism of their overall environmental impact, resource- and material-intensive industries such as chemicals, metals, construction materials, pulp and paper, plastics, and mining have accelerated the adoption of innovative digital technologies as a key strategy to drive efficiency, sustainability, and competitiveness gains [17].

Within this framework, I4.0 technologies have supported a broader strategic response to strengthen governance structures and enhance transparency in environmentally intensive industrial sectors [18]. At the operational level, digital infrastructures built on IoT, artificial intelligence (AI), big data analytics, and blockchain are increasingly used to implement governance regulations that ensure accountability, mitigate information biases, and reinforce trust among regulators, investors, and other stakeholders [19]. Taken together, digital technologies and corporate governance arrangements have converged to embrace this new era, moving away from traditional, reactive sustainability management responses toward data-driven, real-time monitoring, automated reporting, and traceable environmental/social disclosures to enhance sustainability outcomes and the credibility of non-financial information [20]. These dynamics intersect with changes in work processes, shaping new patterns of occupational risk addressed in the next subsection.

1.3. Industry 4.0 and the Changing Nature of Occupational Risks

The transformation of industrial work under I4.0 aligns closely with Sustainable Development Goal 8 (SDG 8), which promotes sustained economic growth, productive employment, and decent work for all [21]. While digital technologies can increase productivity, innovation, and competitiveness, they also reshape job profiles, work organization,

and workers' exposure to Occupational Health and Safety (OHS) risks within industrial systems [22,23]. In particular, Target 8.8 explicitly connects economic transformation and technological modernization with the requirement to ensure safe and healthy working environments, highlighting the need to assess how digitalized industrial systems reconfigure workers' exposure to occupational risks [24]. In this sense, the extent to which I4.0 contributes to SDG 8 depends not only on economic performance gains but also on how emerging digital work environments are designed and governed to address employment quality, worker safety, and health outcomes [25].

From a sustainable development perspective, evaluating I4.0 solely through the lenses of productivity and environmental governance, or transparency, is not enough to reach full corporate sustainability since this approach overlooks hidden implications for workers' health [26]. Given that I4.0 is transforming industrial work environments, it is worth asking whether workers today may already be affected by emerging digital technologies, even if these effects are not yet visible or widely studied. A look at previous industrial revolutions shows that the initial emphasis was largely on productivity, efficiency, and effectiveness, while systematic attention to occupational risk prevention and safety emerged over time [27,28].

Despite a growing body of literature addressing Industry 4.0 and Occupational Health and Safety, most existing studies examine this relationship either at a sector-specific level or through isolated technological applications, offering limited insight into how OHS is structurally positioned within the broader Industry 4.0 research landscape. As a result, it remains unclear whether OHS constitutes an integral dimension of digital transformation research or a specialized, peripheral concern that emerges only under targeted analytical conditions.

1.4. The Need for Evidence in I4.0 and Occupational Health and Safety

Hence, the purpose of this article is not only to examine scientific production on Industry 4.0 and Occupational Health and Safety, but also to clarify how OHS is positioned within the broader Industry 4.0 research landscape. Unlike previous bibliometric or systematic reviews that focus on specific technologies, sectors, or safety applications, this study introduces a multilevel bibliometric framework that moves from the general Industry 4.0 corpus to progressively narrower and conceptually focused datasets.

This framework provides a methodological contribution by enabling a structured mapping of the visibility, thematic concentration, and fragmentation of OHS-related research across different analytical levels, without presupposing its relevance within the broader digital transformation literature. In doing so, the study distinguishes between consolidated, prevention-oriented research streams and more dispersed, early-stage strands addressing emerging risks, offering a more nuanced understanding of how occupational safety and health research evolves alongside Industry 4.0.

To guide this bibliometric exploration, this study addresses the following research questions:

RQ1. How has scientific production on Industry 4.0 and OHS evolved since 2011?

RQ2. What thematic structures, dominant clusters, and intellectual trends characterize current research at the I4.0–OHS interface?

RQ3. Which gaps, understudied areas, and emerging topics reveal opportunities for future research on digital transformation and worker health?

2. Materials and Methods

This study employs a bibliometric approach to examine scientific output at the intersection of I4.0 and OHS. Bibliometric analysis provides a systematic, quantitative

method for mapping research trends, identifying thematic structures, and detecting knowledge gaps within a research field [29]. Accordingly, the methodological procedure for this bibliometric analysis was organized into a series of stages, as described in the following subsections [30].

2.1. Data Source and Search Strategy

All data were retrieved from the Scopus database. Scopus was selected because it is one of the most comprehensive and quality-controlled repositories of peer-reviewed scientific literature and provides structured metadata suitable for bibliometric analysis [31]. The extracted metadata included title, abstract, authors, institutional affiliation, document type, year of publication, authors' keywords, country of origin, and language. The search covered original research articles and reviews published in English and Spanish between 2011 and 2025, beginning with the year when the term 'Industry 4.0' first appeared in the scientific literature [32].

2.2. Multilevel Bibliometric Framework

To examine the relationship between I4.0 and OHS with adequate conceptual precision, this study employs a multilevel bibliometric framework. This framework organizes the analysis into progressively narrower levels of scrutiny, allowing the study to move from broad exploratory mapping to highly focused examinations of specific risk-related domains. Level 1: General landscape of I4.0 (S1). The first level analyzes the full corpus of I4.0 research to determine whether OHS appears naturally as a relevant or structured theme within the broader landscape. No relationship is forced. The goal is to observe OHS visibility and positioning.

Level 2: Explicit I4.0–OHS research (S2). The second level restricts the dataset to publications in which I4.0 and OHS explicitly co-occur. This identifies how the scientific community conceptualizes the intersection and its thematic structure.

Level 3: Detailed scrutiny through specialized subdomains (S3 and S4). Two focused levels refine the analysis further: (a) accident/risk prevention (S3), and (b) emerging risks (S4). These narrower queries reveal conceptual structures that remain diluted in broader datasets.

The multilevel bibliometric procedure used in this study follows a structured, transparent workflow. The Scopus search period, document type, and language scope were consistently defined across all analytical levels. Dataset refinement was limited to removing duplicate records and cleaning keywords to ensure consistency, without applying conceptual exclusion criteria. The complete search strings and the sequential analytical steps for each level (S1 to S4) are summarized in Table 1, providing sufficient detail to ensure full transparency, replicability, and reproducibility of the analysis.

The adoption of this multilevel bibliometric approach responds to the uneven visibility of Occupational Health and Safety within the broader Industry 4.0 literature. At the general level S1, OHS-related topics tend to be diluted by the large volume of publications focused on technological development and performance-oriented benefits of Industry 4.0. By progressively narrowing the analytical focus from the general Industry 4.0 corpus S1 to publications explicitly addressing OHS S2, and further to prevention-oriented studies S3 and emerging risk research S4, this approach enables more detailed scrutiny of thematic areas that could otherwise remain weakly visible or analytically obscured in a single large-scale co-occurrence map. Table 1 summarizes the structured workflow that operationalizes this multilevel bibliometric design.

Table 1. Methodological workflow for the multilevel bibliometric analysis.

Step	Description	Tools/Software
1. Define Research Objectives	Identifying research trends, thematic concentrations, and knowledge gaps in the scientific literature	N/A
2. Literature Search and Data Collection	Database: Scopus Segments: S1: Industry 4.0 S2: Industry 4.0 and Occupational Health and Safety S3: Industry 4.0 and Occupational Health and Safety and Risks Prevention/accidents S4: Industry 4.0 and Occupational Health and Safety and Emerging Risks Search fields: title, abstract, keywords Search Query: S1: (“Industry 4.0” OR “I4.0” OR “Fourth Industrial Revolution” OR “Digital Manufacturing” OR “Smart Manufacturing” OR “Smart Factory” OR “Smart Industry”) S2: S1 AND (“occupational health” OR “occupational safety” OR “occupational health and safety” OR “health and safety” OR “work * safety” OR “industrial safety” OR “worker health” OR “OHS” OR “OSH”) S3: S2 AND (“risk prevention” OR “accident prevention” OR “risk detection” OR “risk identification” OR “hazard identification” OR “safety management” OR “risk management” OR “real-time monitoring” OR wearable * OR “smart wearable *” OR sensor * OR “smart sensor *” OR “predictive safety”) S4: S2 AND (“emerging risk *” OR “new risk *” OR “occupational risk *”OR “psychosocial risk *” OR “technostress” OR “stress” OR “ergonomic risk *” OR “cognitive load” OR “mental workload” OR “human-machine interaction”) Filters: year (2011–2025), document type (Research Articles and Reviews), language (English and Spanish)	Mendeley (version 1.19.8)
3. Data cleaning and Preprocessing	Elimination of duplicates and keyword unification	Bibliometrix MS Excel
4. Selection of Bibliometric Techniques	Co-word analysis, descriptive analysis and clustering	Bibliometrix VOSviewer
5. Data Analysis	Conduct the analysis using chosen techniques	Biliometrix VOSviewer
6. Visualization	Elaboration of maps and tables for data representation	Bibliometrix VOSviewer
7. Interpretation and Reporting	Interpretation of results and preparation of report	MS Word

* Denotes the truncation operator used to include plural and derivative forms of the Keywords.

2.3. Data Processing and Analytical Techniques

Bibliometric techniques included performance analysis, co-occurrence analysis with VOSviewer, thematic mapping with Bibliometrix 5.3.0, and cluster identification. The VOSviewer 1.6.20 software was used because it is widely used in bibliometric analyses, enabling the visualization and analysis of co-occurrence data among documents [33]. The

thematic map was created using the Bibliometrix R package, as it enables analysis of the field's conceptual structure [34]. Finally, Keyword co-occurrence thresholds were defined according to the size and density of each dataset:

- For S1 (Industry 4.0; n = 28,925 documents), a threshold of 50 co-occurrences was applied to capture only the most frequent and structurally dominant terms.
- For S2 (Industry 4.0 & OHS; n = 274 documents), a minimum threshold of 5 co-occurrences was used to reveal meaningful clusters without losing thematic nuance.
- For S3 (Industry 4.0–OHS–Prevention; n = 131 documents), a threshold of 3 co-occurrences allowed the detection of emerging prevention-related patterns.
- For S4 (Industry 4.0–OHS–Emerging Risks; n = 67 documents), a more inclusive threshold of 2 co-occurrences was selected to capture early-stage and low-frequency emerging risk concepts.

To improve consistency and comparability across mappings while preserving author-provided conceptual boundaries, author keyword co-occurrence analyses were conducted using a thesaurus file designed to harmonize synonymous terms and lexical variants. The file unified equivalent concepts (e.g., "Industry 4.0", "I4.0", "4IR", "Fourth Industrial Revolution", including singular and plural forms) under a single label, while preserving distinctions among keywords that reflect different methodological approaches. For instance, "literature review" and "systematic literature review" were intentionally kept as separate terms because they commonly denote distinct research designs.

2.4. Methodological Robustness and Validity

Rigor was ensured by using identical search strings, cleaning metadata only for duplicates, adjusting co-occurrence thresholds based on dataset size, and relying on validated software (VOSviewer and Bibliometrix).

2.5. Limitations

Limitations include dependence on Scopus, language restrictions, sensitivity to keyword definitions, and threshold-related map variations. These limitations do not compromise validity but contextualize the interpretation of findings.

3. Results

3.1. Contraction Patterns in the Multilevel Document Sets

The multilevel bibliometric framework generated four complementary document sets (S1–S4), each providing a different degree of thematic refinement. Quantitatively, the results show a steep contraction of the document sets as the search criteria become more specific. The broad Industry 4.0 document set (S1) comprises 28,925 records (100%). When OHS-related terms are incorporated (S2), the set narrows sharply to 274 records (0.95% of S1). A more targeted subset focused on prevention-related risks and accidents (S3) decreases to 131 records (47.8% of S2; 0.45% of S1). Finally, the segment explicitly centered on emerging risks (S4) declines to 67 records (24.4% of S2; 0.23% of S1). A funnel-shaped pattern emerges when examining these transitions. The reduction from 28,925 documents (S1) to 274 documents (S2) represents a 99% decrease. The shift from S2 to the prevention-focused subset (S3) yields a 52% reduction, while the transition from S2 to the emerging-risk subset (S4) yields a 75% reduction.

3.2. Structural Mapping of the Industry 4.0 Literature

Figure 1 shows a co-occurrence network map of authors' keywords derived from I4.0 research, using a threshold of 50 co-occurrences to identify the most frequent terms that

meet the requirement (n = 227). Node size reflects keyword frequency, while link density indicates the strength of co-occurrence among keywords, and total link strength represents the overall connectivity of a keyword within the network [35]. The co-occurrence structure comprises three core clusters and one peripheral cluster. The first core cluster is the red group, which integrates the application- and management-oriented foundation of the field, anchored in I4.0 and extending to manufacturing, digital technologies, innovations, the circular economy, decision-making, dynamic capabilities, SMEs, COVID-19, and the SDG. The second core cluster is the blue group, which reflects the connected technological infrastructure that sustains I4.0 systems, dominated by IoT, cyber–physical systems, blockchain, cybersecurity, privacy, smart contracts, cloud and fog computing, sensors, and sectoral implementations such as healthcare within broader socio-technical frameworks like society 5.0. The third core cluster is the green group, which consolidates data-driven intelligence and advanced automation, capturing machine learning, deep learning, reinforcement learning, optimization, scheduling, anomaly detection, fault detection, computer vision, robotics, digital manufacturing, and additive manufacturing.

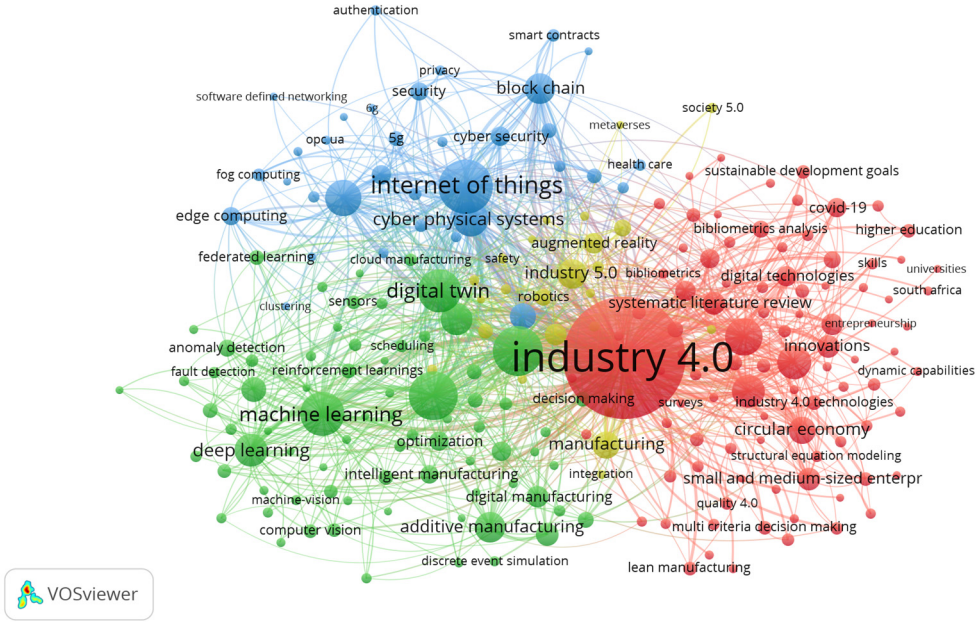


Figure 1. Keyword Co-occurrence network in Industry 4.0 research. Source: VOSviewer Software-Scopus extractions.

In addition to these three central groups, there is a fourth cluster that appears more diffuse and peripheral, represented in yellow. This peripheral cluster coalesces around human-centric and immersive transition themes, with identifiable anchors such as Industry 5.0 and AR. It occupies a bridging position between the infrastructural, automation, and organizational clusters, suggesting an emerging role that links human-centered design, immersive training, and cognitive ergonomics to both enabling technologies and data-driven capabilities. Although OHS does not appear as an explicit or dominant theme in any of the clusters, several keywords across them relate to safety indirectly through secure connectivity, risk detection, operational monitoring, and human-centered technological design, indicating that safety is not an articulated dimension within the broader I4.0 research landscape.

Quantitative Orientation of the Industry 4.0 Literature

Because "Industry 4.0" is the query seed, its very high frequency is an inherent result of the retrieval method and therefore does not add analytical value for comparison.

However, retaining it at this general level serves a diagnostic purpose by illustrating the scale and dominance of technology-oriented research, against which the limited visibility of Occupational Health and Safety becomes apparent. Consequently, the quantitative analysis focuses on the remaining author keywords, as summarized in Table 2, and provides the rationale for progressively refining the analysis toward more focused levels.

Table 2. Research topics clustered by author keywords in Industry 4.0.

Cluster	Name	Keywords	Ocurrences	Total Link Strenght
Red	Industry 4.0 and Sustainability	industry 4.0	11,128	20,067
		sustainability	1055	2606
		digital transformation	859	1884
		digitalization	824	1953
		circular economy	552	1270
		small and medium enterprise	392	874
Blue	Cyber–physical infrastructure 4.0	internet of things	2249	5427
		industrial internet of things	990	2210
		cyber physical systems	951	2451
		smart factory	767	1580
		block chain	694	1861
		big data	536	1556
Green	Enabling technologies 4.0	artificial intelligence	1831	4495
		smart manufacturing	1788	3519
		machine learning	1442	3358
		digital twin	1413	3052
		deep learning	833	1749
		smart factories	767	1580
		additive manufacturing	735	1210
Yellow	Human–centric manufacturing	industry 5.0	684	1610
		manufacturing	551	1338
		automation	372	920
		augmented reality	325	769
		virtual reality	234	536
		robotics	213	573
		human robot collaboration	165	317

According to this criterion, the distribution of occurrences and link strengths indicates that most of the corpus focuses on connectivity-oriented technologies, with the Internet of Things as the most frequent non-seed term (2249 occurrences; total link strength 5427). This category also includes related infrastructural components such as the industrial internet of things (990; 2210), cyber–physical systems (951; 2451), and blockchain (694; 1861). A second cluster appears among the algorithmic and data-driven approaches, where artificial intelligence reaches 1831 occurrences (4495 link strength), smart manufacturing 1788 (3519), machine learning 1442 (3358), and digital twin 1413 (3052). Management-oriented and sustainability-related terms form a smaller but steady layer, with sustainability at 1055 occurrences, digital transformation at 859, digitalization at 824, circular economy at 552, and SMEs at 392. Lastly, human-centered and immersive concepts make up the smallest group, including Industry 5.0 (684 occurrences), AR (325), and VR (234), indicating a more peripheral yet noticeable presence within the co-occurrence structure.

Interpreted in this way, the quantitative profile aligns with the cluster structure by showing that, once the seed term is excluded, the corpus's thematic orientation is driven primarily by connectivity infrastructures and algorithmic intelligence. At the same time, sustainability and human-centric emphases appear as secondary yet detectable elements.

This distribution confirms that the research indexed under the general term I4.0 is heavily concentrated on technological enablers and data-driven automation, with comparatively limited attention to organizational, social, or safety-related dimensions. Although certain keywords in the co-occurrence map indirectly relate to broader notions of safety through risk detection, cybersecurity, and human-centered design, these signals remain diffuse and do not constitute a coherent thematic stream within the corpus. Taken together, these patterns indicate that the first-level analysis provides valuable structural insights but is insufficient for capturing how I4.0 intersects with OHS. Consequently, a more targeted literature search explicitly focused on I4.0 and OHS is necessary to examine this relationship with the level of detail and conceptual precision that the broader query cannot provide.

3.3. Structural Mapping of Industry 4.0 and OHS Literature

Figure 2 displays a co-occurrence network map of author keywords derived from I4.0 and OHS research, using a threshold of five co-occurrences to identify the most frequent terms that meet this requirement (n = 40). The map exhibits a structured configuration in which "Industry 4.0" appears as the central and most influential node, linking the major thematic clusters across the network. The green cluster groups application-oriented and sector-specific themes, such as smart factory, technology, workplace safety, health and safety, sustainable practices, literature reviews, and construction-related terms (including construction 4.0), emphasizing the integration of digital technologies in organizational settings. The yellow cluster features data-oriented safety terms, including occupational health and safety, IoT, AI, machine learning, and risk assessment, highlighting the importance of continuous sensing, data-driven monitoring, and predictive analytics. The red cluster includes human-centered and training-focused concepts such as VR, digital twins, human factors, occupational safety, safety management, wearable sensors, and references to Industry 5.0, indicating a strong focus on simulation, training environments, and managerial oversight. Lastly, the blue cluster emphasizes collaborative robotics and ergonomics, including human–robot collaboration, collaborative robots, and ergonomic considerations.

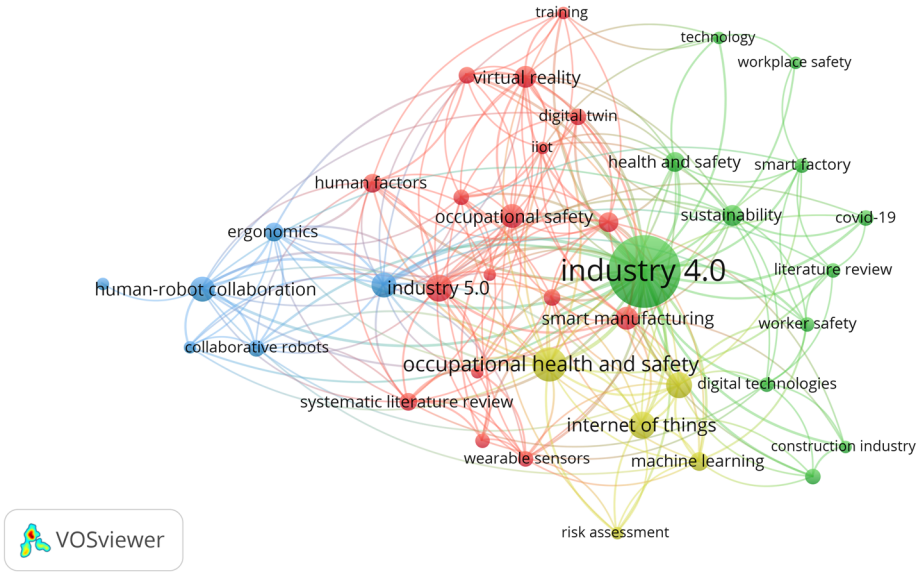


Figure 2. Keyword Co-occurrence network in Industry 4.0 and OHS research. Source: VOSviewer Software-Scopus extractions.

Quantitative Orientation of the Industry 4.0–OHS Literature

Table 3 summarizes the quantitative distribution of author keywords associated with I4.0 and OHS, revealing four coherent thematic clusters. In the green cluster, "industry

4.0" (133 occurrences; total link strength 225), "sustainability" (12; 19), "health and safety" (11; 22), "construction 4.0" (7; 11), and "worker safety" (6; 13) form a set of concepts that structure the general framework linking digital transformation with workplace protection. The yellow cluster groups technological terms related to safety, including "occupational health and safety" (31; 62), "internet of things" (21; 28), "artificial intelligence" (19; 37), "machine learning" (10; 22), and "risk assessment" (5; 12), indicating the central role of sensing, data processing, and analytical tools in the field. The red cluster brings together "industry 5.0" (21; 47), "occupational safety" (16; 31), "smart manufacturing" (15; 28), "virtual reality" (13; 31), "augmented reality" (11; 32), and "human factors" (10; 26), reflecting the presence of immersive and hybrid physical–digital environments associated with safety research. Finally, the blue cluster includes "safety" (18; 42), "human robot collaboration" (17; 34), "ergonomics" (10; 27), "collaborative robots" (8; 19), and "collaborative robotics" (5; 11), showing a consistent emphasis on human–robot interaction within I4.0 settings. Together, these clusters illustrate how conceptual foundations, technological enablers, immersive approaches, and human-centered automation operate as distinct yet interconnected components of the I4.0–OHS research landscape.

Table 3. Research topics clustered by author keywords in I4.0 and OHS.

Cluster	Name	Keywords	Ocurrences	Total Link Strenght
Green	Conceptual framework I4.0–OHS	industry 4.0	133	225
		sustainability	12	19
		health and safety	11	22
		construction 4.0	7	11
		worker safety	6	13
Yellow	Technologies 4.0 for OHS	occupational health and safety	31	62
		internet of things	21	28
		artificial intelligence	19	37
		machine learning	10	22
		risk assesment	5	12
Red	Transition to Industry 5.0	industry 5.0	21	47
		oocupational safety	16	31
		smart manufacturing	15	28
		virtual reality	13	31
		augmented reality	11	32
		human factors	10	26
Blue	Human–robot interaction	safety	18	42
		human robot collaboration	17	34
		ergonomics	10	27
		collaborative robots	8	19
		collaborative robotics	5	11

Figure 3 shows the thematic map constructed from the authors' keywords, illustrating the current conceptual structure of the I4.0–OHS field. The map consists of four quadrants representing motor, basic, niche, and emerging or declining themes. In the motor theme quadrant, a group comprising "sustainability," "digital technologies," "literature review," and "smart factory" was identified, indicating that these themes are well developed, consolidated, and highly relevant within the current body of literature. In contrast, the basic theme quadrant includes "Industry 4.0," "occupational health and safety," "Industry 5.0," and "safety," representing essential, widely used concepts that remain fundamental yet require further theoretical and empirical development. In the niche theme quadrant, the map shows a cluster that includes "collaborative robotics," "human-robot interaction," "as-

sembly," and "human-centered design," indicating a specialized yet mature line of research. The thematic map also displays a cluster of I4.0 technologies such as "Internet of Things," "artificial intelligence," "smart manufacturing," and "machine learning," positioned near the center, suggesting their role as cross-cutting elements that connect multiple thematic areas across the I4.0–OHS landscape. Finally, "deep learning" appears in the emerging or declining themes quadrant, reflecting a developing topic with limited maturation but potential relevance for future research.

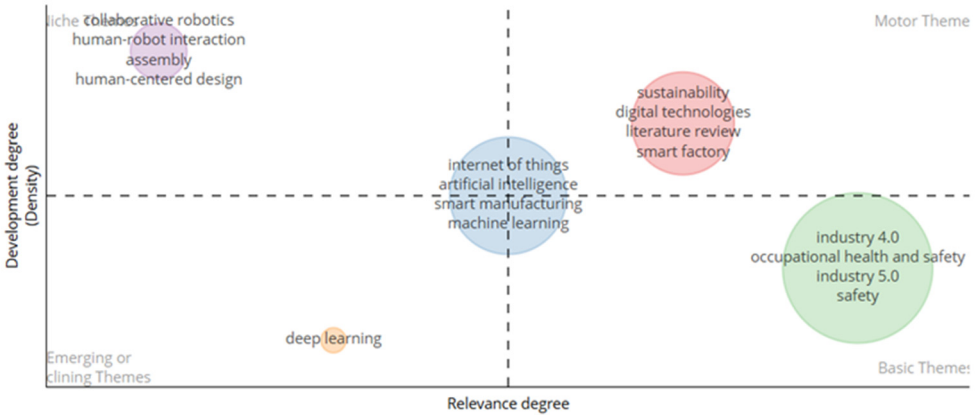


Figure 3. Thematic map in the field I4.0–OHS. Source: Bibliometrix-Scopus extractions.

The observed patterns highlight the prominence of safety-related and prevention-oriented terms, alongside a more limited but identifiable presence of concepts associated with emerging risks. This imbalance suggests the need for an additional level of inquiry to reveal how preventive mechanisms and emerging risk dynamics evolve within I4.0 environments. Such complementary searches enable the results to capture both the dominant technological approaches to safety and the less visible dimensions of the complexity of novel risks. These considerations provide the basis for the results presented in the following subsection.

3.4. Prevention and Emerging Risks in Industry 4.0 and OHS Research

3.4.1. Industry 4.0–OHS-Prevention of Accidents/Risk

Figure 4 displays a co-occurrence network map of authors' keywords from I4.0, OHS, and prevention research, using a threshold of three co-occurrences to identify the most frequent terms (n = 39). This map reveals the conceptual structure of prevention-oriented studies, showing five distinct thematic clusters. The red cluster centers on Industry 4.0 and extends toward safety management, workplace safety, and smart factory, highlighting how digital infrastructure is translated into operational safety practices. The blue cluster, led by IoT, AI, machine learning, and risk assessment, represents the technological backbone of prevention, emphasizing real-time monitoring, predictive analytics, and sensor-based hazard detection. The green cluster combines digital twin, smart manufacturing, operator 4.0, AR, VR, illustrating the rise of simulation-based training and design-for-safety approaches. Lastly, the yellow cluster, characterized by human–robot collaboration, ergonomics, and safety, reflects a growing focus on human-centered prevention, particularly in collaborative and semi-autonomous work environments.

Quantitative Orientation of the Industry 4.0–OHS–Prevention Accident/Risks Literature

Table 4 summarizes the distribution of author keywords in prevention-focused research on I4.0 and OHS, revealing five clear thematic clusters. The red cluster includes "industry 4.0" (69 occurrences; total link strength 139), "safety management" (8; 15), "man-

ufacturing" (4; 12), "safety 4.0" (4; 11), and "smart factory" (4; 10), highlighting the strong link between prevention and digitally enabled manufacturing environments. The blue cluster groups technological mechanisms for prevention, such as "occupational health and safety" (19; 45), "internet of things" (13; 23), "artificial intelligence" (9; 25), "machine learning" (4; 12), and "industrial safety" (4; 9), emphasizing sensing, data processing, and analytic capabilities. The yellow cluster emphasizes human–robot interaction and ergonomic safety, featuring "safety" (14; 35), "human robot collaboration" (9; 19), "ergonomics" (6; 17), "collaborative robots" (5; 16), and "human factors" (5; 15). The purple cluster covers applied occupational safety topics such as "occupational safety" (9; 17), "wearable sensors" (7; 20), "health and safety" (7; 12), "systematic literature review" (6; 18), and "construction" (5; 14). Lastly, the green cluster combines human-centered digital technologies, including "industry 5.0" (7; 23), "wearable technologies" (7; 19), "augmented reality" (6; 17), "smart manufacturing" (6; 17), and "virtual reality" (6; 17), illustrating the increasing presence of immersive and worker-focused digital tools in prevention research.

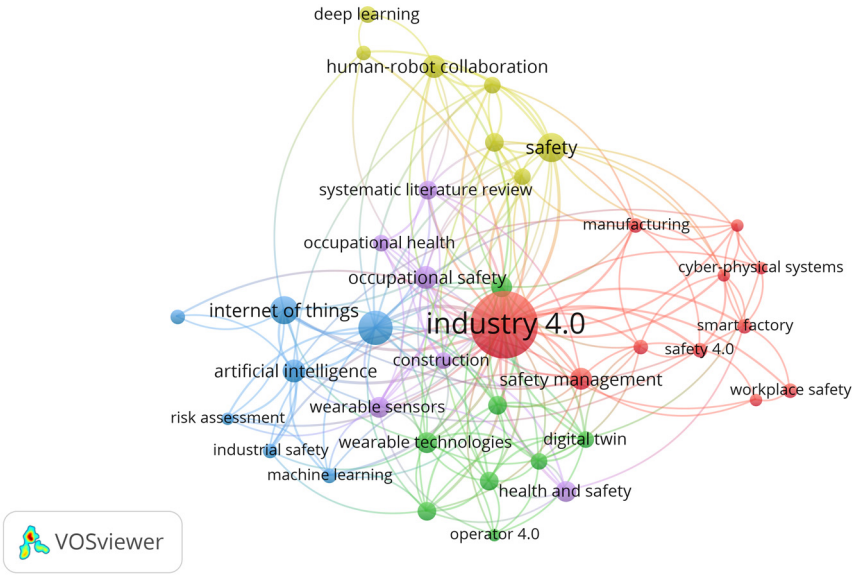


Figure 4. Keyword Co-occurrence network in Industry 4.0 and OHS prevention. Source: VOSviewer Software-Scopus extractions.

Table 4. Research topics clustered by author keywords in I4.0 and OHS prevention.

Cluster	Name	Keywords	Ocurrences	Total Link Strenght
Red	Safety in manufacturing 4.0	industry 4.0	69	139
		safety management	8	15
		manufacturing	4	12
		safety 4.0	4	11
		smart factory	4	10
Blue	Tecnologies 4.0 in OHS	occupational health and safety	19	45
		internet of things	13	23
		artificial intelligence	9	25
		machine learning	4	12
		industrial safety	4	9
Yellow	Human–robot interaction and ergonomic safety	safety	14	35
		human robot collaboration	9	19
		ergonomics	6	17
		collaborative robots	5	16
		human factors	5	15

Table 4. *Cont.*

Cluster	Name	Keywords	Ocurrences	Total Link Strenght
Purple	Applied Occupational Safety	occupational safety	9	17
		wearable sensors	7	20
		health and safety	7	12
		systematic literature review	6	18
		construction	5	14
Green	Human–Centered Digital Technologies	industry 5.0	7	23
		wearable technologies	7	19
		augmented reality	6	17
		smart manufacturing	6	17
		virtual reality	6	17

3.4.2. Industry 4.0–OHS–Emerging Risks

Figure 5 displays the co-occurrence network illustrating the structure of the I4.0, OHS, and Emerging Risks research field, based on 67 author keywords that appear at least twice. As with the prevention-focused map, Industry 4.0 is positioned at the center and serves as the primary linking concept throughout the network. Seven distinct thematic clusters can be identified. The first cluster (yellow) includes "industry 4.0," "occupational health and safety", "human factors," and "occupational risks" located near "stress." The second and third clusters (blue/orange) contain "industry 5.0.", "ergonomics," "occupational health", "human robot collaboration", "musculoskeletal disorders" and "psychosocial risks". The fourth and fifth clusters (red/pink) include "safety," "workplace safety," "operator 4.0", "technology" "hazard", "cyber-physical systems," and "augmented reality". The sixth and seventh cluster (purple/green) includes "occupational safety", "machine learning", "deep learning", "EEG", "virtual reality", "artificial intelligence" and "iiot". All clusters are connected through multiple co-occurrence links.

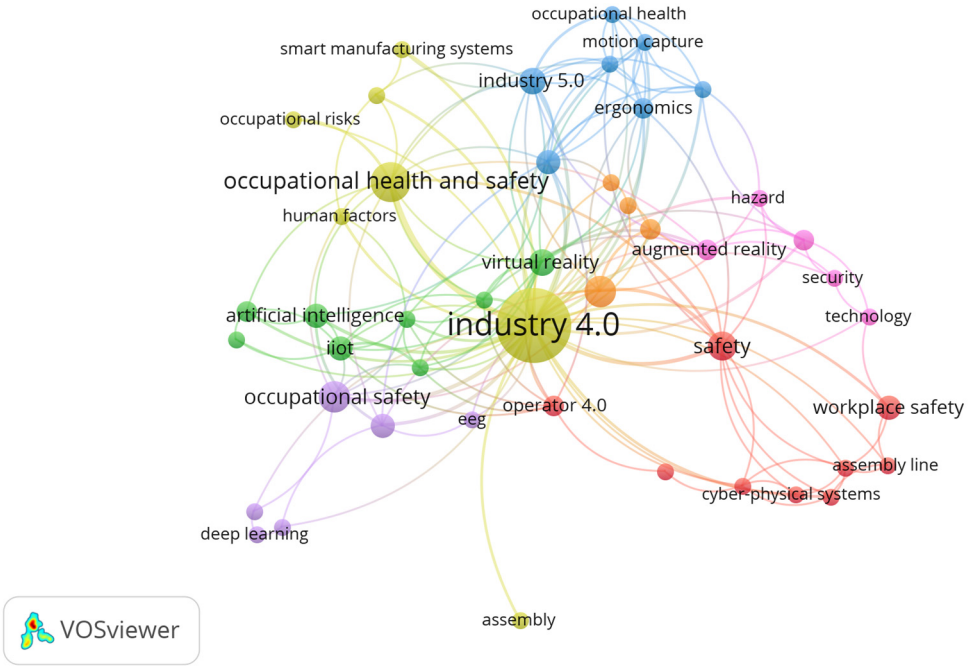


Figure 5. Keyword Co-occurrence network in Industry 4.0, OHS, and Emerging Risks. Source: VOSviewer Software-Scopus extractions.

Quantitative Orientation of the Industry 4.0–OHS-Emerging Risks Literature

Finally, Table 5 shows the quantitative distribution of author keywords related to I4.0, OHS, and emerging risks, highlighting several clear thematic clusters. In the yellow cluster, "industry 4.0" appears 38 times with a total link strength of 83, followed by "occupational health and safety" (11; 25), "stress" (2; 6), "human factors" (2; 6) and "occupational risks" (2; 3), forming a conceptual framework that connects key OHS concepts with early indicators of psychosocial risk. The orange cluster focuses on human–technology interaction, featuring "human robot collaboration" (7; 14), "collaborative robots" (3; 6), "psychosocial risks" (2; 3), and "musculoskeletal disorders" (2; 3), indicating connections between collaborative robotics and emerging physical and psychosocial concerns. The blue cluster organizes applied and contextual elements such as "industry 5.0" (5; 17), "wearable sensors" (4; 14), "ergonomics" (3; 13), "construction" (2; 10), and "systematic literature review" (2; 10).

Table 5. Research topics clustered by author keywords in I4.0–OHS–Emerging risks.

Cluster	Name	Keywords	Ocurrences	Total Link Strenght
Yellow	Conceptual framework I4.0–OHS	industry 4.0	38	83
		occupational health and safety	11	25
		stress	2	6
		human factors	2	6
		occupational risks	2	3
Orange	Human–technology interaction and risks	human-robot collaboration	7	14
		collaborative robots	3	6
		phycosocial risks	2	3
		musculoskeletal disorders	2	3
Blue		industry 5.0	5	17
		wearable sensors	4	14
		ergonomics	3	13
		construction	2	10
		systematic literature review	2	10
Red	Workplace safety	safety	6	17
		workplace safety	4	5
		operator 4.0	3	8
		worker safety	2	7
		smart factory	2	7
Pink		health and safety	3	8
		augmented reality	3	8
		hazard	2	6
		security	2	4
		technology	2	4
Purple	Technologies for risk prevention and monitoring	occupational safety	7	11
		machine learning	4	10
		sensors	2	3
		egg	2	3
		ppe	2	3
Green		virtual reality	5	17
		iiot	4	11
		artificial intelligent	4	9
		internet of things	3	6
		digital twin	2	11
		wearable technologies	2	8

The red cluster includes "safety" (6; 17), "workplace safety" (4; 5), "operator 4.0" (3; 8), "worker safety" (2; 7), and "smart factory" (2; 7), reflecting the emergence of safety considerations within digitally enabled work systems. The pink cluster groups terms linked to augmented and technology-mediated risk conditions, including "health and safety" (3; 8), "augmented reality" (3; 8), "hazard" (2; 6), "security" (2; 4), and "technology" (2; 4).

Lastly, the purple and green clusters group technologies related to risk prevention and monitoring, including "occupational safety" (7; 11), "machine learning" (4; 10), "sensors" (2; 3), "egg" (2; 3), "ppe" (2; 3), "virtual reality" (5; 17), "iiot" (4; 11), "artificial intelligent" (4; 9), "internet of things" (3; 6), "digital twin" (2; 11), and "wearable technologies" (2; 8), indicating the presence of advanced sensing and immersive technologies within emerging risk research.

4. Discussion

The following discussion addresses the three research questions by first clarifying the structural position of OHS within Industry 4.0 research (RQ1), then examining thematic consolidation and emerging blind spots (RQ2), and finally identifying implications and future research directions related to prevention and emerging risks (RQ3).

In the safety domain, recent review-based studies often adopt a bounded lens, focusing on manufacturing safety challenges through prevention-oriented design perspectives and the integration of human factors, rather than mapping how Occupational Health and Safety is structured within the broader Industry 4.0 knowledge base. For instance, Vigoroso et al. [36] report that accident rates in manufacturing have not decreased significantly despite stricter regulatory requirements and attribute this persistence to insufficient consideration of human factors in human–technical system interactions. Complementing this prevention-through-design perspective, Nioata et al. [37] show, in an automotive setting, how smart manufacturing integrated systems and cyber–physical systems are operationalized through Safety 4.0 practices such as predictive maintenance, traceability, and real-time monitoring, while identifying ergonomic and cognitive strain in collaborative robotics and cybersecurity exposure as salient hazards. At a broader OHS 4.0 level, Jiang et al. [38] emphasize that Industry 4.0 technologies expand real-time monitoring and decision-support capabilities. Yet, they also highlight persistent barriers, such as privacy concerns and cybersecurity requirements, that can limit adoption and worker acceptance.

Beyond design-oriented and case-based contributions, a recurring pattern in the literature is the trade-offs between risk reduction and risk generation as digitalization advances. Arana Landín et al. [39] report that Industry 4.0 technologies tend to reduce physical, mechanical, and ergonomic risks, but they also generate specific emerging risks, especially psychosocial risks such as stress, anxiety, perceived surveillance, and fear of job loss, alongside mechanical risks linked to remote machine startup, reduced situational awareness, and complex human–machine interfaces.

4.1. What the Multilevel Evidence Reveals for the Field

This study employed a multilevel bibliometric framework to clarify how OHS is integrated into I4.0 research, resulting in three key insights. First, OHS is not a central part of digital transformation but a peripheral specialization, as only a small portion of the overall I4.0 literature explicitly addresses safety and health despite the field's broad scope. Second, when this connection is made, research tends to focus on technological themes, particularly data-driven prevention methods such as IoT, machine learning, AI, and wearable sensors, as well as immersive environments for training and safety design, such as VR, AR, and digital twin applications. These studies also emphasize human–automation interaction, including topics like ergonomics and collaborative robots. Third, research on potential emerging risks remains in its early stages, as studies linking OHS with I4.0

primarily focus on workplace safety or accident prevention and, to a lesser extent, on cognitive load, psychosocial stressors, and human–autonomy interactions.

4.2. Thematic Consolidation and Blind Spots

The clusters in S2 and S3 show a strong connection among sensing, analytics, decision support, and training in prevention-focused research. Continuous sensing is performed through IoT and wearable sensors, AI and machine learning manage data interpretation, and decision support involves risk assessment and safety management [40]. In industrial settings, training and design tasks have been improved by the use of digital tools such as VR, AR, and digital [41,42].

On the other hand, S4 presents scattered terms related to cognitive load, psychosocial stressors, and human–autonomy interaction, pointing to socio-technical exposures that have not yet been examined with the same level of detail as prevention mechanisms. Furthermore, in S2, S3, and S4, it was not possible to identify a meaningful relationship between safety indicators from physiological or positional sensors and validated measures of mental workload, fatigue, and psychosocial risks. The latter aligns with a literature review that shows limited coverage of aspects related to emerging risks [39,43]. In general, the lack of integration between these two types of approaches reflects a conceptual gap that may indicate a limitation in embedding worker well-being within digital safety systems.

4.3. Implications for Practice and Policy

Findings in this study provide important insights for key stakeholders. For practitioners, the S3 clustering suggests that organizations already have a sufficiently mature evidence base for implementing IoT-enabled monitoring, learning-based risk assessment, and VR, AR, and digital twin applications in training or design tasks. Additionally, given the thematic variety observed in S4, there is a critical need for guidance on emerging risks in digitalized work environments, which is especially important for regulators and standard-setting organizations. This issue is highlighted by Cunha, Silva & Maggioli [44], who state that areas requiring attention include managing cognitive and psychosocial risks, establishing parameters for human–robot collaboration, and defining requirements to enhance transparency in AI-supported safety decisions.

4.4. Limitations and Future Sustainability Research Directions

This study has several strengths that influence how its findings can be interpreted. Its multilevel design places OHS within the I4.0 literature and compares its marginality using visibility ratios, while employing individual co-occurrence thresholds across datasets to enhance analytical consistency. These features support a thorough analysis of prevention mechanisms and emerging hazards. However, the study also has limitations that restrict the generalizability of its results. Relying on a single database, limiting the languages to English and Spanish, depending on user-provided keywords, and the sensitivity of cluster formation to threshold choices all restrict the completeness and stability of the mapped structures.

Within these established boundaries, three primary dimensions of future sustainability research emerge from the multilevel analysis evidence and directly address SDG 8 aspirations by connecting technological modernization to safe, healthy workplaces: First, future work should further strengthen the convergence of human factors with digital traces, given that environmental, positional, and physiological sensors rarely map to validated measures of cognitive load, attentional dynamics, or psychosocial stress. Second, the rise of collaborative robotics and adaptive automation necessitates more nuanced models of human–autonomy teaming, moving beyond task-level approaches to explore joint activities and the gradients of authority and error recovery. The third observation, the thematic dis-

persion in S4, highlights the importance of establishing taxonomies and reporting standards for emerging risks to develop shared constructs, measures, and thresholds that reduce fragmentation and foster a more unified approach to research.

The content addresses the three research questions by examining the limited evolution of the I4.0–OHS connection, clarifying the thematic structures that organize current work, and identifying gaps and emerging lines of inquiry across prevention and emerging risks. It also aligns with the article's purpose by showing that OHS remains unevenly integrated into digital transformation research and by outlining how prevention mechanisms, human autonomy dynamics, and emerging risk categories will shape the field's future development.

5. Conclusions

The study achieved its purpose by examining how OHS is positioned within the expanding research landscape of I4.0. The multilevel bibliometric strategy clarified that OHS remains marginal within the broader digital transformation literature, appearing mainly in focused subsets that explicitly address prevention mechanisms and emerging risks. This approach also made it possible to distinguish areas of conceptual consolidation from those that are still developing and lack common frameworks.

Occupational Health and Safety is a foundational concern wherever digital technologies reshape work organization, tasks, and human–technology interactions. However, the evidence from this study shows that, despite this practical and societal relevance, OHS has not yet become a transversal or structurally embedded dimension within the dominant Industry 4.0 research landscape. Instead, it remains largely confined to narrowly focused, thematically segmented research streams. This misalignment between the centrality of protecting workers' lives and health in real-world digitalized work environments and its marginal position in the scientific discourse underscores the importance of making this gap explicit. In this sense, the contribution of the present study lies not only in mapping existing research but also in revealing a structural disconnect that must be addressed if digital transformation is to support safe, healthy, and sustainable forms of work.

As digital transformation accelerates, strengthening OHS is essential to align technological modernization with the objectives of SDG 8, which emphasize productive employment and safe and healthy working environments. Future progress will depend on integrating human factors more systematically into digital systems, improving the characterization of emerging risks, and ensuring that AI-based safety applications operate with transparency and accountability. Advancing these elements will help move OHS from a peripheral position to a more structural and influential role in I4.0 research and practice, supporting productive, safe, and sustainable forms of industrial modernization.

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Abbreviations

The following abbreviations are used in this manuscript:

I4.0	Industry 4.0
OHS	Occupational Health and Safety
SDG	Sustainable Development Goal
GDP	Gross Domestic Product
MVA	Manufacturing Value Added
IoT	Internet of Things
AI	Artificial Intelligence
AR	Augmented Reality
VR	Virtual Reality

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