Industry 5.0: defining a Research Agenda for the future of manufacturing

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Abstract: Industry 4.0 is transforming traditional manufacturing processes through the integration of intelligent technologies. The emergence of Industry 5.0 marks a new era characterized by collaboration between humans and intelligent systems. This paper proposes a research agenda to identify the key challenges and opportunities associated with the implementation of Industry 5.0. The key pillars of Industry 5.0 (human-centricity, sustainability, and resilience) will be analysed through various dimensions, i.e. the volume of contributions in the literature (number of papers). The aim is to provide a clear overview of priority research areas, guiding progress in Industry 5.0 research and applications. The key findings reveal that human-centricity is the most emphasized pillar, although the concept of the 'human digital twin' presents an interesting avenue for exploration., followed by an increasing focus on sustainability. Finally, resilience - this growing emphasis is reinforced by increasing disruptions along supply chains, mainly due to post-pandemic situations, material shortages and crises. The ultimate purpose of this study is to shape the future of industrial production towards the realization of the Industry 5.0 paradigm. One of the most important outcomes lies in uncovering emerging concepts, such as Lean 5.0 and Product Lifecycle Management 5.0 (PLM 5.0). This work provides a comprehensive analysis from an academic perspective, outlining a roadmap. From a managerial perspective, it serves as a guide for companies embracing the Industry 5.0 challenge.

Keywords: Industry 5.0, Roadmap, Human Centric Manufacturing, PLM

1.Introduction

The advent of Industry 4.0 revolutionized the landscape of manufacturing with its emphasis on automation, data exchange, and advanced technologies (Abdous *et al.*, 2023). As we navigate further into the digital era, a new paradigm is emerging Industry 5.0 (I5.0)(Ghobakhloo *et al.*, 2023). This next evolutionary phase extends beyond the technological prowess of its predecessor by reintegrating the human element at the core of industrial processes. I5.0 emphasizes collaboration between humans and smart systems, aiming to foster a balance between automated efficiency and human creativity and decision-making (Agrawal *et al.*, 2023). This shift reflects a strategic pivot from mass production to personalized production, highlighting the growing importance of sustainability, resilience, and worker empowerment in modern manufacturing environments (Ahmed *et al.*, 2023). Narkhede et al. (2024) and Espina-Romero et al. (2023) have already proposed agendas on I5.0, which track scientific activity and identify influential industries, associated topics, and future research directions. Narkhede et al. (2024) emphasize the role of Industry 5.0 in driving sustainability within the manufacturing sector, proposing frameworks for effective implementation and highlighting the importance of interdisciplinary collaborations, policy support, and stakeholder engagement for realizing sustainable manufacturing practices. However, their work primarily focuses on sustainability, potentially overlooking the equally crucial aspects of human-centricity and resilience. Espina-Romero et al. (2023) focus on the most influential industries and associated topics in I5.0, presenting a detailed analysis of the current state and prospects. While comprehensive, their work is largely quantitative and lacks an in-depth exploration of practical challenges and implications for industry practitioners. Given the profound implications of I5.0, a comprehensive research agenda is necessary to fully understand and leverage this new paradigm. Such an agenda must explore the multifaceted challenges and opportunities that I5.0 presents, ranging from technological innovations to societal impacts. This paper proposes to delineate these areas of research, aiming to provide a structured framework that guides academic inquiry and practical applications alike. By defining a clear research agenda, we aim to catalyse the development of strategies that not only drive industrial advancement but also prioritize human well-being and environmental sustainability. The paper is structured as follows: section 2 provides the theoretical background, section 3 describes the research methodology, and section 4 presents and discusses the main findings. Finally, conclusions are presented.

2. Theoretical Background

Xu et al. (2021) underscore the need for a transition from I4.0 to I5.0, highlighting how the former's focus on automation and efficiency often neglected sustainability and resilience. Their study provides a foundational perspective on the inception, conception, and perception of I5.0, emphasizing the necessity for a human-centric approach to ensure long-term sustainability and resilience (Xu et al., 2021). While I4.0 primarily focused on technological advancements to increase efficiency and flexibility, it often overlooked the essential aspects of sustainability and human-centric values, thereby necessitating the evolution to I5.0. The concept of I5.0 is subject to various interpretations, reflecting the multifaceted nature of this emerging paradigm. Among the plethora of definitions that exist within academic and industrial circles (Caggiano et al., 2023), the one posited by the European Commission (2021) has garnered substantial recognition from the academic community for encapsulating the essence of I5.0. According to this definition, the potential of industry not just as a mere engine for job creation and economic growth, but as a resilient cornerstone capable of delivering prosperity in harmony with the environment. It is an ambitious vision that envisions production systems respecting the boundaries of our planet while simultaneously elevating the well-being of the industry worker to the heart of the production process. I5.0 is based on three main pillars: human-centric, sustainability, resilience (Caggiano *et al.*, 2023). Human-centric manufacturing puts the worker's well-being first (Lu *et al.*, 2022). This means designing ergonomics evaluation methods (Gualtieri *et al.*, 2024) and creating safe and inclusive workplaces where psycho-physical health is essential (Leng *et al.*, 2022). According to Sustainability pillar, I5.0 can actively contribute to developing circular processes to save, reuse and recycle energy resources and reduce waste for protecting the environment (Narkhede *et al.*, 2023). Resilience in I5.0 refers to system's ability to withstand disruptions (Camarinha-Matos *et al.*, 2024). It involves recovering from unexpected events to maintain system tasks. European Commission (2021) also defines enabling technologies of I5.0 and then they were outlined in literature (Maddikunta *et al.*, 2022; Narkhede *et al.*, 2023). Edge computing processes data closer to the source, such as on the factory floor, enabling faster response times and reducing the need for long-distance data transmission (Zafar *et al.*, 2024). Digital twins, which are virtual replicas of physical systems, allow for real-time monitoring and predictive maintenance, thereby reducing downtime and improving operational efficiency (Lanzini *et al.*, 2023). Cobots work alongside human operators, enhancing productivity and work quality by handling hazardous, strenuous, or repetitive tasks, allowing humans to focus on more skilled activities (Dornelles *et al.*, 2023). The Internet of Everything (IoE) integrates people and processes, facilitating a comprehensive and cohesive operation across all manufacturing levels (Leng *et al.*, 2022). Big Data Analytics can be used to extract insights for smarter business decisions, leading to improved operational efficiency, product quality, and predictive maintenance (Atif, 2023). Artificial Intelligence aids in complex decision-making processes (Chabane *et al.*, 2023), while Blockchain ensures secure and transparent transactions across the supply chain (Leng, Zhu, *et al.*, 2023). The transition to 6G networks will provide even faster and more reliable communication technologies, supporting more complex and time-sensitive industrial operations (Narkhede *et al.*, 2023).

3. Research Methodology

The foundation of this research hinges on a systematic literature review, meticulously designed to capture the essence of I5.0 within the manufacturing sector, particularly focusing on the three key pillars of human interaction, sustainability, and resilience. The primary database employed for this review was Scopus, owing to its extensive repository of peer-reviewed literature. We conducted a targeted search using the following string: *TITLE-ABS-KEY (("industry 5.0" AND "manufacturing" AND ("human" OR "sustainability" OR "resilience"))) AND (LIMIT-TO (DOCTYPE , "re") OR LIMIT-TO (DOCTYPE , "ar"))*, which yielded 222 documents initially. Given the preliminary nature of this investigation, a conscious decision was made to include only articles and reviews (denoted as "re" and "ar" in the document type field, respectively), thereby excluding conference papers at this juncture. This approach ensures a focus on comprehensive studies and expert analyses that have undergone thorough peer-review processes. To refine the dataset to the most relevant and high-quality contributions, we implemented a sequential exclusion criterion, visually represented in the provided flowchart (Figure 1).

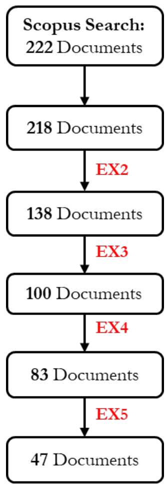

Figure 1: Flowchart depicting the literature selection process.

The exclusion criteria were as follows. EX1: Language not English – To maintain consistency and ensure clarity in analysis, non-English documents were excluded. EX2: Unrelated Title – Titles not directly pertaining to the core themes of I5.0 in manufacturing were omitted. EX3: Unrelated Abstract – Abstracts that did not explicitly address the intersection of I5.0 with human elements, sustainability, or resilience were filtered out. EX4: Full Paper Not Available – Documents where the full text was not accessible were removed to ensure a thorough evaluation could be conducted. EX5: Journal IS NOT Q1 – To maintain a standard of excellence, we included only those articles published in top-tier, Q1 journals as classified by Scopus. This process whittled down the initial pool to a final sample of 47 documents. Each selected paper was subjected to a comprehensive analysis, wherein the relevance and contribution to the I5.0 dialogue were critically assessed.

4.Key findings and Discussion

The word cloud generated from the bibliometric analysis of the 47 articles reviewed for this research provides a visually striking depiction of the key themes and terms that dominate the current discourse on I5.0 (Figure 2).

Figure 2. Keyword Plus of literature selected (Bibliometrix)

It was created using Bibliometrix software (Aria and Cuccurullo, 2017), which analyzed the frequency and co-occurrence of keywords in the selected literature and the size of each word reflects its prominence. Central to this discourse is the term "Industry 5.0" itself, which looms large, indicating its significance as a new paradigm in manufacturing. Human-centric aspects are evidently at the forefront, as indicated by the words "human-centric" "workers" and "ergonomics" suggesting a marked emphasis on human involvement and the value of human skills in the manufacturing process. This focus on the human element within I5.0 is further supported by terms like "collaborative robots" and "human-robot collaboration" which imply a synergistic integration of advanced technologies with human intelligence and capabilities. The prominence of "sustainable development" and "sustainability" underscores a pivotal shift towards environmental considerations and the endurance of industrial practices over time. Equally, the word "resilience" reflects an increasing focus on the ability of manufacturing systems to withstand and adapt to disruptions, ensuring long-term viability. Artificial intelligence, hinted at by "artificial intelligence" is highlighted as key driver for innovation in I5.0, enabling smart manufacturing systems that are not only automated but also intelligent and adaptive. The presence of "supply chain management" and "cyber-physical systems" in the word cloud indicates a convergence of physical operations with digital technologies, optimizing supply chains and enhancing the cyber-physical interaction. The systematic analysis of the literature has crystallized around the three pillars fundamental to I5.0—Human-Centricity, Sustainability, and Resilience—each further delineated into three distinct domains. These domains not only categorize the research contributions but also shed light on the nuanced focus areas within each pillar. Evidently, each pillar incorporates two core conceptual domains and one domain with a technological orientation, showcasing a comprehensive approach to I5.0 that intertwines human, ecological, and resilience aspects with technological advancements (Table 1).

Table 1: Classification of analysed literature

Human-Centricity	*Operator well-being*	(Abdous *et al.*, 2023); (Battini *et al.*, 2022); (Gualtieri *et al.*, 2024); (Ling *et al.*, 2024); (Lu *et al.*, 2022); (Nourmohammadi *et al.*, 2022); (Peruzzini *et al.*, 2023); (Pistolesi *et al.*, 2024); (Rožanec *et al.*, 2022); (Tran, Pentek, *et al.*, 2023); (Tran, Ruppert, *et al.*, 2023); (Verna *et al.*, 2023); (Wang, Zhang, *et al.*, 2024)
	Worker involvement and human leadership	(Battini *et al.*, 2022); (Brauner and Ziefle, 2022); (Destouet *et al.*, 2023); (Gladysz *et al.*, 2023); (Lu *et al.*, 2022); (Nair *et al.*, 2024); (Olsson *et al.*, 2024); (Wan and Leirmo, 2023)
	Human-centric work environment technologies	(Chabane *et al.*, 2023); (Dornelles *et al.*, 2023); (Du Plooy *et al.*, 2024); (Gladysz *et al.*, 2023); (Gualtieri *et al.*, 2024); (Leng *et al.*, 2022); (Li *et al.*, 2023); (Ling *et al.*, 2024); (Lou *et al.*, 2024); (Lu *et al.*, 2022); (Maddikunta *et al.*, 2022); (Nair *et al.*, 2024); (Nourmohammadi *et al.*, 2022); (Peruzzini *et al.*, 2023); (Pistolesi *et al.*, 2024); (Rožanec *et al.*, 2022); (Turner and Garn, 2022); (Verna *et al.*, 2023); (Wan and Leirmo, 2023); (Wang, Zhou, *et al.*, 2024); (Wang, Zhang, *et al.*, 2024); (Zafar *et al.*, 2024)
Sustainability	*Sustainable development and skills*	(Atif, 2023); (Modgil *et al.*, 2023); (Narkhede *et al.*, 2024); (Narkhede *et al.*, 2023)
	Efficiency and sustainability	(Atif, 2023); (Caggiano *et al.*, 2023); (Camarinha-Matos *et al.*, 2024); (Destouet *et al.*, 2023); (Dhayal *et al.*, 2023); (Dwivedi *et al.*, 2023); (Ghobakhloo *et al.*, 2023); (Narkhede *et al.*, 2024); (Narkhede *et al.*, 2023); (Sharma and Gupta, 2024a); (Sharma and Gupta, 2024b)
	Sustainable and environmental technologies	(Atif, 2023); (Caggiano *et al.*, 2023); (Camarinha-Matos *et al.*, 2024); (Chabane *et al.*, 2023); (Dhayal *et al.*, 2023); (Dolgui and Ivanov, 2023); (Dwivedi *et al.*, 2023); (Ghobakhloo *et al.*, 2023); (Leng *et al.*, 2022); (Maddikunta *et al.*, 2022); (Narkhede *et al.*, 2024); (Narkhede *et al.*, 2023); (Sharma and Gupta, 2024a); (Sharma and Gupta, 2024b); (Wang, Xue, *et al.*, 2024)

Resilience	*Adaptability and timely response*	(Destouet *et al.*, 2023); (Leng, Zhu, *et al.*, 2023); (Ling *et al.*, 2024)
	Resilience planning and management	(Agrawal *et al.*, 2023); (Ahmed *et al.*, 2023); (Dolgui and Ivanov, 2023); (Ivanov, 2023); (Leng, Zhong, *et al.*, 2023); (Modgil *et al.*, 2023)
	Resilient technologies	(Agrawal *et al.*, 2023); (Ahmed *et al.*, 2023);(Chabane *et al.*, 2023); (Ivanov, 2023);(Leng *et al.*, 2022); (Leng, Zhong, *et al.*, 2023); (Leng, Zhu, *et al.*, 2023);(Ling *et al.*, 2024); (Maddikunta *et al.*, 2022); (Modgil *et al.*, 2023); (Sharma and Gupta, 2024a)

Human-Centricity emerged prominently, emphasizing the value of people in the manufacturing process. The domain of "*Operator well-being*" reflects a conscientious approach toward safeguarding the physical and mental health of workers, resonating with a shift towards workplaces that prioritize employee health as a cornerstone of productivity and innovation. Physical safeguarding could regard Ergonomic and Safety, concepts, mental health could be related to stress. Ergonomic is considered in assembly line design problem (Abdous *et al.*, 2023), and for solving job assignment problem by simultaneously considering different sociotechnical factors as objectives: workers' experience, physical capacity and limitations, postural ergonomic risks (Battini *et al.*, 2022). Safety is considered in updating design guidelines for cognitive ergonomics in human-centred collaborative robotics application (Gualtieri *et al.*, 2024) improving safety and reliability in human–robot collaborative manufacturing (Wang, Zhang, *et al.*, 2024). Also stress in considered in this domain, Tran et al. (2023a) use heart rate variability measurement to assess acute work-content-related stress of workers in industrial manufacturing environment and Verna et al. (2023) propose a novel tool which combines the analysis of overall defects generated during product variant manufacturing with the evaluation of human wellbeing in terms of stress response. The "*Worker involvement and human leadership*" domain captures the evolving dynamics of employee engagement and the significance of leadership styles that elevate human value and participation in decision-making processes. It signifies a departure from autocratic models to more human-centric leadership. S. Wang et al. (2024) outline the Human Needs Pyramid, while Brauner and Ziefle (2022) explore serious games for learning in industrial settings. Gladysz et al. (2023) stress the importance of transitioning to Operator 5.0, involving workers and leadership. Nair et al. (2024) provide insights for implementing human-centric practices in Industry 5.0, focusing on workforce empowerment and data security. Olsson et al. (2024) advocate for leadership practices that prioritize worker involvement and continuous learning. Meanwhile, "*Human-centric work environment technologies*" concentrate on the integration of technology in a manner that is symbiotic with human operators, recognizing the imperative of designing systems that are adaptive to human skills and limitations. In this context Chabane et al. (2023) propose a systematic approach to transition, emphasizing the importance of considering societal and environmental goals. Similarly, Gladysz et al. (2023) examine the readiness of Industry 4.0 technologies for a transition to Operator 5.0, focusing on resilience, humanism, and sustainability. Likewise, Lu et al. (2022) highlight the need for a shared understanding of human-centered manufacturing and its frameworks and Maddikunta et al. (2022) undertook an extensive investigation into the enabling technologies and potential applications of this new industrial era.. These efforts provide an in-depth overview of the challenges and opportunities in transitioning to I5.0, highlighting the centrality of the human-centered approach. Meanwhile, the collaboration between humans and robots plays a crucial role in the industry's evolution. Dornelles et al. (2023) explore the impact of collaborative robots on workers' skills, while others focus on cognitive ergonomics in human-centric collaborative robotics applications (Gualtieri *et al.*, 2024). Additionally, addressing the challenge of balancing and planning assembly lines with human-robot collaboration tasks (Nourmohammadi *et al.*, 2022). These studies reveal the potential of collaboration technologies to enhance efficiency and safety in the workplace. The digitization of human experience emerges as another crucial research area, proposing the concept of Human Digital Twin to integrate human aspects into intelligent production systems (Wang, Zhou, *et al.*, 2024). Finally, artificial intelligence plays a fundamental role in I5.0, with Peruzzini et al. (2023) presenting a framework for designing intelligent production systems based on human-automation symbiosis. An agenda for human-centered production systems was outlined by Turner and Garn, (2022), focusing on DES simulation as a key tool for process design and optimization. A new diagnostic tool for quality monitoring, centered on human-robot collaboration in the production environment, was presented by Verna et al., (2023). The state of the art in defect-proof manufacturing centered on humans was examined by Wan and Leirmo, (2023) highlighting perspectives and challenges. Switching to **Sustainability** as a pillar has been dissected into domains that collectively aim to mitigate the ecological footprint while bolstering economic viability. "*Sustainable development and skills*" foreground the need for educational and professional development programs that empower stakeholders to contribute to sustainability goals. Analysing the alignment between circular economy and Industry 4.0 nexus with the I5.0 era, (Atif, 2023) emphasizes the transition towards a more value-driven vision, placing human-centric approaches at the forefront of sustainable and resilient smart manufacturing. A focus on developing human capabilities for supply chains within the context of I5.0, highlighting the importance of managerial, operational, and advanced technical skills for supply chain professionals is outlined (Modgil *et al.*, 2023). Further delve into the role of I5.0 in driving sustainability in the manufacturing sector, proposing frameworks for effective implementation and highlighting the importance of interdisciplinary collaborations, policy support, and stakeholder engagement for realizing sustainable manufacturing practices (Narkhede *et al.*, 2023, 2024). The domain of "*Efficiency and sustainability*" interlinks the dual aims of enhancing operational efficiency with the overarching goal of sustainable practices, marking a strategic alignment of resource management with environmental stewardship. Several studies propose strategies for transitioning to I5.0 and sustainable manufacturing. Caggiano et al. (2023) advocate for intelligent cooperation between humans and machines for efficiency. Camarinha-Matos et al., (2024) highlight collaborative networks' role in addressing sustainability demands. Destouet et al. (2023) and Dhayal et al. (2023) emphasize integrating human and environmental factors into manufacturing scheduling. Sharma and Gupta (2024b, 2024a) explore Cognitive Digital Twins and strategies for cleaner production, aligning industrial advancements with sustainability goals. These studies emphasize resource management aligned with environmental stewardship for operational efficiency and sustainability in manufacturing. "*Sustainable and environmental technologies*" acknowledges the role of innovative technologies in reducing environmental impact, signalling a shift towards eco-friendly solutions that are becoming increasingly prevalent in forward-thinking organizational strategies. Real-time data collection and analysis emerge as fundamental, enabling manufacturers to make informed decisions based on up-to-date information about their processes (Atif, 2023). Additionally, information and communication technologies (ICT) play a crucial role in enhancing connectivity between physical devices, paving the way for more efficient and integrated manufacturing systems (Caggiano et al., 2023). Automation and Artificial Intelligence (AI) are emphasized in several papers, showcasing their potential to streamline processes and optimize resource usage (Camarinha-Matos et al., 2024). Big data analytics are also highlighted as key, enabling manufacturers to extract valuable insights from large datasets to improve efficiency and implement proactive sustainability measures (Ghobakhloo et al., 2023). Furthermore, the Internet of Things (IoT) is recognized as a supporting technology for I5.0, offering interconnectedness between devices and systems. Edge computing is another technology mentioned, providing real-time processing capabilities at the edge of the network, enhancing responsiveness, and reducing latency (Maddikunta et al., 2022). Digital twins, which replicate physical entities in a virtual environment, are explored for their transformative capabilities in achieving sustainable development goals (Sharma and Gupta, 2024a). Blockchain technology is also discussed for its potential to ensure transparency and accountability in supply chains, contributing to sustainable industrialization (Peruzzini et al., 2023), (Sharma and Gupta, 2024b). Cloud computing emerges as a technology facilitating supply chain management, particularly in the context of metaverse-driven operations (Dolgui and Ivanov, 2023). Additionally, agent-based modeling and discrete event simulation are employed in hybrid simulation models to analyze sustainable metrics in supply chain design, offering insights into optimizing resource usage and enhancing overall sustainability (X. Wang et al., 2024). **Resilience** captures the capacity of organizations to withstand and adapt to challenges. The "*Adaptability and timely response*" domain stresses the importance of agility and flexibility in operational practices, enabling organizations to respond swiftly to immediate disruptions. These studies contribute to the resilience pillar by enhancing manufacturing systems' ability to adapt and respond to operations disruptions. Destouet et al. (2023) focus on scheduling with human and environmental factors. Leng et al. (2023a) propose a blockchain system for decentralized manufacturing. Ling et al. (2024) mitigate ergonomic risks in real-time. Peruzzini et al. (2023) promote human-automation collaboration for adaptive decision-making. Strategic foresight is at the heart of "*Resilience planning and management*", a domain dedicated to the proactive identification of risks and the development of contingency plans. Agrawal et al. (2023) and Ahmed et al. (2023) explore how I5.0 technologies and artificial intelligence can mitigate disruptions in supply chains, considering pandemics and other crises. Dolgui and Ivanov (2023) investigate the impact of the metaverse on supply chain and operations management, anticipating future challenges and opportunities. Ivanov (2023) proposes sustainable recovery strategies in the supply chain, emphasizing the importance of preparedness and proactive environmental measures. Leng et al. (2023a) introduce a decentralized autonomous manufacturing paradigm, envisioning resilient manufacturing systems while Modgil et al. (2023) focus on developing human capabilities for I5.0 supply chains, aligning skills with future needs through strategic planning. These studies anticipate and prepare for future disruptions, aligning with the proactive approach of strategic foresight in resilience planning and management. Finally, "*Resilient technologies*" underlines the criticality of incorporating robust and flexible technological solutions that ensure continuity and recovery in the face of adversity. I5.0 is outlined aims to integrate human creativity with intelligent machines to achieve efficient and personalized production solutions and supply chains (Agrawal *et al.*, 2023; Leng, Zhong, *et al.*, 2023; Maddikunta *et al.*, 2022; Sharma and Gupta, 2024a). Ahmed et al. (2023) analyze how artificial intelligence can be employed to enhance the resilience of supply chains in the post-COVID-19 era. The adoption of technologies such as blockchain and IoT is explored by Leng et al. (2023b) in the context of decentralized and autonomous production, and Ivanov (2023)highlights the importance of sustainable strategies such as additive manufacturing and electric vehicles to enhance the resilience of supply chains. These domains outline a comprehensive framework for I5.0, balancing technological advancement with human well-being, environmental sustainability, and resilience. This classification guides literature analysis and provides a structured lens for assessing and developing future research and industrial innovations.

5.Conclusions

The analysis of the distribution of contributions across different pillars and domains can significantly inform the proposed research agenda. The predominance of contributions in the Human-Centric domain (29) suggests that the research agenda should continue to prioritize the exploration of human-automation interaction. However, there is an opportunity to further delve into how these human-centric approaches can be harmoniously integrated with sustainability and resilience initiatives. The number of contributions to Sustainability (18) and Resilience (13) indicate these areas are established but not yet saturated, signalling the need for a more detailed roadmap for future research. The agenda should stimulate research that closes the gap between current sustainability practices and the aspirational goals of I5.0, which would necessitate innovation in resource-efficient technologies and strategies. Given the fewer contributions that span Human-Centricity, Sustainability, and Resilience together (4), a major component of the research agenda should be the interdisciplinary studies that link these pillars. Such research could explore frameworks for production systems that not only boost efficiency and adaptability but also enhance worker empowerment and contribute positively to the environment. Operator Well-being (13) and Human-Centric Work Environment Technologies (22) have received significant focus, highlighting them as current research hotspots while Worker involvement and human leadership has been less investigated (8). The agenda should now aim to translate these academic insights into practical applications and standard practices within the industry. Meanwhile, areas like Sustainable Development and Skills (4), Adaptability and Timely Response (4), and Resilience Planning and Management (4) —with fewer contributions—demand an increased focus. This indicates a need for skill development programs, technologies, and management practices that can facilitate a swift and sustainable response to the changing industrial landscape. Lastly, the moderate attention to Efficient and Sustainable Practices (11) and Resilient Technologies (11) indicates a steady interest in these areas. The research agenda should encourage the development of technologies that ensure resilience through efficiency, thereby supporting long-term sustainable growth. Furthermore, intersections among the domains of the three pillars illustrate the interconnected nature of Industry 5.0. For instance, the overlap of production efficiency, a core aspect of lean manufacturing, and human involvement suggests fertile ground for the evolution of Lean 5.0, blending operational excellence with enhanced worker participation. Similarly, the convergence of sustainability and human-centric approaches across the product lifecycle signals the emergence of PLM 5.0, integrating environmental awareness into all phases of product development and utilization. These intersections highlight key development frontiers for Industry 5.0. The research agenda should address the current focus on human-centric studies and equally promote environmental and resilience aspects. This strategy should integrate these three pillars to foster innovation in a manufacturing sector that is human-friendly, ecologically responsible, and robust against future challenges.

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