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Advancing sustainable manufacturing: a systematic exploration of Industry 5.0 supply chains for sustainability, human-centricity, and resilience

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ABSTRACT

The emergence of Industry 5.0 provides new perspectives for the manufacturing sector, aiming to create sustainable, human-centric, and resilient approaches. Supply chains perform a vital role in realising these objectives by connecting suppliers to customers and providing value-added products and services. However, despite growing interest, the consideration for this paradigm shift in the manufacturing industry remains amorphous. In order to address this gap, this paper presents a systematic literature review of 103 research articles from an initial corpus of 8,079 and proposes a conceptual framework for Supply Chain 5.0 within the manufacturing sector. The framework is scaffolded on a thematic analysis of the literature, including drivers to transition, impacts on manufacturing supply chains, challenges, and outcomes. This study provides valuable insights for researchers, practitioners, and policymakers seeking to examine the implications of Industry 5.0 supply chains, highlighting its potential to enhance sustainability, social well-being, and economic growth. Furthermore, the proposed conceptual framework and research opportunities serve to guide future research and practical applications around this emerging topic.

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Industry 5.0; manufacturing; supply chains; sustainability; resilience; supply chain 5.0

1. Introduction

1.1. Transitioning from Industry 4.0 to Industry 5.0: Emphasising sustainability, human-centricity, and resilience

The concept of Industry 5.0 aspires to create a manufacturing ecosystem that prioritises sustainability, resilience, and human-centred values (Lyngstadaas and Berg 2022; Madsen and Berg 2021). This paradigm shift is propelled by academic research and policy initiatives aiming to fulfil societal objectives that transcend mere employment and economic expansion (van Oudenhoven et al. 2022). One of its key features is the prioritisation of employee well-being in production processes and the responsible use of the earth's resources through advanced technologies (Breque, De Nul, and Petridis 2021).

Industry 5.0 is partly emerging as a result of Industry 4.0's perceived limitations pertaining to humanisation and sustainability, prioritising technology development and adoption to enhance production efficiency, while forestalling elements of sustainability and social fairness (Grabowska, Saniuk, and Gajdzik 2022; Leng, Sha, Wang, et al. 2022). The prevailing focus of organisations on dehumanising production systems and the increased energy consumption resulting from technology adoption is therefore fostering interest among researchers and policymakers (Raja Santhi and Muthuswamy 2023). For example, the literature indicates an imperative to enhance supply chain performance under the Industry 4.0 framework with respect to sustainability (Bai et al. 2020; Birkel and Müller 2021; Ding, Ferràs Hernández, and Agell Jané 2021; Ghobakhloo 2020), human-centricity (Mukhuty, Upadhyay, and Rothwell 2022; Neumann et al. 2021), and resilience (Ivanov and Dolgui 2021; Razak, Hendry, and Stevenson 2021; Spieske and Birkel 2021). However, it is significant that neither environmentally nor socially sustainable development has been imperatively regarded as a fundamental design principle by practitioners or researchers.

Research has recently started to demonstrate the potential for significant transformation within the industry, surpassing the original scope of Industry 4.0 (Ivanov 2022; Lyngstadaas and Berg 2022; van Oudenhoven et al. 2022). Nonetheless, current research has largely focused on exploring individual components or discussing them in paired combinations. Notable examples include economic and environmental sustainability, sustainability and human-centricity, or sustainability and resilience (Bai et al. 2020; Ivanov 2018; Kamble, Gunasekaran, and Gawankar 2018; Kazancoglu et al. 2021; Li, Dai, and Cui 2020; Luthra and Mangla 2018; Mubarik et al. 2021; Ralston and Blackhurst

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2020; Scavarda et al. 2019). Industry 5.0, however, should recognise the critical role of companies in addressing societal challenges across various dimensions, including resource conservation, climate change, and social stability, by establishing a comprehensive context and triangulating sustainability, human-centricity and resilience in supply chain management (Leng, Sha, Lin, et al. 2022; Maddikunta et al. 2022; Mourtzis, Angelopoulos, and Panopoulos 2022a, 2022b; Saniuk, Grabowska, and Straka 2022). Research into Industry 5.0 is intrinsically based on the progression of Industry 4.0. As Industry 4.0 advances, its associated challenges, notably the substitution of human labour with automation, escalating energy consumption, and environmental emissions, are becoming more acute. Industry 5.0 has been suggested as an enhancement or refinement of Industry 4.0. It aims to address and potentially reverse the disruptive impacts that may emerge in supply chains and the broader societal sustainability amid the continuing development of Industry 4.0.

1.2. Influence of Industry 5.0 on supply chains in the manufacturing sector

Supply chains serve as the mainstay of companies operating in the manufacturing sector, facilitating the transformation of raw materials into finished products, and connecting suppliers to customers (Gawusu et al. 2022; Yadav et al. 2020). Industry 4.0, which emerged in the decade of the 2010s, represented a paradigm shift towards technology-centric transformation. Its principal objective was the optimisation of productivity and efficiency through the application of emergent technologies. This transition entailed a comprehensive digitalisation of the manufacturing sector, encompassing the development of smart manufacturing and the digitisation of the entire value chain (Xu et al. 2021). In contrast, Industry 5.0 has emerged as a subsequent iteration of Industry 4.0, signifying a transition from a focus on discrete technological innovations to a holistic, systematic approach. This approach advocates for industrial sustainability by fostering an integration of human ingenuity with the capabilities of intelligent, efficient, and precise machinery (Maddikunta, Pham, B, et al., 2022). The adoption of Industry 4.0 in supply chains has previously been referred to as “supply chain 4.0” or “digital supply chain” (Büyüközkan and Göçer 2018; Garay-Rondero et al. 2020; Pandey, Singh, and Gunasekaran 2021). These terms encapsulate the adoption and application of advanced technologies to streamline supply chain activities and processes, thereby advancing stakeholders in the supply chain processes (Frederico et al. 2020; Hahn 2020; Makris, Hansen, and Khan 2019). In contrast, Industry 5.0 introduces a new value perspective and novel requirements that challenge the existing industrial structure and power dynamics between supply chain actors, leading to a reconfiguration of the existing chain (Maddikunta et al. 2022; Sharma et al. 2022). As such, Industry 5.0 supply chains may leverage the extant technological advantages of Industry 4.0 and create a balanced human-robot collaboration environment to enable mass customisation. In addition, Industry 5.0 supply chains can influence energy consumption and emissions reduction whilst supporting employee interests and improving product efficiency (Frederico 2021; Humayun 2021; Maddikunta et al. 2022; Sindhwani et al. 2022).

As noted, researchers are increasingly focusing on the promising impact of Industry 5.0 supply chains (Lyngstadaas and Berg 2022; Tran et al. 2022; Yuan et al. 2022). Some are reviewing the transition from Industry 4.0 to Industry 5.0 and identified potential new applications and supporting technologies (Zizic et al. (2022); Maddikunta et al. (2022). Others such as Mukherjee, Raj, and Aggarwal (2023) are looking into the necessity to integrate technology, human agency, and sustainability when implementing Industry 5.0. There exists a notable scarcity of prior research dedicated to facilitating the transition to Industry 5.0 within the supply chain domain. Frederico (2021) proposed a framework and highlighted the pressing need for industry strategies to effectively balance human-machine relationships to contribute to a sustainable society, adopting advanced technologies and innovation. Ivanov (2022) added a scaffold that Industry 5.0’s influence on supply chains should be reviewed from the perspectives of organisation, management, technology, and performance evaluation.

These attempts offer a limited perspective on the role of Industry 5.0 in advancing supply chain management in various organisational and operational dimensions (Leng, Sha, Wang, et al. 2022; Madsen and Berg 2021). This limitation underscores the need for a comprehensive systematic review that encompasses not only the drivers, definitions, and challenges of Industry 5.0, but also evaluates its potential for sustainable development in the manufacturing sector (Alexa, Pîslaru, and Avasilcăi 2022; Leng, Sha, Wang, et al. 2022; Maddikunta et al. 2022). Furthermore, as the successful implementation of Industry 5.0 is largely contingent upon a comprehensive understanding of its influences (Huang et al. 2022), a detailed examination of its relevant aspects is essential for both research and practical applications. Such examination is particularly critical for identifying and addressing the dynamic challenges in supply chain management. However, an analysis of the existing literature reveals a notable dearth of comprehensive frameworks specific to Industry 5.0 within the manufacturing supply chain domain.

We undertake a Systematic Literature Review (SLR) using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology to address the identified research gap. We aim to comprehensively survey the latest research on supply chains within the context of Industry 5.0. In this vein we aim to develop a holistic understanding of Industry 5.0 and its associated factors by reviewing and synthesising the most frequently cited definitions of Industry 5.0 in academic literature, and by identifying key potential influences of Industry 5.0 on manufacturing supply chain operations. We propose a conceptual framework for Supply Chain 5.0, designed to fill theoretical gaps and establish a foundation for future research. Consequently, this study seeks to address the following main research question: *How does the implementation of Industry 5.0 transform manufacturing supply chains?* This is underpinned by several objectives. First, establishing a comprehensive definition of Industry 5.0

by analysing and summarising existing evidence and understanding. Second, identifying the key enablers that are driving the adoption of Industry 5.0. Third, discussing the impacts and challenges posed by Industry 5.0 on manufacturing supply chains. Lastly, pinpointing the main areas for future research to address the gaps in the current literature related to Industry 5.0 and supply chain transformation.

2. Review framework

To assess the influence of Industry 5.0 on supply chains in the manufacturing sector, we employ a systematic literature review guided by the PRISMA framework (Page et al. 2021), and thematic grouping (Braun and Clarke 2006; Levac, Colquhoun, and O'Brien 2010) as an established protocol for examining associated domains of knowledge, including supply chains, and manufacturing (Almeida et al. 2022; Gayer, Saurin, and Wachs 2021; Schulze and Dallasega 2023; Thomé, Scavarda, and Scavarda 2016; Tortorella et al. 2022). Systematic reviews, as argued by Denyer and Tranfield (2009), support robust methodologies that allow for the identification, selection, analysis, and evaluation of relevant literature sources pertaining to a specific research inquiry, by employing techniques to reduce the risk of bias and errors (Dong et al. 2024; Tranfield, Denyer, and Smart 2003). Adhering to the PRISMA protocol ensures that our review process is transparent, reproducible, and consistent, thereby enhancing the reliability and credibility of the findings (Moher et al. 2015). The framework comprises four fundamental steps, namely, identification of potential literature sources, screening, verification of eligibility, and determination of inclusion or exclusion (Page et al. 2021). Figure 1 provides a representation of the systematic literature review process following the PRISMA protocol adopted in this study.

2.1. Identification

We conducted a comprehensive search using three prominent electronic databases: Scopus, Web of Science, and Google Scholar (Harzing and Alakangas 2016). The construction of search strings was centred on the paradigm shift from Industry 4.0 to Industry 5.0, specifically within the context of supply chains in the manufacturing sector. The initial phase entailed identifying pertinent records within these databases. We defined the relevant keywords within the desired scope as "Supply chain", "Manufacturing", "Industry 5.0", and the three core values of Industry 5.0, which are "Human-centricity", "Sustainability", and "Resilience".

Our search strings are based on these three sets of keywords. The first search string targets literature in the supply chain domain. The second aims to limit the search to the manufacturing industry context. The third one is grounded on the keywords of Industry 5.0 and its core values: "Industry 5.0", "Society 5.0", "human-centricity (Human)", "sustainability (Sustainab*)" and "resilience (Resilien*)". The query adopted for this SLR is the association of the three search strings connected by the Boolean logic and submitted to the identified databases:

[Supply chain] AND [Manufactur*] AND [Industry 5.0 OR Society 5.0 OR Human OR Sustainab* OR Resilien*].

We incorporated Society 5.0 as a keyword in our search strings. The term originated in the Fifth Science and Technology Basic Plan in 2016 by Keidanren, Japan's Foremost Business Federation, and is a paradigm aimed at building an ideal future society that combines the real and virtual domains through the use of advanced enabling technologies (Fukuda 2020). Emerging research has explored the relationship between Society 5.0 and Industry 5.0, noting their common objectives and ideals, including a concerted effort to balance economic growth with social issues and foster a sustainable, human-centred society (Carayannis, Draper, and Bhaneja 2021; Dautaj and Rossi 2022; Huang et al. 2022; Paschek, Mocan, and Draghici 2019). Although Society 5.0 is concerned with broader social challenges beyond specific economic sectors, both perspectives emphasise a shift from technology-oriented progress to a more human-centred and sustainable approach. Society 5.0 and Industry 5.0 are often discussed in tandem, particularly in relation to the implications of Industry 5.0 for manufacturing and supply chains (Carayannis et al. 2022; Minculete, Bã,rsan, and Olar 2021; Thakur and Kumar Sehgal 2021). Therefore, the inclusion of Society 5.0 as a keyword in our research was deemed pertinent.

The search parameters encompassed scholarly studies that: (i) integrated the specified keywords in the article title, abstract, or keywords; (ii) were published between 2016 and 2023; (iii) appeared in peer-reviewed journals or conference proceedings; and (iv) were published in English. We set 2016 as the starting point as the "Industry 5.0" concept was then introduced to academic discourse (Aslam et al. 2020; Özdemir and Hekim 2018). As there is a lack of consensus regarding conference proceedings' reliability as a credible source of empirical data (Choudhury et al. 2020; Dallasega, Marengo, and Revolti 2021; Estabrooks, Scott-Findlay, and Winther 2004; Jackson, Spiegler, and Kotiadis 2024), only those with established academic merit are included in this SLR to extract insights of the emerging research topic (Sony and Naik 2020)

2.2. Screening

The screening phase involved a systematic evaluation of the relevant literature (Page et al. 2021) to eliminate any duplication of content within our corpus (Moher et al. 2015). We established specific criteria that focused on the relevance of the article's Title, Year, and Abstract-based characteristics to ensure an efficient and accurate selection process. Any discrepancies that arose within the research team were addressed through discussion and consensus to ensure the reliability of our screening appraisal. Throughout this process, we maintained transparency and a systematic approach in line with the PRISMA guidelines, documenting the number of articles excluded based on each criterion. Focusing our selection on literature closely aligned with our research questions allowed us to prioritise the central topic of our study

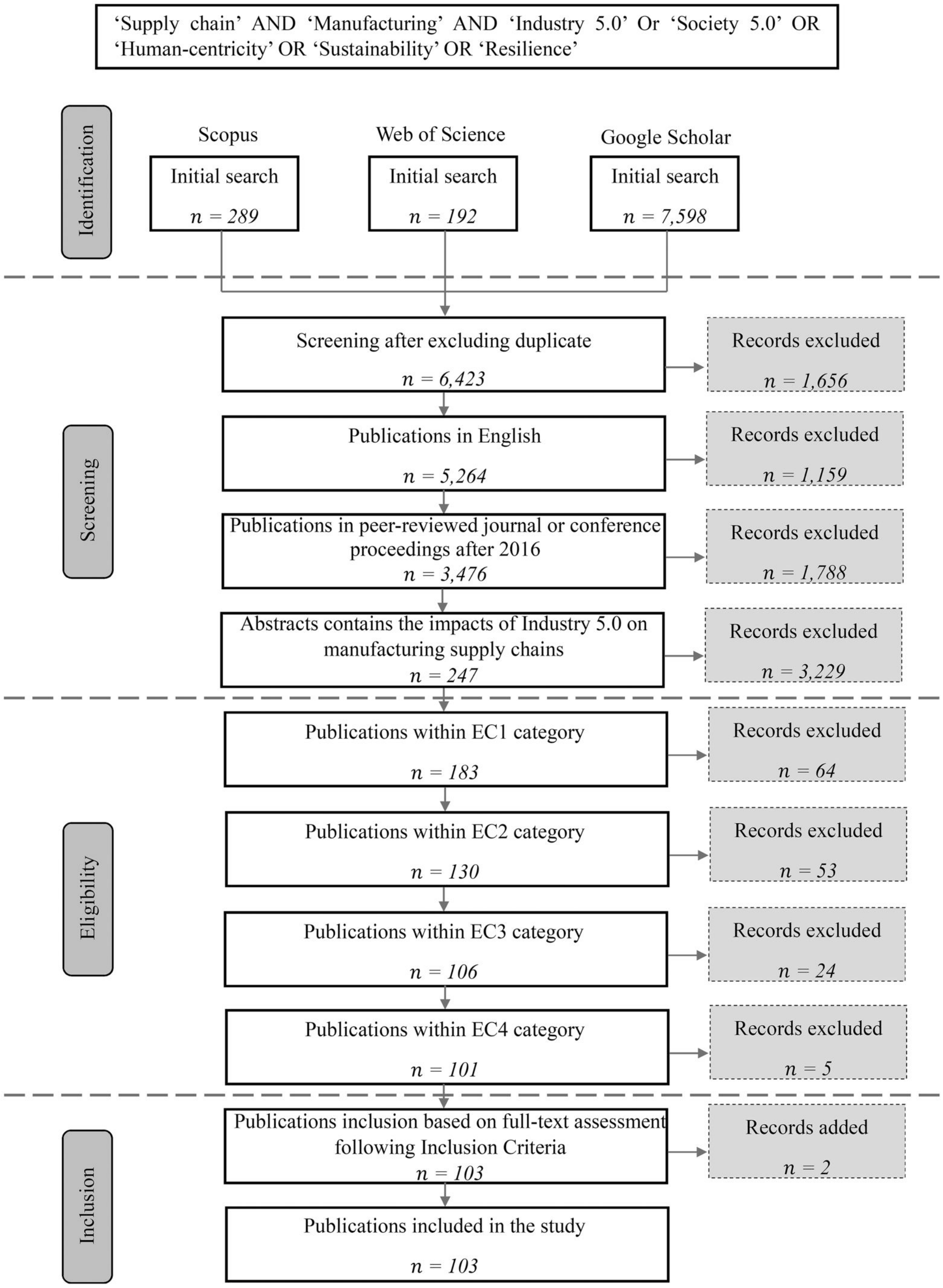

Figure 1. PRISMA review process.

and avoid extraneous concerns that may not contribute to our objectives.

2.3. Eligibility

After completing the screening phase, we conducted a comprehensive evaluation of the eligibility of publications, taking into account any non-relevant articles that were identified through an in-depth examination of their complete texts (Page et al. 2021; Tortorella et al. 2022). This thorough process involved subjecting all remaining articles to a full-text analysis that was guided by the Eligibility Criteria (EC) outlined in Table 1. Specifically, EC1 dictates the exclusion of articles where full-text access was unavailable. Despite efforts to secure these articles, including interlibrary loans and direct communication with authors, some had to be omitted due to restricted access to databases or academic libraries. EC2 pertains to articles that mention Industry 5.0 or the supply chain solely as a keyword, an example, a fact, or a cited expression, without any substantial relevance to the research questions. For instance, articles that only briefly discuss the concept of Industry 5.0 without any further analysis were excluded under this criterion. Similarly, EC3 involves articles that discuss Industry 5.0 or supply chains in the context of research trends or recommendations, without any substantial investigation of these phenomena. Finally, EC4 pertains to articles that do not focus

Table 1. Eligibility criteria.

Eligibility Criteria	
EC1	Full-text not available
EC2	Industry 5.0 or supply chain is only used as a keyword, example, fact or cited expression.
EC3	Industry 5.0 or supply chain is only used to describe research trends or recommendations.
EC4	The research does not focus on the manufacturing sector.

Table 2. Inclusion criteria.

Inclusion Criteria	
IC1	The paper investigates Industry 5.0 and supply chains in the manufacturing sector.
IC2	The research shows the impacts of Industry 5.0 on the whole or part of the supply chain.
IC3	Supply chain and Industry 5.0 are part of the main research effort.

on the manufacturing sector; that is, while an article may reference Industry 5.0 or supply chains, its primary focus may be on a different industry or area of research.

2.4. Inclusion

In this phase, we mandated that papers investigate Industry 5.0 and supply chains in the manufacturing sector, or that these areas constituted their primary research focus. This facilitated the refinement of our selection to only those articles that were most conducive to fulfilling our research objectives. Table 2 delineates the Inclusion Criteria (IC) that were formulated explicitly based on our research objectives. IC1 requires that the selected papers under review investigate the intersection of Industry 5.0 and supply chain management in the manufacturing sector. IC2 stipulates that the article should provide evidence of Industry 5.0's impacts on the entire or a part of the supply chain. Lastly, IC3 requires that the supply chain and Industry 5.0 were central to the study's primary research objectives, rather than peripheral issues that were unrelated to the research questions. Furthermore, as the body of research on Industry 5.0 is rapidly expanding, systematic review guidelines recommend conducting periodic search updates throughout the writing process. This is crucial to ensure the inclusion of all relevant and recent articles (Rethlefsen et al. 2021). In this vein, the initial phase of the SLR was conducted from January to December 2022, and in order to maintain the currency of our review, a subsequent search adhering to the same criteria was undertaken from December 2022 to March 2023, leading to the identification of two additional significant articles. Ultimately, 103 articles were selected for review following the application of the inclusion criteria. A comprehensive exposition of the selected articles is provided in Appendix A. This phase represented a critical juncture of the systematic review protocol as it marked the conclusive identification and selection of the articles subject to our analysis.

3. Analysis

The analysis involved a detailed examination of selected literature, providing insights into various research approaches, emergent themes, and current trends. The contribution of systematic literature reviews to concept building in supply chain management is acknowledged as significant (Carter and Washispack 2018; Durach, Kembro, and Wieland 2017; Seuring et al. 2022). Instead of a theory-developing or theory-testing approach (Durach, Kembro, and Wieland 2021; Siems, Land, and Seuring 2021), we position this literature review as a conceptualisation of Industry 5.0 and its impacts on manufacturing supply chains. To this end, thematic analysis has been employed to identify and understand key themes and patterns (Braun and Clarke 2006). Our analysis highlights the temporal growth of studies in this domain, the methodological preferences of scholars, and the thematic foci of Industry 5.0 research. The ensuing subsections delve deeper into the particulars of the publications by year, research approaches employed, and the emerging thematic dimensions in the literature, namely the definition of Industry 5.0, drivers of transition, impacts on supply chains, and challenges associated with transitioning to Industry 5.0.

3.1. Publications by year

Figure 2 shows a marked upward trajectory in the volume of published papers on supply chain operations within the context of Industry 5.0. This trend has proliferated since 2016, with a significant increase in the number of articles published from 2021 to 2023: 82 out of the total 103 publications emerged from 2021 onwards, indicating substantial growth in research activity focused on supply chain operations and Industry 5.0.

3.2. Distribution of Industry 5.0 papers based on research type and content

Figure 3 displays the various research methods employed in investigating the relationship between Industry 5.0 and supply chains within the considered period. The studies are broadly divided into two categories: conceptual and empirical. The empirical investigations encompass the application of Industry 5.0 in practice, employing methodological approaches such as case studies, simulations, experimentation, and surveys. The papers were classified as conceptual studies focusing on theories, challenges, and prospects of Industry 5.0, without collecting primary data or engaging in empirical methods.

Figure 3 reveals that the majority of the published research leans towards conceptual studies. Although there has been a gradual increase in the number of empirical publications employing simulation, experimentation, and prototyping to analyse Industry 5.0, there remains a notable lack of practical applications within the existing literature. Therefore, we integrate conceptual insights with practical implementations to highlight the influence of Industry 5.0 on supply chain management, design, and the strategies that organisations formulate in response to this paradigm shift (Akundi et al. 2022; Maddikunta et al. 2022; Prassida and Asfari 2022).

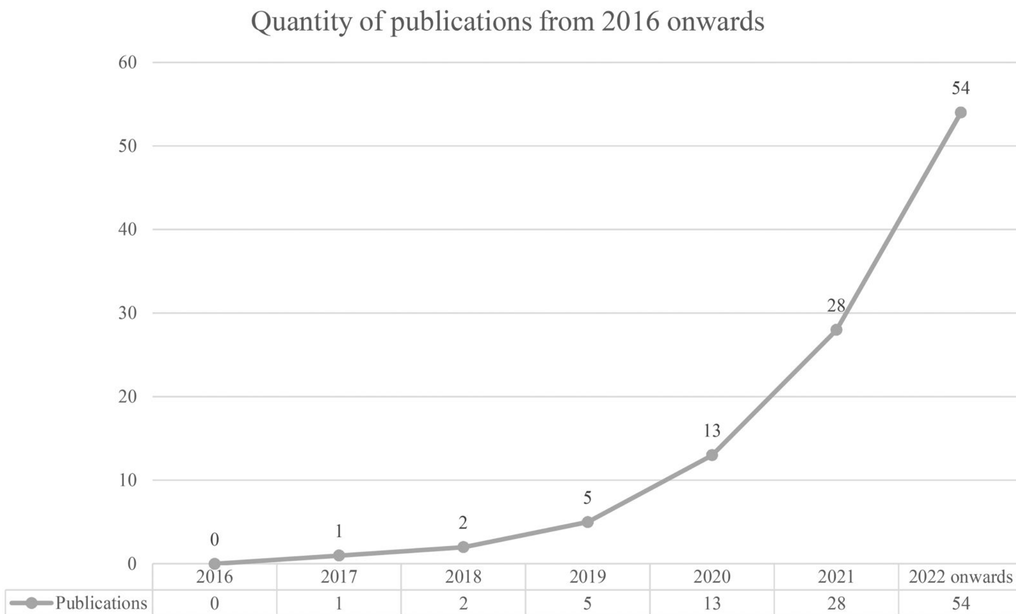

Figure 2. Comprehensive compilation of 103 pertinent research publications from 2016.

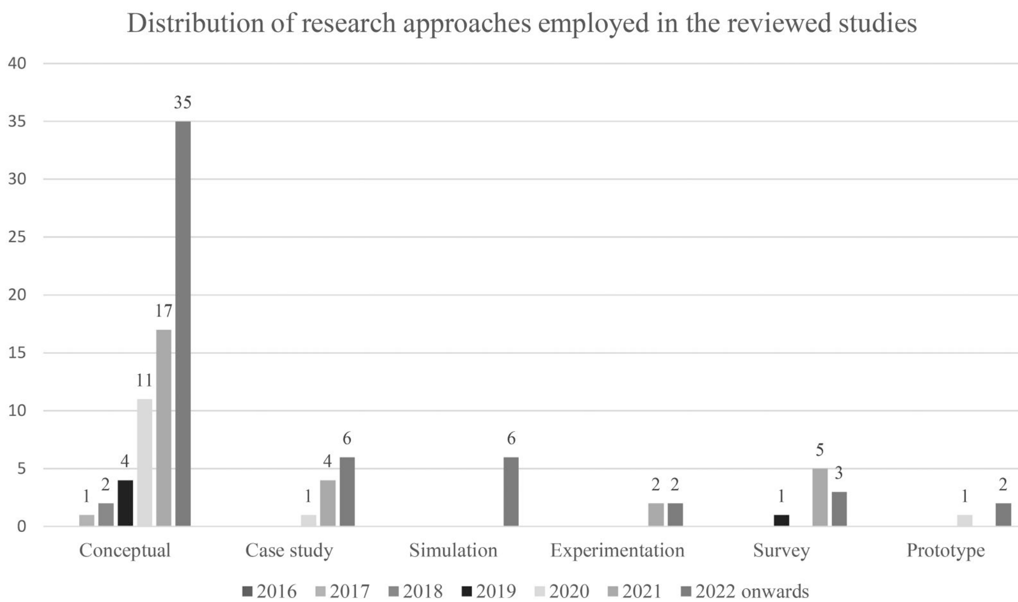

Figure 3. Distribution of research approaches employed in the reviewed studies.

3.3. Emergent themes

A thematic analysis was employed to extract a coherent representative narrative from our corpus of 103 papers (Braun and Clarke 2006; Levac, Colquhoun, and O'Brien 2010; Michalakopoulou et al. 2023). This approach is deemed appropriate for our purposes as it enables a methodical identification, organisation, and thematic rendering of our data (Braun and Clarke 2012). Moreover, it decomposes datasets into content units and processes them through descriptive analysis (Chen 2020; Clarke and Braun 2016). This enables a comprehensive examination of the themes inherent within the data. It can also facilitate the identification of overarching themes and trends that are crucial to the study. Therefore, thematic analysis enables us to encompass and interpret the richness of the data to build a comprehensive and in-depth framework to analyse and reveal Industry 5.0 supply chains. Following the meticulous review of the 103 articles summarised in Appendix A, we classified Industry 5.0-related factors arising from the thematic analysis under specific themes to affect a cohesive and practicable research analysis. The analysis was developed iteratively to identify, evaluate, and interpret themes (Braun and Clarke 2012). In this manner, the initial phase was data compilation, comprising a meticulous examination to extract statements relevant to the objectives of the study. The data were then subjected to encoding, employing identified categories to discern meaningful themes and concepts inherent in the collected data. Sub-themes were categorised under their respective main themes. From this analysis, four principal themes surfaced: (i) Definition of Industry 5.0, (ii) Drivers of Transition to Industry 5.0, (iii) Impacts of Industry 5.0 on supply chains, and (iv) Challenges to transition to Industry 5.0. These themes not only reflect the essential aspects of the literature but also provide an inclusive understanding of the various dimensions of Industry 5.0.

The definition of Industry 5.0 encompasses related concepts and theories (Breque, De Nul, and Petridis 2021; Demir, Döven, and Sezen 2019; Longo, Padovano, and Umbrello 2020; Maddikunta et al. 2022; Nahavandi 2019; Özdemir and Hekim 2018). The distribution of research categories, as shown in Figure 4, reveals that most attention was paid to Industry 5.0 concepts and theories and enabling technologies.

The second theme, which emerged from the analysis, relates to the drivers of transition to Industry 5.0. According to Breque, De Nul, and Petridis (2021), these drivers include human-centricity, sustainability, and resilience, which serve as essential catalysts for adopting Industry 5.0 in the manufacturing and supply chain sectors. The third theme pertains to the impacts of Industry 5.0 on supply chains, characterised by the central values of Industry 5.0 that are further ingrained in the triple bottom line dimensions, i.e., economic, environmental, and social (Birkel and Müller 2021). Understanding these impacts is crucial for organisations seeking to adapt and thrive in an Industry 5.0 landscape. The final theme identified in the analysis addresses the challenges (Kembro, Näslund, and Olhager 2017) that arise during the transition to Industry 5.0. They encompass the necessity to comprehend how Industry 5.0 impacts supply chain design and management and how the manufacturing sector can effectively initiate a transition to Industry 5.0.

These themes underscore the need for more empirical studies to bridge the gap between conceptual understanding and practical application of Industry 5.0., and they represent a fundamental framework for more in-depth exploration. Consequently, in the ensuing section, we discuss these emergent themes, offering a comprehensive review of their significance and implications. The discussion section incorporates other literature to enhance the comprehensiveness and depth of the findings.

4. Results and discussion

4.1. Definition of Industry 5.0

The definition of Industry 5.0, which encompasses a series of key concepts and theories. Notwithstanding the ongoing development, heretofore research largely adopts a conceptual approach. Therefore, we provide a thorough discussion of the concepts and theories underpinning Industry 5.0. Table 3 summarises them as they appear in the most frequently cited literature.

Table 3 denotes that Industry 5.0 represents the next phase of industrial evolution, characterised by a synthesis between human expertise and autonomous machines. On this basis, we summarise that Industry 5.0 is the next phase of industrial evolution, characterised by a synthesis between human expertise and autonomous machines, focusing on three fundamental values: human-centricity, sustainability, and resilience, to promote prosperity while considering social, economic, and environmental aspects (Breque, De Nul, and Petridis 2021; Demir, Döven, and Sezen 2019; Longo, Padovano, and Umbrello 2020; Maddikunta et al. 2022; Nahavandi 2019; Özdemir and Hekim 2018).

4.2. Drivers of Transition to Industry 5.0

To discuss the factors that drive the transition to Industry 5.0, we contextualise the preceding concept of Industry 4.0 (Almeida et al. 2022; Ding, Ferràs Hernández, and Agell Jané 2021; Ivanov and Dolgui 2021; Kazancoglu et al. 2021; H. Lu, Zhao, et al. 2022; Sony and Naik 2020). Often referred to as

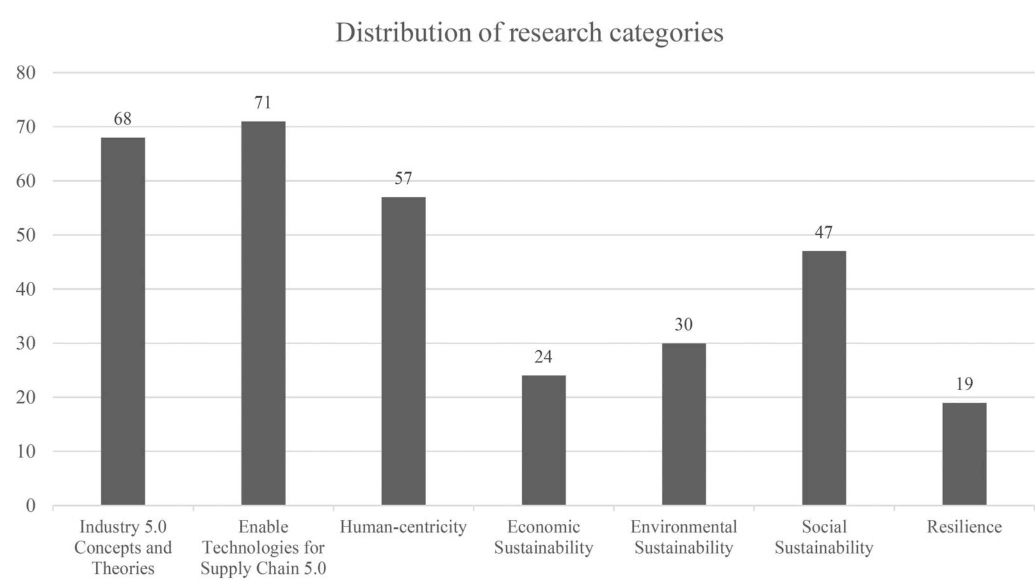

Figure 4. Distribution of research categories.

Table 3. Definitions of Industry 5.0 concepts in the cited literature.

Author(s)	Definition of Industry 5.0 concepts
Nahavandi (2019)	Industry 5.0 is a synergy between humans and autonomous machines. The autonomous workforce will be perceptive and informed about human intention and desire.
Demir, Döven, and Sezen (2019)	Two visions emerge for Industry 5.0. The first one is "human-robot co-working" where robots and humans will work together whenever and wherever possible. The second vision is a bioeconomy where smart use of biological resources for industrial purposes will help to achieve a balance between ecology, industry, and economy.
Maddikunta et al. (2022)	Industry 5.0 is conceptualised to leverage the unique creativity of human experts to collaborate with powerful, smart, and accurate machinery.
Özdemir and Hekim (2018)	Industry 5.0 is an evolutionary, incremental (but critically necessary) advancement that builds on the concept and practices of Industry 4.0. The primary objective of Industry 5.0 is to address the underappreciated asymmetries in Industry 4.0 including extreme integration without a "safe exit strategy" from networks, filter bubbles versus open systems, acceleration versus deceleration of innovations and technology versus societal outcomes.
Longo, Padovano, and Umbrello (2020)	Industry 5.0 is the era of a "Social Smart Factory", where every single cooperative building block of a Cyber-Physical Production Systems (CPPS) will be able to communicate with the human component through enterprise social networks.
Breque, De Nul, and Petridis (2021)	Industry 5.0 recognises the power of industry to achieve societal goals beyond jobs and growth, to become a resilient provider of prosperity by making production respect the boundaries of our planet and placing the well-being of the industry worker at the centre of the production process. Industry 5.0 complements the existing Industry 4.0 paradigm by having research and innovation drive the transition to a sustainable, human-centric and resilient European industry.

the age of digitisation, the primary objective of Industry 4.0 is to enhance productivity and efficiency through the adoption of smart factories (Osterrieder, Budde, and Friedli 2020). This approach incorporates cyber-physical systems that connect machines and processes across entire supply chain networks, facilitating the real-time exchange of information among organisations. As a result, Industry 4.0 transforms processes, leading to improved economic outcomes, including enhanced productivity, competition, and revenue growth (Bonilla et al. 2018; Liao et al. 2017). However, Yadav et al. (2020) expressed concerns about the limitations of Industry 4.0, such as its disregard for human factors and lack of sustainability awareness and proposed further Industry 4.0 development by emphasising social and environmental considerations, in addition to focusing on economic benefits and employing technological innovations to support employees.

As the introduction of human factors and the redefinition of their roles is a fundamental factor driving the transition from Industry 4.0 to Industry 5.0, several opportunities for improvement in Industry 4.0 have been identified (Birkel and Müller 2021). These include reducing environmental influences (Javaid et al. 2020), creating a circular economy (Nguyen et al. 2022; Xu et al. 2021), increasing supply chain flexibility, and mass personalisation (Akundi et al. 2022; Huang et al. 2020; Mourtzis, Angelopoulos, and Panopoulos 2022b). The identified drivers are those that motivate the industry to leverage Industry 5.0 in their supply chain systems and relate to human-centricity, sustainability and resilience (Breque, De Nul, and Petridis 2021). An overview of the drivers is presented and discussed in Table 4.

4.2.1. Human-centricity

The core of Industry 4.0 is digitalisation, which aims to develop advanced technologies to achieve higher productivity and to enhance the competitiveness in the global market. Interestingly, numerous studies have identified a common oversight within the concept of Industry 4.0, which is the neglect of the human factor (Robert, Giuliani, and Gurau 2022; Zarte, Pechmann, and Nunes 2020). It is crucial to note that the intended paradigm shift is not to supplant human abilities and skills, but rather to supplement and address human needs in an effort to enhance both human well-being and production performance (Kadir, Broberg, and Conceição 2019). Consequently, the implementation of advanced technologies should be premised on meeting human needs, as opposed to supplanting human involvement.

Xu et al. (2021) argue that Industry 4.0 is primarily driven by financial motivations, often overlooking the human element in process optimisation. Digitalizatiuon and the integration of artificial intelligence into organisational processes have the potential to benefit decision-makers by predicting and managing risks, as well as selecting appropriate strategies. However, Vogt (2021) warns that these changes could have negative consequences for employee interests, as the increasing use of machines to replace human labour may lead to job losses (Johri et al. 2021; Nahavandi 2019; Rajnai and Kocsis 2017).

Demir, Döven, and Sezen (2019) advocate this position, highlighting workers' reservations regarding the application of robots and artificial intelligence in the workplace (Doyle-Kent and Kopacek 2020). As a result, scholars emphasise the importance of examining the relationship between technology and humans in the new digital landscape. Longo, Padovano, and Umbrello (2020) call for a re-evaluation of the relationship between humans and technology, while Kaasinen et al. (2022) and Fatima et al. (2022) advocate for a collaborative approach that combines human intelligence with technological development. Studies by Gaiardelli et al. (2021) and Aslam et al. (2020) also underscore the value of integrated value chains that recognise the human element. Industry 4.0 drivers highlight the need for a nuanced approach to technology adoption that considers human-machine cooperation, socio-technical approach, and work-life balance, as the transition to Industry 5.0 builds upon these factors (Birkel and Müller 2021; Xu et al. 2021).

Table 4. Drivers of transition to Industry 5.0.

Core values	Drivers	Source(s)
Human- centricity	Complement Industry 4.0	Birkel and Müller (2021); Xu et al. (2021)
	Digital culture	Tran et al. (2022)
	Negative attitude to robots	Doyle-Kent and Kopacek (2020); Demir, Döven, and Sezen (2019)
	Relationship between humans and technologies	Longo, Padovano, and Umbrello (2020)
	Human-technologies collaboration	Kaasinen et al. (2022); Fatima et al. (2022)
	Integrated value chains	Gaiardelli et al. (2021); Aslam et al. (2020)
Sustainability	Profit increase	Fazal et al. (2022)
	Resource efficiency	Javaid and Haleem (2020);
	Energy saving	ElFar et al. (2021)
	Carbon neutrality	Fraga-Lamas, Lopes, and Fernández-Caramés (2021); Hu, Yang, and Yin (2022)
	Job loss	Rajnai and Kocsis (2017); Johri et al. (2021)
	Labour welfare	Akundi et al. (2022); Battini et al. (2022)
	Workforce training	Cillo et al. (2022); Maddikunta et al. (2022)
Resilience	Demand for mass personalisation	Akundi et al. (2022)
	Fulfil customer requirements	Javaid and Haleem (2020); Saptaningtyas and Rahayu (2020)
	Disruptions and catastrophic events	Bakon et al. (2022); Foresti et al. (2019)
	Supply chain flexibility	Huang et al. (2022); Mourtzis, Angelopoulos, and Panopoulos (2022b)
	Integrated performance management	Ghobakhloo et al. (2022); Yin and Yu (2022)

4.2.2. Sustainability

The extant literature underscores the potential unsustainability of Industry 4.0's profit-driven paradigm (Ghobakhloo et al. 2022). Sustainability is a balance between the economic, environmental, and social needs of the present and future generations. Fazal et al. (2022) draw attention to the scant attention paid to the environmental and social dimensions of sustainability in Industry 4.0's goals, which predominantly focus on enhancing economic performance, and therefore propose that Industry 5.0 should balance profits and broader sustainability considerations. Regarding environmental sustainability, Javaid and Haleem (2020) assert the importance of resource efficiency as a critical component of sustainable supply chain management in the future. Moreover, ElFar et al. (2021) argue that energy-saving strategies such as bioenergy derived from algae could serve as a viable carbon capture approach. Fraga-Lamas, Lopes, and Fernández-Caramés (2021), in addition to Hu, Yang, and Yin (2022), contend that achieving carbon neutrality plays a crucial role in enhancing environmental sustainability in the industry.

Concerning social sustainability, the literature calls attention to potential job losses, labour welfare, and the interaction between human labour and intelligent machines. Rajnai and Kocsis (2017) and Johri et al. (2021) caution that digital technological developments could have adverse effects on employment opportunities. Moreover, Akundi et al. (2022) and Battini et al. (2022) stress the significance of prioritising labour welfare, while Pokorni, Popescu, and Constantinescu (2022) underscore that this interaction could affect people's acceptance due to their perceived loss of control. Cillo et al. (2022) and Maddikunta et al. (2022) also acknowledge the critical importance of investing in workforce training to adapt to Industry 4.0's dynamic technological landscape. As such, the literature highlights the need for a more balanced approach in Industry 5.0 that prioritises ethical technology use and encompasses sustainability considerations that are environmental, social, and economic.

4.2.3. Resilience

The current state of supply chains under Industry 4.0 has raised concerns regarding their capacity to meet customer requirements and expectations adequately. Recent studies reveal an increasing demand for mass personalisation as a means of enabling customers to express themselves, which cannot be achieved through automated processes alone (Akundi et al. 2022; Javaid and Haleem 2020; Saptaningtyas and Rahayu 2020). Therefore, scholars have called for the integration of human critical thinking and creativity with high-precision automation to enhance manufacturing flexibility and cater to the needs of mass personalisation (Javaid and Haleem 2020; Johri et al. 2021; Y. Lu, Zhao, et al. 2022).

Rauch (2020) argues that in the current industrial environment, achieving customer satisfaction and engagement requires supply chains to have resilient decision-making processes and mass personalisation capabilities. Moreover, the COVID-19 pandemic (Sonjit, Dacre, and Baxter 2021) has highlighted the fragility of supply chains, underlining the importance of supply chain resilience and flexibility in managing disruptions and major unforeseen events (Bakon et al. 2022; Foresti et al. 2019; Sarfraz et al. 2021). Consequently, studies have investigated supply chain resilience as a critical component for managing critical crisis events (Huang et al. 2022; Mourtzis, Angelopoulos, and Panopoulos 2022b). Furthermore, integrated performance management has emerged as a crucial aspect of transforming traditional manufacturing industry supply chains (Ghobakhloo et al. 2022; Yin and Yu 2022). However, there is currently limited evidence on the effectiveness of incorporating mass personalisation in supply chains and the potential outcomes of such a transformation.

4.2.4. Human-centricity, sustainability, and resilience drivers

Essentially, the transition to Industry 5.0 calls for an approach that encompasses fostering human-centricity, sustainability, and resilience in supply chains to ensure success in an evolving industrial landscape. The literature highlights the importance of shifting from a purely profit-driven paradigm to one that accounts for the human element in process optimisation. A human-centric approach to technology adoption should focus on the collaboration between humans and machines, upskilling and reskilling the workforce, and prioritising labour welfare.

In terms of sustainability, Industry 5.0 needs to strike a balance between economic growth, environmental conservation, and social equity. Strategies such as resource efficiency, energy-saving initiatives, and carbon neutrality are essential for environmental sustainability while addressing job losses and ethical technology use promotes social sustainability. A holistic approach to sustainability in Industry 5.0 will ensure that economic, social, and environmental concerns are all addressed.

Resilience within supply chains is essential for meeting evolving customer requirements and expectations, particularly in an era increasingly defined by the demand for mass personalisation. Consequently, Industry 5.0 necessitates the prioritisation of agile decision-making processes, resilient supply chain management strategies, and comprehensive performance management systems. These are vital for adapting effectively to disruptions and significant unforeseen priorities. The adoption of these principles is instrumental in enabling Industry 5.0 to forge a manufacturing landscape that is not only more inclusive and sustainable but also resilient. This would ensure alignment with customer expectations and effectively addresses the complexities of modern organisational challenges.

4.3. Impact of Industry 5.0 on supply chains

In this discussion we draw an association between the impacts and the central values that underpin the transition to Industry 5.0, thereby following a similar set of subcategories introduced as drivers. This considers factors such as the design and management of supply chain systems, the adoption of technologies and tools, innovative business models, energy and material sources selection, and costs and risks (Al-Mhdawi et al. 2024). Therefore, the overarching construct is to review the performance of supply chains in the manufacturing sector and examine sustainable and flexible supply chain systems in line with the principles of Industry 5.0.

4.3.1. Human-machine synergy in supply chains

The concept of human-centricity in Industry 5.0 signifies a paradigm shift towards prioritising the well-being of individuals within the production process. In contrast to Industry 4.0, which emphasises digitisation and automation technologies over human involvement, Industry 5.0 seeks to integrate humans and machines in a collaborative approach to manufacturing (Carayannis and Morawska-Jancelewicz 2022; Kaasinen et al. 2022; Wang et al. 2022). At the heart of Industry 5.0 lies the synergy between humans and machines (Ghobakhloo 2020; Longo, Padovano, and Umbrello 2020), and leveraging technologies and tools to align with societal needs and support human collaboration (Breque, De Nul, and Petridis 2021). In this context, Industry 5.0 represents a novel and innovative strategy within the manufacturing sector. It seeks to optimise human-machine interactions and create a collaborative working framework that emphasises inclusivity rather than replacing human labour with robots. Such an approach considers social and technical elements as interdependent factors rather than separate components (Bednar and Welch 2020; Wang et al. 2022).

At the supply chain management level, Industry 5.0 affords approaches to prioritise human needs and promote inclusive practices. Demir, Döven, and Sezen (2019) suggest that adopting Industry 5.0 will enable individuals to co-work with machines in the manufacturing sector, thereby enhancing efficiency and productivity. Moreover, the collaboration of robots and human intelligence has the potential to automate the manufacturing process while ensuring precision and speed with creative control, which is a fundamental requirement of personalisation (Zheng et al. 2018). This suggests that Industry 5.0 has the potential to improve the efficiency of supply chains in the manufacturing sector by optimising human-machine interactions and promoting a collaborative framework.

4.3.2. Sustainability in Industry 5.0 supply chains

Sustainability is a complex construct related to different aspects such as business, industry, urban development, and agriculture and encompasses over a hundred keywords in research (Jose and Ramakrishna 2021; Ruggerio 2021). Despite its prevalent use and increasing importance in research and practice, there is ongoing debate regarding the definition of sustainability in the extant literature (Souza et al. 2015). In the context of sustainable supply chains, its conceptualisation has typically been predicated on Elkington's (1997) triple bottom-line framework, which posits that sustainability can be understood within economic, environmental, and social dimensions.

From an economic dimension, Industry 5.0 is characterised by a marked emphasis on integrating social and ecological sustainability with economic development in supply chain management (Aslam et al. 2020; Xu et al. 2021). Appropriate system design and implementation to achieve enhanced efficiency, quality of service, and environmental and social responsibility are crucial components of successful supply chain management under this framework. Unlike in previous frameworks, efficiency and effectiveness enhancement of the supply chain no longer remain the sole priorities under Industry 5.0. Therefore, Industry 5.0 has a notable focus on sustainability, requiring companies to balance economic sustainability with environmental and social sustainability.

Fatima et al. (2022) propose that employing Industry 5.0 enabling technologies may facilitate efforts towards environmental and social sustainability, yet the significant technological development investment required creates tension across the economic dimension. The investment required to transition to Supply Chain 5.0 remains one of the major concerns of stakeholders (Sharma et al. 2022; Yuan et al. 2022). Furthermore, these tensions are further mediated by consumer behaviour and governmental policies and decisions (ElFar et al. 2021). Therefore, Industry 5.0 affords the opportunity to reduce social-ecological impacts while underpinning financial benefits.

When considering the environmental dimension of sustainability within the manufacturing sector, Industry 5.0 implies having multiple supply chain management goals, including waste prevention and recycling, renewable energy sources, energy-efficient data storage, transmission, analysis and intelligent autonomous sensors (Akundi et al. 2022). According to Nahavandi (2019), several technologies related to Industry 4.0 have the potential to enhance sustainable development from an environmental perspective, although the environmental protection aspect may not be a core focus of this concept or employed by specific technologies. Consequently, there is a requirement to focus on the technological prospects for Industry 5.0 in light of environmental challenges and therefore draw on relevant extant research. As an illustration, Gorodetsky, Laryukhin, and Skobelev (2019) previously advocated for the adoption of cloud resources and services for smart sensor networks, which could mitigate resource usage and waste, thus reducing environmental impact. Additionally, smart additive manufacturing technologies (Mehrpouya et al. 2019) have also been proposed as a solution to reduce energy, material, and resource consumption in supply chain operations, with the goal of achieving a pollution-free supply chain (Javaid et al. 2021). However, studies have revealed that there appears to be a notable exigency for the availability of affordable, clean and sustainable energy resources in order to effectively decrease environmental impacts in supply chain operations (ElFar et al. 2021). To this end, prior research has examined the application of alternative fuels in Industry 5.0, for example, bioenergy (ElFar et al. 2021; Maddikunta et al. 2022; Sindhwani et al. 2022), hydrogen (Chai et al. 2021), nuclear energy (Carayannis, Draper, and Bhaneja 2021), and through the application of life cycle assessment, this can be used to determine the environmental performance of supply chains, particularly for energy or material sources that result from both renewable and non-renewable pathways (Huang et al. 2022; Xu et al. 2021). As such, the integration of renewable energy and materials is an instrumental component in facilitating the attainment of Industry 5.0 environmental sustainability in the manufacturing sector (Abubakr et al. 2020).

The social dimension of sustainability addresses human well-being (Mohamed and Paleologos 2021). Within the context of supply chains, the assessment of social sustainability involves the evaluation of various indicators pertinent to product and process elements, such as labour health, benefits, safety, hygiene, education, wages, housing, and gender equality (Battini et al. 2022; Mani et al. 2016). Social sustainability also includes two critical components: the "needs" themselves and the constraints posed by the available technologies, management strategies, and organisational priorities to address these needs (Santiteerakul et al. 2015). Furthermore, innovations such as FinTech can support economic empowerment for informal businesses at the bottom of the economic pyramid, contributing to social sustainability (Senyo et al. 2023). Y. Lu, Zhao, et al. (2022) established a model focused on human needs and categorised them into five layers, namely: "Safety", "Health", "Belonging", "Esteem", and "Self-actualization". Their findings underscore that the Industry 4.0-centric approach has only been able to address simple human needs confined to "safety" and "health". Thus, there remains a lacuna for further inquiry to determine approaches to improve the well-being of employees within an Industry 5.0 paradigm. For example, Ávila-Gutiérrez, Aguayo-González, and Lama-Ruiz (2021) suggest a framework for enhancing the inclusion of employees within Industry 5.0, as their analysis indicates that key enabling technologies can monitor and regulate the entire manufacturing process. New job roles, including digital twin engineers, robot teaming coordinators, smart factory managers, and smart schedulers, will likely form part of the landscape (Chowdhury et al. 2022; Golovianko et al. 2023; Nahavandi 2019). In this vein, robots will no longer be viewed solely as programmable machines but rather as partners in executing routine tasks in collaboration with humans (Johri et al. 2021). In essence, the objective of Industry 5.0 in relation to the social dimension of sustainability is to enhance the socially responsible nature of the manufacturing sector by addressing the social impact and performance of all actors in the supply chain and by prioritising the welfare of human beings in supply chain operations (Ghobakhloo et al. 2022; Ivanov 2022).

4.3.3. Resilience enhancement in Industry 5.0 supply chains

The notion of supply chain resilience underscores its capacity to react and recover effectively from unexpected disruptions (Tukamuhabwa, Stevenson, and Busby 2017; Wong et al. 2020). This construct encompasses two key constituents: vulnerabilities and capabilities. Vulnerabilities denote inherent factors that amplify the susceptibility of organisations to disruptions that are unpredictable in nature, while capabilities denote the features that allow organisations to anticipate, mitigate, and recover from such disruptions (Pettit, Croxton, and Fiksel 2013). Thus, supply chain resilience highlights the planning, flexibility, responsiveness, and recuperative capabilities of organisations in the face of unforeseen events and critical incidents, in order to enhance organisational performance and vest a competitive advantage (Chowdhury and Quaddus 2017; Yu et al. 2019).

The literature reveals that the emergence of Industry 5.0 carries the potential to enhance supply chain resilience and performance. For instance, Ghobakhloo et al. (2022) posit that virtual models of supply chain processes, created by employing simulation and big data analytics (Brookes et al. 2020; Dacre, Kockum, and Senyo 2021), offer the means to identify vulnerabilities, risks, and potential disruptions. This ultimately facilitates enhanced flexibility and responsiveness. Therefore, the integration of Industry 5.0 affords the creation of agile (Baxter et al. 2023), efficient, and innovative value chains that are capable of anticipating and adapting to the rapid changes in the business landscape resulting from unpredictable events (Coito et al. 2022; Grabowska, Saniuk, and Gajdzik 2022; Romero and Stahre 2021; Tran et al. 2022). This collaborative approach facilitates real-time access to data and insights, ultimately contributing to the overall resilience of the supply chain (Feng, Lai, and Zhu 2022; Golovianko et al. 2023). Furthermore, the application of automation and artificial intelligence technologies holds significant potential for enhancing resilience by fostering a collaborative and interconnected ecosystem with all supply chain actors integrated and sharing information (Hsu et al. 2022; Ivanov 2022; Romero and Stahre 2021; Taj and Zaman 2022).

4.3.4. Transformative effects of Industry 5.0 on supply chain dynamics

Our findings indicate that the arrival of Industry 5.0 may well be driving profound alterations in the way supply chains operate, notable in three key domains - namely, human-machine collaboration, sustainability integration, and resilience enhancement. This appears to underscore an approach with a strong focus on people, which highlights the necessity for the establishment of collaborative frameworks that enable human-machine interactions to be optimised, thus leading to greater effectiveness and productivity across the manufacturing sector. Correspondingly, it offers a strategy that embraces sustainability in a comprehensive manner, one that takes on board economic, environmental, and social dimensions as a collective whole. As such, this major shift of paradigm imparts a challenge to organisations, urging them to incorporate sustainable practices, assign resources to solutions that are environmentally friendly and make use of renewable energy, as well as pursue social responsibility throughout their supply chains. Ultimately, the technologies brought about by Industry 5.0 reinforce supply chain resilience by providing real-time data and creating room for more dextrous, cutting-edge value chains better equipped to anticipate and adapt to unforeseen events.

4.4. Challenges to transition to Supply Chain 5.0

The fourth theme identified through thematic analysis relates to the challenges that may hinder the adoption and implementation of Industry 5.0 within supply chains in the manufacturing sector. In this study, a challenge is considered a complicating factor that can potentially be resolved or mitigated to facilitate the integration of Industry 5.0 into supply chains, as defined by Kembro, Näslund, and Olhager (2017). As a result, a total of 23 challenges were identified from the literature through thematic analysis and organised into five interconnected categories: Economic challenges, Managerial and operational challenges, Socio-cultural challenges, Process challenges, and Technological challenges (Appendix B).

4.4.1. Economic challenges

Economic challenges refer to factors that may affect economic growth or exert pressure on economic development (Saniuk, Grabowska, and Straka 2022) in dint of the need to balance economic growth with the need for environmental protection and social development. This also necessitates conducting economic efficiency reviews and managing substantial financial investments whilst addressing uncertain outcomes. It also entails addressing additional facility and cost requirements (Appendix B). For instance, the integration of emergent technologies such as digital twins, IoT, and robotic systems, rests on substantial capital investments to implement Industry 5.0 in supply chains (Cimini et al. 2022; Nimfa et al. 2021). Although the potential benefits of Industry 5.0 have been conceptualised, some tangible outcomes likely remain unclear until necessary investments are committed by organisations (Özdemir and Hekim 2018; Yuan et al. 2022; Zengin et al. 2021). Furthermore, the complexity of new processes generally necessitates cost strategies that differ from traditional approaches (Bednar and Welch 2020; Nguyen et al. 2022). It is also valuable to note that significant costs may arise from training employees since the adoption of Industry 5.0 is reliant on the extensive implementation of technical and digital competencies, such as collaborating with "cobots" and smart machines, leading to increased financial commitment (Fraga-Lamas, Lopes, and Fernández-Caramés 2021; Maddikunta et al. 2022). Additionally, some cases may require continuous training coupled with equipment upgrades to ensure a skilled workforce can adapt to changing priorities (Fazal et al. 2022). As a result, decision-makers within organisations are likely to implement advanced workforce strategies (Doyle-Kent and Kopacek 2020; Saptaningtyas and Rahayu 2020).

4.4.2. Managerial and operational challenges

The adoption of Industry 5.0 in supply chains is notably influenced by managerial and operational challenges (Appendix B). The literature suggests that a paucity of knowledge pertaining to Industry 5.0 and its potential benefits may serve as a barrier to its adoption in supply chains. For example, managers may lack a comprehensive understanding of how Industry 5.0 could help them achieve their sustainability objectives or enhance their operational procedures (Humayun 2021; Sharma et al. 2022). This uncertainty can foster scepticism and resistance towards the adoption of Industry 5.0.

The unavailability of policy actions and support also suggests that inadequate incentives from governmental bodies and industry associations can constrain the realisation of Industry 5.0 in supply chains. Without clear regulations and guidelines, organisations may be hesitant to invest in new technologies and sustainable practices. To this end, the discourse concerning the impact of Industry 5.0 on policy development, regulatory frameworks, and legal mandates has been examined by Sharma et al. (2022), Y. Lu, Zhao, et al. (2022) and Nahavandi (2019). These studies identified several legal concerns, including the absence of legislative provisions that define the types of machines acceptable in work environments, inadequate methodologies for assessing the cognitive load experienced by human operators collaborating with robotics, and insufficient privacy and data protection regulations for users.

Ineffective employee training for new technologies and sustainability enhances a distinct set of skills and knowledge (Dacre, Senyo, and Reynolds 2019), which otherwise may not be readily available within organisations (Mourtzis, Angelopoulos, and Panopoulos 2022a). Consequently, training employees in new technologies and sustainable practices is instrumental (Dong, Dacre, and Bailey 2021). However, training programs may be expensive, time-consuming, and counterproductive (Gkogkidis and Dacre 2023) if not implemented effectively, and creating collaborative working environments as part of this process, can be challenging, especially when considering the varying interests and priorities of different supply chain stakeholders (Doyle-Kent and Kopacek 2020). Furthermore, collaboration among supply chain members is critical since ineffective collaboration can lead to communication breakdown, misaligned goals and objectives, and a lack of trust among members (Fornasiero and Zangiacomi 2021). The analysis also suggests that traditional employment laws may inadequately address the challenges posed by Industry 5.0 (Coronado et al. 2022), particularly with respect to employment conditions, employment relationships, and intellectual property rights. Without clear guidelines, ambiguity and uncertainty can arise, hampering its adoption in supply chains.

4.4.3. Socio-cultural challenges

The initial cluster of socio-cultural challenges pertains to ethical considerations, which are instrumental in ensuring that the implementation of increasingly popular technologies such as artificial intelligence and robotics does not result in adverse societal effects. For instance, Fraga-Lamas, Lopes, and Fernández-Caramés (2021) highlight that the adoption of these technologies carries potential ethical implications. Similarly, Coronado et al. (2022) accentuate that ethical concerns, such as misgivings over displacement, miscommunication, and resistance to emergent technologies, can significantly impact attitudes towards working with robots. In order to address these ethical quandaries effectively, research suggests identifying and addressing concerns during the initial development and implementation stages (Fornasiero and Zangiacomi 2021; Johri et al. 2021; Wang et al. 2019).

Another socio-cultural challenge emerging from Industry 5.0 encompasses the establishment of effective strategies to assess social welfare outcomes. Pokorni, Popescu, and Constantinescu (2022) posited an assistance system to augment social welfare while acknowledging that determining the appropriate method to appraise outcomes during the working process can be overly challenging. Longo, Padovano, and Umbrello (2020) concurred that designing personalised systems tailored to divergent technologies and individual preferences is instrumental in evaluating social welfare. Furthermore, comprehending both organisational objectives and employee priorities is instrumental in achieving a balanced evaluation of socio-cultural challenges.

4.4.4. Process challenges

The demand for environmental sustainability from both customers and suppliers has a significant impact on decision-makers in dint that companies can either plan for the adoption of innovation in their supply chains or respond to customer and supplier requirements in this regard (Krajčík 2021). Driven by the support of customers and sustainability criteria from suppliers, organisations therefore may be compelled to reduce the harmful effects of their operations on the environment, such as through the use of efficient energy, resource management, and reducing their carbon footprints (Saptaningtyas and Rahayu 2020). As such, enhancing process efficiency may not only contribute to economic performance but also pertain to the prudent use of resources (Abubakr et al. 2020; Huang et al. 2022).

Another challenge is the implementation of personalisation in both products and processes. Despite advances in technology, it remains unclear how enabling technologies can effectively support the design of personalised products and services on a large scale (Javaid and Haleem 2020). Furthermore, the high costs associated with optimising energy consumption and the difficulties in predicting the environmental impact of such initiatives will have an impact on the adoption of green business strategies (Fazal et al. 2022; Fraga-Lamas, Lopes, and Fernández-Caramés 2021). In essence, process challenges include customer-oriented approaches, resource planning and control, materials processing, energy re-use and reduction of energy consumption, realising personalisation in products and processes, addressing the lack of green initiatives, and overcoming customers' unwillingness (Appendix B). Furthermore, organisations are likely to rely on effective monitoring and evaluation mechanisms to measure the success in their supply chains to identify areas for improvement (Chowdhury et al. 2022; Khan and Abonyi 2022).

4.4.5. Technological challenges

The implementation of Industry 5.0 in sustainable supply chains poses significant technological challenges, which are integral to its adoption. These challenges can be categorised into three domains: "Lack of technological standards and framework", "Technology acceptance and trust", and "Security and privacy issues" (Appendix B). Although Industry 5.0 draws on the technologies of its predecessor, Industry 4.0, it adheres to a more rigorous set of standards that could impede technological advancement (Duggal et al. 2022). For instance, Nguyen et al. (2022) examined the adoption of digital twins and physical internet technologies in supply chain management. We uncovered that incorporating digital twins in manufacturing and logistics systems can facilitate the reduction of environmental impacts by enhancing energy efficiency. However, the adoption of digital twin-enabled supply chains prompted a multitude of challenges, including emission evaluation and social welfare.

Security and privacy issues represent another challenge when implementing Industry 5.0 technologies. Security concerns may emerge as a result of the handling of diverse data and the use of cloud services by supply chain actors (Hayashi et al. 2017; Peraković et al. 2020). Moreover, the preservation of privacy in data accumulation poses ethical issues that must be considered when providing customised goods or services to customers (Choi et al. 2022; Jain et al. 2022; Singh, Lee, and Park 2022). These obstacles, compared to previous technological developments, are difficult to control for manufacturers and suppliers (Bednar and Welch 2020; Fatima et al. 2022).

4.4.6. Navigating the obstacles in the transition to Supply Chain 5.0

The transition to Supply Chain 5.0, underpinned by Industry 5.0 technologies and principles, presents a complex matrix of challenges that must be addressed in order to achieve success. This study has identified a multitude of challenges spanning economic, managerial, operational, socio-cultural, process, and technological areas. For instance, to overcome the economic hurdles, careful consideration must be given to the financial viability of investment, balanced against the potential long-term benefits. The managerial and operational obstacles can be tackled, at least in part, through collaboration between stakeholders, bridging knowledge gaps, and supportive policies and regulatory frameworks. Addressing socio-cultural challenges must factor in concerns around ethics, social welfare, and inclusivity as new technologies are developed and implemented. Process challenges can be overcome through the adoption of customer-centric approaches, efficient resource management, and green initiatives, which focus on reducing environmental impact. Lastly, overcoming technological challenges necessitates the establishment of industry standards, frameworks, and the creation of trust in new technologies. Data security and privacy must be also addressed when developing new technological approaches. In order to conceptually illustrate these elements, we present a framework for the application of Supply Chain 5.0 principles within the manufacturing sector in the following section.

4.5. *Framework* for supply chain 5.0 integration

Our study presents an examination of the existing literature with regard to Industry 5.0, which encompasses four key perspectives: (i) defining the concept of Industry 5.0, (ii) examining the drivers that propel the transition to Supply Chain 5.0, (iii) scrutinising the impacts of Industry 5.0, and (iv) evaluating the challenges that arise from adopting Supply Chain 5.0. Despite this thorough investigation, an identified research gap pertains to the absence of a model or framework capable of revealing the intricate relationships between Industry 5.0 and supply chain management in the manufacturing sector. Hence, we propose a conceptual Supply Chain 5.0 framework (Figure 5) underpinned by the 23 challenges identified in our study, which are categorised into five interrelated groups. This is particularly salient considering that current literature offers varied discussions on the impact of Industry 5.0 on supply chain management, however these largely tend to focus on single specific elements. Therefore, these offer limited insights into examining the influence of Industry 5.0 on supply chain management from a holistic perspective in the manufacturing sector.

A comprehensive understanding of Industry 5.0, which encapsulates the focus on collaborative interaction between humans and machines, sustainability, and the integration of advanced technologies, sets the foundation. This provides the foundation for exploring the drivers that prompt the implementation of Industry 5.0 in manufacturing supply chains. These include the adoption of advanced technological adoption, swift responses to market disruptions, changing customer preferences, and the imperative for sustainable practices. As these driving factors accelerate the transition to Industry 5.0, their significant impact on manufacturing supply chains becomes increasingly relevant. Industry 5.0's transformative impact is evidenced by enhanced operational flexibility, sustainable methodologies, capabilities for mass-personalisation in production, and the optimisation of supply chain processes. However, managing this transition poses its own set of challenges, including the requirement for a skilled workforce, significant investments in technology, and the complexity inherent in adopting innovative practices. Thus, an in-depth understanding of Industry 5.0 is crucial to mapping the journey from its driving forces to its effects on manufacturing supply chains, and to comprehending the intricate dynamics of this evolving industrial environment.

The framework bridges the gap between the conceptual theory of Industry 5.0 and its practical application in supply chain management. For instance, the value shift of Industry 5.0 emphasises the importance of triangulating human-centricity, sustainability and resilience. In the transition to Supply Chain 5.0, ignoring balancing factors or the interrelationship between factors might lead to unsuitable business strategies and the failure of the transition. Based on our study, we therefore suggest that companies adopting Industry 5.0 are more likely to succeed with the development of sustainable, digital, and resilient supply chains, leading to potential competitive advantages and improved overall performance. However, it must be emphasised that such a shift requires changes in how supply chains are developed and managed. The complexity of the transition process, in turn, calls for the cautious balancing of multiple internal and external factors and drivers as highlighted in our framework.

5. Future research perspectives

The emergence of Industry 5.0 will bring about a significant shift in values, which will in turn lead to new policy requirements, evolving customer expectations, and emerging competitive dynamics. This transition is poised to catalyse significant organisational restructuring, encompassing asset reallocation, the evolution of job roles - including both the obsolescence of certain positions and the creation of new ones - a pivot towards a circular economy, and the formulation of innovative business models. In this new landscape, the assessment of competitiveness, efficacy, and performance of supply chains demands reconsideration within the context of the Industry 5.0 value framework. As such this presents fertile ground for future research. This SLR provides a foundation for exploring multiple research trajectories that can further expose and expand upon the implications and practical applications of Industry 5.0.

5.1. Decision-making model for supporting stakeholders in adopting Industry 5.0

The development and application of a decision-making model is crucial for discerning the optimal choice amidst

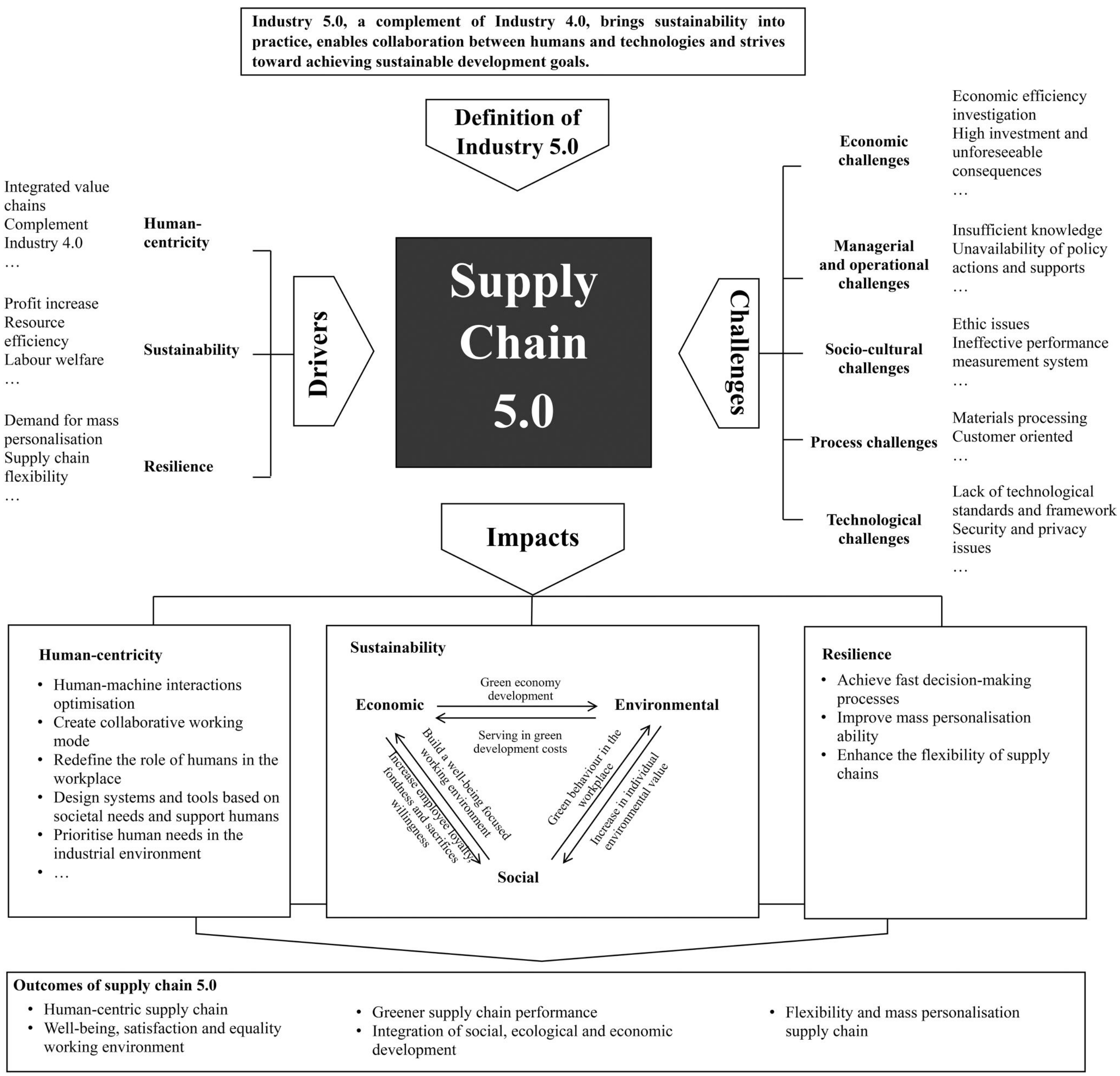

Figure 5. Supply Chain 5.0 framework.

multiple, often conflicting, criteria (Köksalan, Wallenius, and Zionts 2011). These models have found expansive application within the manufacturing sector, especially for the analysis of business strategies (Bai, Satir, and Sarkis 2019; Dockree, Wang, and Frei 2021; Mathiyazhagan et al. 2022), and the importance of decision-making has been notably recognised in Industry 4.0 (Chang, Chang, and Lu 2021; Gupta, Kumar, and Wasan 2021; Hsu et al. 2022; Lo et al. 2020). In the context of Industry 5.0, the evaluation of Supply Chain 5.0 solutions through a decision-making framework is crucial for instigating impactful benefits, allowing for the alignment of sustainability dimensions and the promotion of sustainable development goals.

The emergence of Industry 5.0 has seen the introduction of data-driven decision-making frameworks, which have shown promise in enhancing supply chain performance (van Kollenburg et al. 2022). While some current frameworks in Industry 5.0 supply chain management have incorporated case studies for application validation, the literature indicates a gap in the use of decision-making techniques for increasing relevance and applicability (Sharma et al. 2022). Future research could involve expert interviews and empirical analyses for further validation. However, challenges in developing decision-making tools for Industry 5.0 include defining appropriate criteria and addressing the relative paucity of research in this area, especially concerning SMEs.

5.2. The transition of Supply Chain 5.0 in SMEs

SMEs constitute a crucial pillar in numerous global economies, playing a pivotal role both within regional and international supply chains of larger organisations. Their contributions extend beyond employment generation and entrepreneurship to encompass broader industrial development (Pereira et al. 2022; Tarutė and Gatautis 2014). Despite this, there is a noticeable lag in the proactive adoption of advanced supply chain management practices among many SMEs (Kot, Haque, and Baloch 2020; Partanen et al. 2020; Singh and Kumar 2020).

SMEs often function as suppliers within manufacturing supply chains to larger entities. These larger buying firms frequently impose their sustainability standards upon SMEs to enhance sustainability in their upstream supply chains (Errico, De Noni, and Teodori 2022). Consequently, SMEs face pressures not only from downstream businesses but also from broader societal demands for more sustainable supply chain practices. However, this transition towards Supply Chain 5.0 presents more substantial challenges. For instance, literature highlights several distinct challenges for SMEs, such as the incomplete transition to Industry 4.0 (Chege and Wang 2020; Krajčík 2021; Kurniawan et al. 2022), financial constraints in adopting new technologies (Sahi, Gupta, and Cheng 2020), and reluctance towards embracing Industry 5.0 (Chen 2020). Therefore, further research is mandated to address these challenges, particularly within the context of Industry 5.0, which introduces new requirements and higher standards.

5.3. Policy impacts on Industry 5.0

An additional area of limited focus in existing literature is the impact of governmental and public perspectives on the evolution of Industry 5.0. A review of the literature reveals that the absence of targeted policies and regulatory frameworks is a significant barrier deterring decision-makers from fully embracing sustainable supply chain practices under the Industry 5.0 paradigm (Cillo et al. 2022; Pangarso et al. 2022). As such, effectively navigating this landscape requires a strategic balance of sustainability considerations with operational performance. For instance, in this context the role of policy interventions and governmental regulations becomes critical. Such measures can act as potent catalysts, providing direct incentives that encourage the rapid adoption of sustainable practices and the principles of Industry 5.0.

There is also an inherent role for policymakers in initiating campaigns to increase the public's awareness of Industry 5.0, and endowments to encourage industry participation (Sharma et al. 2022). The pursuit of equilibrium in these domains, particularly in promoting human well-being, is contingent upon the development of innovative business models and supportive policy frameworks. For instance, contemporary supply chain models, such as closed-loop supply chains (Govindan and Soleimani 2017; Long et al. 2022; Siegel et al. 2022), green supply chains (Feng, Lai, and Zhu 2022; Xu et al. 2019) and circular supply chains (Lahane, Kant, and Shankar 2020; H. Lu, Zhao, et al. 2022; Nasir et al. 2017) afford solutions to sustainability challenges. Effective policy engagement, informed by evidence, could assist policymakers in incentivizing the adoption of Industry 5.0, mitigating the risks of committing to inappropriate technologies and strategies.

6. Conclusion

This study presents a systematic review of the transformative effects of Industry 5.0 on manufacturing supply chains, directly addressing the central research question *How does the implementation of Industry 5.0 transform manufacturing supply chains*? In total, 103 academic articles from several databases were selected following the PRISMA framework. First, we provided descriptive statistics of the state-of-the-art and identified the research trends in the research field. Second, a Supply Chain 5.0 framework was established based on the findings of the content review under four themes to address the research question and objectives, (i) definition of Industry 5.0, (ii) drivers to transition to Industry 5.0, (iii) impacts of Industry 5.0 to supply chains in the manufacturing industry, and (iv) challenges of Industry 5.0 adoption. Furthermore, a total of 23 challenges were identified from the literature through thematic analysis and organised into five interconnected categories, namely economic challenges, managerial and organisational challenges, socio-cultural challenges, process challenges and technological challenges. This study offers a thorough exploration of Industry 5.0, delineating its key driving factors and tracing their influences on manufacturing supply chains, along with the challenges that emerge in this context. It emphasises the complex nature of Industry 5.0's evolving industrial landscape, underscoring the breadth of its impact.

The insights derived from our findings hold numerous implications for research. Firstly, our conceptual framework provides a holistic perspective on the interrelationships between Industry 5.0 and supply chain management, thereby enabling a greater understanding of the emerging paradigm. Researchers can employ this framework to guide future empirical studies and test the relationships between the identified drivers, impacts, challenges, and outcomes in various manufacturing contexts. Secondly, our research has highlighted the importance of human-centricity, sustainability, and resilience as core values in Industry 5.0 supply chains. Researchers can further explore the implications of these values on supply chain design and performance, and identify practices for integrating them into supply chains. Lastly, future investigations may also include examining the role of emerging technologies in enabling Supply Chain 5.0, developing performance metrics for Industry 5.0 supply chains, and exploring the impact of Industry 5.0 on policy development and regulatory frameworks.

The findings also yield significant practical implications for industry stakeholders, such as manufacturers, suppliers, and policymakers. The proposed conceptual framework can serve as a reference point for practitioners to assess their current supply chain practices and identify areas for improvement in line with Industry 5.0 principles. The identified drivers, impacts, and challenges can help practitioners make informed decisions when adopting Industry 5.0 technologies and embedding them into their supply chains. The proposed framework provides practitioners with a practical structure for designing and managing supply chains in Industry 5.0, and can offer valuable insights to decision-makers through the lenses of human-centricity, sustainability, and resilience.

It also supports policymakers in developing evidence-based policies and regulatory frameworks that encourage the adoption of Industry 5.0 in the manufacturing sector.

As such, the paper contributes to the expanding literature on Industry 5.0 and its potential impact on supply chain management in the manufacturing sector. However, this research has some key limitations. Firstly, the study is based on a systematic literature review, and despite adopting the PRISMA approach, there may still be potential biases in the selection and analysis of the included articles. Additionally, Industry 5.0 is at a nascent stage and still evolving, and the empirical data in Supply Chain 5.0 is still sparse. Therefore, the proposed framework is conceptual in nature and requires empirical validation in different manufacturing contexts. This study focuses primarily on the manufacturing sector, and the findings may not be generalisable to other sectors. Further, the research has not developed or validated the existing theories in the domain of supply chain design and management since our main focus is conceptualisation. However, future studies can explore and establish connections between the relationships uncovered in this research and existing theories, thereby enhancing understanding through empirical investigation.

In summary, the integration of Industry 5.0 principles into supply chains represents a significant shift in the manufacturing sector, with the potential to enhance sustainability, social well-being, and economic growth. A comprehensive understanding of the drivers, impacts, challenges, and outcomes of Supply Chain 5.0 is essential, and researchers, practitioners, and policymakers should aim to work in collaboration to shape the future of manufacturing and contribute to a more sustainable, human-centric, and resilient global economy.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Appendices

Appendix A. Details of the reviewed articles

No.	Authors	Industry 5.0 Concepts and Theories	Drivers of Implementing Supply Chain 5.0	Impacts and Challenges of Implementing Supply Chain 5.0					Source Title	Research Type
					Sustainability					
				Human-centricity	Economic	Environmental	Social	Resilience		
1	Yin and Yu (2022)		√		√	√			Journal of Cleaner Production	Journal
2	Leng, Sha, Wang, et al. (2022)		√					√	International Journal of Production Research	Journal
3	Pokorni, Popescu, and Constantinescu (2022)		√	√	√		√		Applied Sciences	Journal
4	Mladineo et al. (2021)		√	√			√		10th International Conference on Mechanical Technologies and Structural Materials	Conference proceeding
5	Fatima et al. (2022)	√	√	√	√		√		Applied Sciences	Journal
6	Kaasinen et al. (2022)	√		√			√	√	Sustainability	Journal
7	Romero and Stahre (2021)			√				√	Procedia CIRP	Conference proceeding
8	Saptaningtyas and Rahayu (2020)	√	√						Proceedings of the 5th NA International Conference on Industrial Engineering and Operations Management	Conference proceeding
9	Sindhwani et al. (2022)	√	√	√				√	Technology in Society	Journal
10	Javaid and Haleem (2020)	√	√	√	√	√	√		Journal of Industrial Integration and Management	Journal
11	Mukherjee, Raj, and Aggarwal (2023)	√	√	√	√	√	√		International Journal of Production Economics	Journal
12	Humayun (2021)	√	√	√			√		International Journal of Advanced Computer Science and Applications(IJACSA)	Journal
13	Xu et al. (2021)	√	√	√	√	√	√	√	Journal of Manufacturing Systems	Journal
14	Grabowska, Saniuk, and Gajdzik (2022)	√		√		√	√		Scientometrics	Journal
15	Javaid et al. (2020)	√	√						Journal of Industrial Integration and Management	Journal
16	Nahavandi (2019)	√	√	√			√		Sustainability	Journal
17	Nguyen et al. (2022)	√	√		√	√			International Journal of Production Economics	Journal
18	Sharma et al. (2022)	√			√	√	√		IEEE Transactions on Engineering Management	Journal
19	Johri et al. (2021)	√	√	√			√		2021 10th International Conference on System Modelling & Advancement in Research Trends (SMART)	Conference proceeding
20	Majerník et al. (2022)	√							Advances in Science and Technology Research Journal	Journal
21	Patera et al. (2021)	√	√						Sensors	Journal
22	Duggal et al. (2022)	√	√	√	√	√	√		IET Communications	Journal
23	Doyle-Kent and Kopacek (2020)	√	√	√					IFAC-PapersOnLine	Journal

(*continued*)

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No.	Authors	Industry 5.0 Concepts and Theories	Drivers of Implementing Supply Chain 5.0	Impacts and Challenges of Implementing Supply Chain 5.0					Source Title	Research Type
					Sustainability					
				Human-centricity	Economic	Environmental	Social	Resilience		
24	Nourmohammadi, Fathi, and Ng (2022)	√	√	√			√		Computers and Operations Research	Journal
25	Rega et al. (2021)		√	√					Applied Sciences	Journal
26	Welfare et al. (2019)		√				√		HRI '19: 14th ACM/IEEE International Conference on Human-Robot Interaction	Conference proceeding
27	Singh, Lee, and Park (2022)	√	√						Computers & Industrial Engineering	Journal
28	Jain et al. (2022)		√						IEEE Transactions on Industrial Informatics	Journal
29	Fraga-Lamas, Lopes, and Fernández-Caramés (2021)	√	√			√			Sensors	Journal
30	Gaiardelli et al. (2021)		√	√					2021 Forum on specification & Design Languages (FDL)	Conference proceeding
31	Turner and Garn (2022)		√	√			√		Journal of Industrial Information Integration	Journal
32	Lu, Zhao, et al. (2022)			√			√		Journal of Manufacturing Systems	Journal
33	Bednar and Welch (2020)			√			√		Information Systems Frontiers	Journal
34	Longo, Padovano, and Umbrello (2020)	√	√	√					Applied Sciences	Journal
35	Fazal et al. (2022)	√	√	√	√	√	√		Advancement in Materials, Manufacturing and Energy Engineering	Conference proceeding
36	Bhargava et al. (2022)		√						International Journal of System Assurance Engineering and Management	Journal
37	Maddikunta et al. (2022)	√	√		√	√	√		Journal of Industrial Information Integration	Journal
38	Ali Shah et al. (2020)	√			√	√	√		Tehnički glasnik	Journal
39	Fornasiero and Zangiacomi (2021)	√		√			√		IFIP Advances in Information and Communication Technology	Conference proceeding
40	Prassida and Asfari (2022)	√	√	√					Procedia Computer Science	Conference proceeding
41	Margherita and Braccini (2021)	√							Proceedings of the 7th International Workshop on Socio-Technical Perspective in IS Development (STPIS 2021)	Conference proceeding
42	ElFar et al. (2021)	√	√			√			Energy Conversion and Management: X	Journal
43	Krajčík (2021)	√							Acta Montanistica Slovaca	Journal
44	Demir, Döven, and Sezen (2019)	√		√					Procedia Computer Science	Conference proceeding
45	Alvarez-Aros and Bernal-Torres (2021)	√			√	√			Anais da Academia Brasileira de Ciencias	Journal
46	Ávila-Gutiérrez, Aguayo-González, and Lama-Ruiz (2021)			√		√	√		Sensors	Journal

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No.	Authors	Industry 5.0 Concepts and Theories	Drivers of Implementing Supply Chain 5.0	Impacts and Challenges of Implementing Supply Chain 5.0					Source Title	Research Type
				Human-centricity	Sustainability			Resilience		
					Economic	Environmental	Social			
47	de Miranda et al. (2021)		√			√	√		Sustainability (Switzerland)	Journal
48	Özdemir and Hekim (2018)	√	√				√		OMICS: A Journal of Integrative Biology	Journal
49	Akundi et al. (2022)	√	√	√		√	√	√	Applied System Innovation	Journal
50	Ahsan and Murtaza, TJPRC (2018)			√					International Journal of Mechanical and Production Engineering Research and Development	Journal
51	Aquilani et al. (2020)	√	√	√			√		Sustainability	Journal
52	Bartoloni et al. (2022)	√	√	√			√		Technovation	Journal
53	Coronado et al. (2022)	√	√	√			√		Journal of Manufacturing Systems	Journal
54	Foresti et al. (2019)		√	√			√		Engineering	Journal
55	Fukuda (2020)	√				√			International Journal of Production Economics	Journal
56	Hayashi et al. (2017)	√	√						56th Annual Conference of the Society of Instrument and Control Engineers of Japan (SICE)	Conference proceeding
57	Huang et al. (2022)	√	√	√	√	√	√	√	Journal of Manufacturing Systems	Journal
58	Kalogeras et al. (2021)	√	√						Cyber Physical Systems for Smarter Society: a use case in the manufacturing sector	Conference proceeding
59	Mourtzis, Angelopoulos, and Panopoulos (2022b)	√	√					√	Journal of Machine Engineering	Journal
60	Narvaez Rojas et al. (2021)	√	√	√	√	√	√		Sustainability	Journal
61	Nimfa et al. (2021)				√	√	√		International Conference on Society 5.0	Conference proceeding
62	Pangarso et al. (2022)					√	√		Journal of Innovation and Entrepreneurship	Journal
63	Kumar et al. (2021)	√		√					Human Empowerment by Industry 5.0 in Digital Era: Analysis of Enablers	Conference Proceeding
64	Peraković et al. (2020)	√	√	√					XXXVIII Simpozijum o novim tehnologijama u poštanskom i telekomunikacionom saobraćaju - PosTel	Conference Proceeding
65	Rauch (2020)	√	√					√	Design, Simulation, Manufacturing: The Innovation Exchange	Conference Proceeding
66	Sarfraz et al. (2021)	√	√						Pakistan Journal of Medical Sciences	Journal
67	Smuts and Van Der Merwe (2022)	√			√	√	√		Sustainability	Journal
68	Tabaa et al. (2020)	√	√						Energy Reports	Journal
69	Wang et al. (2019)		√					√	IEEE Transactions on Computational Social Systems	Journal
70	Xiong et al. (2022)		√				√		IEEE Transactions on Computational Social Systems	Journal
71	Yuan et al. (2022)	√							Industrial Management & Data Systems	Journal
72	Zengin et al. (2021)	√			√	√			Sustainability	Journal
73	John, Adarsh, and Pattali (2020)	√	√				√		AIP Conference Proceedings	Conference Proceeding

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No.	Authors	Industry 5.0 Concepts and Theories	Drivers of Implementing Supply Chain 5.0	Impacts and Challenges of Implementing Supply Chain 5.0					Source Title	Research Type
					Sustainability					
				Human-centricity	Economic	Environmental	Social	Resilience		
74	Doyle-Kent and Kopacek (2020)	√	√	√		√			International Conference on Production Research	Journal
75	Jefroy, Azarian, and Yu (2022)	√		√					Logistics	Journal
76	Battini et al. (2022)	√	√	√			√		International Journal of Production Economics	Journal
77	Madsen and Berg (2021)	√		√					Applied System Innovation	Journal
78	Noor-A-Rahim et al. (2022)		√	√					IEEE Communications Magazine	Journal
79	Wang et al. (2022)			√					Journal of Manufacturing Systems	Journal
80	Hu, Yang, and Yin (2022)		√			√			Systems	Journal
81	Khamaisi et al. (2022)			√	√		√		Robotics and Computer-Integrated Manufacturing	Journal
82	Taj and Zaman (2022)	√	√	√			√		International Journal of Computing and Digital Systems	Journal
83	Rožanec et al. (2022)			√				√	Future Internet	Journal
84	Tribe et al. (2022)		√	√					The International Journal of Advanced Manufacturing Technology	Journal
85	Ijaz, Noor-A-Rahim, and Pesch (2022)	√	√			√			IEEE 17th International Conference on Control & Automation (ICCA) 2022	Conference proceeding
86	Ghobakhloo et al. (2022)	√		√		√		√	Sustainable Production and Consumption 2022	Journal
87	Tran et al. (2022)		√					√	IEEE Access	Journal
88	Fernandes, Barros, and Campos-Rebelo (2022)	√	√		√	√			2022 IEEE 31st International Symposium on Industrial Electronics (ISIE)	Journal
89	Cimini et al. (2022)	√	√	√					Computers & Industrial Engineering	Journal
90	Wang et al. (2022)		√	√			√		Journal of Manufacturing Systems	Journal
91	Liu, Tian, and Kan (2022)		√					√	Journal of Manufacturing Systems	Journal
92	Khan and Abonyi (2022)		√		√				Cleaner Logistics and Supply Chain	Journal
93	Arents and Greitans (2022)		√	√					Applied Sciences	Journal
94	Toichoa Eyam, Mohammed, and Martinez Lastra (2021)	√	√	√			√		Sensors	Journal
95	Porambage et al. (2021)	√	√						IEEE Open Journal of the Communications Society	Conference Proceeding
96	Bakon et al. (2022)	√	√	√					IEEE Access	Journal
97	Moraru and Popa (2021)	√					√		MATEC Web of Conferences Les Ulis 2021	Conference Proceeding
98	Abina et al. (2022)				√		√		Sustainability	Journal
99	Bitsch (2022)			√			√		Procedia CIRP	Conference Proceeding
100	Chowdhury et al. (2022)	√	√	√	√	√	√	√	2022 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM)	Journal
101	Minculete, Bã,rsan, and Olar (2021)	√			√			√	Review of International Comparative Management	Journal
102	Coito et al. (2022)		√	√				√	Automation	Journal
103	Golovianko et al. (2023)	√	√					√	Procedia Computer Science	Journal

Appendix B. Challenges of industry 5.0 to manufacturing supply chains

Categories	Challenges	References
Economic challenges	Balance the economic growth with environmental and social development	Pokorni, Popescu, and Constantinescu (2022); Sindhwani et al. (2022); Gaiardelli et al. (2021); Bednar and Welch (2020); Krajčík (2021); Coronado et al. (2022); Smuts and Van Der Merwe (2022); Doyle-Kent and Kopacek (2020); Jafari, Azarian, and Yu (2022)
	Economic efficiency investigation	Pokorni, Popescu, and Constantinescu (2022); Sindhwani et al. (2022); Javaid and Haleem (2020); Humayun (2021); Xu et al. (2021); Sharma et al. (2022); Bednar and Welch (2020); Longo, Padovano, and Umbrello (2020); Jafari, Azarian, and Yu (2022); Tran et al. (2022)
	High investment and unforeseeable consequences	Fatima et al. (2022); Humayun (2021); Xu et al. (2021); Sharma et al. (2022); Bednar and Welch (2020); Özdemir and Hekim (2018); Fukuda (2020); Yuan et al. (2022); Zengin et al. (2021); Madsen and Berg (2021); Hu, Yang, and Yin (2022)
	Additional facilities and cost	Fatima et al. (2022); Xu et al. (2021); Sharma et al. (2022); Rega et al. (2021); ElFar et al. (2021); Demir, Döven, and Sezen (2019); Mourtzis, Angelopoulos, and Panopoulos (2022b); Sarfraz et al. (2021); Zengin et al. (2021); Carayannis et al. (2022); Khamaisi et al. (2022)
Managerial and operational challenges	Insufficient knowledge	Yin and Yu (2022); Pokorni, Popescu, and Constantinescu (2022); Mladineo et al. (2021); Fatima et al. (2022); Saptaningtyas and Rahayu (2020); Sindhwani et al. (2022); Humayun (2021); Nahavandi (2019); Sharma et al. (2022); Johri et al. (2021); Rega et al. (2021); Fornasiero and Zangiacomi (2021); Margherita and Braccini (2021); Krajčík (2021); Aquilani et al. (2020); Pangarso et al. (2022); Yuan et al. (2022); Tribe et al. (2022)
	Unavailability of policy actions and support	Humayun (2021); Xu et al. (2021); Nahavandi (2019); Nguyen et al. (2022); Sharma et al. (2022); Johri et al. (2021); Duggal et al. (2022); Maddikunta et al. (2022); Özdemir and Hekim (2018); Bartoloni et al. (2022); Hayashi et al. (2017); Pangarso et al. (2022); Kumar et al. (2021); Peraković et al. (2020); Doyle-Kent and Kopacek (2020)
	Ineffective employee training for new technologies and sustainability	Fatima et al. (2022); Romero and Stahre (2021); Humayun (2021); Grabowska, Saniuk, and Gajdzik (2022); Nahavandi (2019); Nguyen et al. (2022); Sharma et al. (2022); Johri et al. (2021); Duggal et al. (2022); Lu, Zhao, et al. (2022); Fazal et al. (2022); Maddikunta et al. (2022); Fornasiero and Zangiacomi (2021); Demir, Döven, and Sezen (2019); de Miranda et al. (2021); Bartoloni et al. (2022); Foresti et al. (2019); Fukuda (2020); Huang et al. (2022); Mourtzis, Angelopoulos, and Panopoulos (2022b); Pangarso et al. (2022); Sarfraz et al. (2021); Smuts and Van Der Merwe (2022); Doyle-Kent and Kopacek (2020); Noor-A-Rahim et al. (2022); Khamaisi et al. (2022); Ghobakhloo et al. (2022); Wang et al. (2022)
	Lack of labour law	Nahavandi (2019); Sharma et al. (2022); Johri et al. (2021); Duggal et al. (2022); Lu, Zhao, et al. (2022); Demir, Döven, and Sezen (2019); Coronado et al. (2022); Kumar et al. (2021); Doyle-Kent and Kopacek (2020)
	Hard to create collaborative working environment	Mladineo et al. (2021); Kaasinen et al. (2022); Sindhwani et al. (2022); Javaid and Haleem (2020); Humayun (2021); Sharma et al. (2022); Duggal et al. (2022); Gaiardelli et al. (2021); Maddikunta et al. (2022); Prassida and Asfari (2022); Margherita and Braccini (2021); Krajčík (2021); Ávila-Gutiérrez, Aguayo-González, and Lama-Ruiz (2021); de Miranda et al. (2021); Aquilani et al. (2020); Foresti et al. (2019); Huang et al. (2022); Narvaez Rojas et al. (2021); Pangarso et al. (2022); Kumar et al. (2021); Smuts and Van Der Merwe (2022); Xiong et al. (2022); Doyle-Kent and Kopacek (2020); Wang et al. (2022); Rožanec et al. (2022); Cimini et al. (2022); Wang et al. (2022); Bitsch (2022)
	Ineffective collaboration between members on supply chains	Bednar and Welch (2020); Fazal et al. (2022); Fornasiero and Zangiacomi (2021); Krajčík (2021); Peraković et al. (2020); Smuts and Van Der Merwe (2022); Tabaa et al. (2020); Hu, Yang, and Yin (2022); Liu, Tian, and Kan (2022)
Socio-cultural challenges	Ethic issues	Kaasinen et al. (2022); Romero and Stahre (2021); Nahavandi (2019); Sharma et al. (2022); Johri et al. (2021); Longo, Padovano, and Umbrello (2020); Fornasiero and Zangiacomi (2021); Coronado et al. (2022); Kumar et al. (2021)
	Ineffective strategy of evaluation the social welfare	Pokorni, Popescu, and Constantinescu (2022); Mladineo et al. (2021); Kaasinen et al. (2022); Romero and Stahre (2021); Xu et al. (2021)
	Ineffective performance measurement system	Kaasinen et al. (2022); Sindhwani et al. (2022); Xu et al. (2021); Lu, Zhao, et al. (2022); Coronado et al. (2022); Sarfraz et al. (2021); Yin and Yu (2022)
Process challenges	Realising individualism (personalisation) in products and processes	Leng, Sha, Wang, et al. (2022); Sindhwani et al. (2022); Javaid and Haleem (2020); Humayun (2021); Duggal et al. (2022); Maddikunta et al. (2022); Özdemir and Hekim (2018); Xiong et al. (2022); Jafari, Azarian, and Yu (2022); Wang et al. (2022); Liu, Tian, and Kan (2022)
	Customer oriented	Saptaningtyas and Rahayu (2020); Sindhwani et al. (2022); Xu et al. (2021); Grabowska, Saniuk, and Gajdzik (2022); Fornasiero and Zangiacomi (2021); de Miranda et al. (2021); Pangarso et al. (2022); Wang et al. (2019)

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Categories	Challenges	References
	Lack of green initiatives	Saptaningtyas and Rahayu (2020); Sharma et al. (2022); Fraga-Lamas, Lopes, and Fernández-Caramés (2021)
	Customers' unwillingness	Sharma et al. (2022); Madsen and Berg (2021)
	Resource planning and control	Javaid and Haleem (2020); Duggal et al. (2022); Fraga-Lamas, Lopes, and Fernández-Caramés (2021); Fazal et al. (2022); Fornasiero and Zangiacomi (2021); Nimfa et al. (2021); Smuts and Van Der Merwe (2022); Noor-A-Rahim et al. (2022); Wang et al. (2022); Ijaz, Noor-A-Rahim, and Pesch (2022); Fernandes, Barros, and Campos-Rebelo (2022); Coito et al. (2022)
	Materials processing	Sindhwani et al. (2022); Javaid and Haleem (2020); Duggal et al. (2022); Fraga-Lamas, Lopes, and Fernández-Caramés (2021); Fazal et al. (2022); Huang et al. (2022)
	Energy re-use and reduction of energy consumption	Saptaningtyas and Rahayu (2020); Sindhwani et al. (2022); Javaid and Haleem (2020); Fazal et al. (2022); Maddikunta et al. (2022); Hayashi et al. (2017); Huang et al. (2022); Zengin et al. (2021); Carayannis et al. (2022); Ijaz, Noor-A-Rahim, and Pesch (2022); Coito et al. (2022)
Technological challenges	Lack of technological standards and framework	Mladineo et al. (2021); Kaasinen et al. (2022); Saptaningtyas and Rahayu (2020); Javaid and Haleem (2020); Xu et al. (2021); Nahavandi (2019); Nguyen et al. (2022); Sharma et al. (2022); Johri et al. (2021); Patera et al. (2021); Rega et al. (2021); Welfare et al. (2019); Longo, Padovano, and Umbrello (2020); Fazal et al. (2022); Fornasiero and Zangiacomi (2021); Prassida and Asfari (2022); Margherita and Braccini (2021); Krajčík (2021); Foresti et al. (2019); Hayashi et al. (2017); Kalogeras et al. (2021); Rauch (2020); Yuan et al. (2022); John, Adarsh, and Pattali (2020); Jafari, Azarian, and Yu (2022); Ghobakhloo et al. (2022); Cimini et al. (2022); Wang et al. (2022); Coito et al. (2022)
	Technology acceptance and trust	Fatima et al. (2022); Xu et al. (2021); Sharma et al. (2022); Johri et al. (2021); Lu, Zhao, et al. (2022); Bednar and Welch (2020); Demir, Döven, and Sezen (2019); Coronado et al. (2022); Doyle-Kent and Kopacek (2020)
	Security and privacy issues	Fatima et al. (2022); Javaid and Haleem (2020); Sharma et al. (2022); Rega et al. (2021); Singh, Lee, and Park (2022); Jain et al. (2022); Lu, Zhao, et al. (2022); Bednar and Welch (2020); Bhargava et al. (2022); Maddikunta et al. (2022); Fornasiero and Zangiacomi (2021); Coronado et al. (2022); Hayashi et al. (2017); Peraković et al. (2020); Doyle-Kent and Kopacek (2020); Carayannis et al. (2022); Wang et al. (2022); Taj and Zaman (2022); Tran et al. (2022); Cimini et al. (2022); Liu, Tian, and Kan (2022); Khan and Abonyi (2022)