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Innovation forge: a hybrid review about resilience and technology readiness in the manufacturing sector

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ABSTRACT

This study addresses the gap in the comprehensive literature on the intersection of readiness technology and changes in the manufacturing sector. This study employs a hybrid review (bibliometric analysis and conceptual framework) to offer a panoramic overview of the field. We scrutinised 77 publications from peer-reviewed journals, from 2005 to 2023, using methodological lenses such as keyword co-occurrence networks and thematic maps. The review reveals the major contributors (publication trends, themes, and topics) to *integrating 3D printing, additive manufacturing, Tech Competition and Lifecycle Assessment in Manufacturing, and Smart Manufacturing Strategies*. Based on these insights, we advocate a focused research agenda to expand scholarly contributions to this field. We introduce a framework that offers a theoretically robust tool for scholars and practitioners studying the impact of technology readiness in the manufacturing sector. Consequently, this study not only distils the existing literature, but also sets the stage for future research. This study places significant emphasis on the implementation of technological solutions as a means to improve production operations. Additionally, this research emphasises the significance of ensuring that investment strategies follow the organisation's technological preparedness. An additional crucial implication concerns the cybersecurity protocols. This is consistent with the research's emphasis on investigating cybersecurity concerns in the manufacturing industry.

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1. Introduction

1.1. Motivation and study background

The manufacturing sector is crucial for innovation and economic progress in the current global economy. The industry has seen an extraordinary surge in technical improvements, transforming the creation, manufacture, and delivery (Cavalheiro, Ratchev, and Summers 2013). From automation and artificial intelligence to integrating information and technological devices, these transformational technologies have streamlined manufacturing processes and changed the fundamental core of market competitiveness. As the twenty-first century has progressed, the ability of industrial firms to accept and adapt to evolving technology has become a critical factor in their survival and profitability (Antony et al. 2023). Technological readiness in manufacturing incorporates organisations' readiness and competence to accept and use cutting-edge technologies (Jones et al. 2012). This preparedness entails more than just the presence of an innovative gear; it also includes organisational agility, worker skills, and strategic vision. Understanding and assessing industrial entities' technological readiness has far-reaching repercussions, including market positioning, investment decisions, and the entire trajectory of technological progress (Nimawat and Gidwani 2023).

The motivation for this study was based on the continued change in manufacturing driven by rapid technological advances. Thus, the integration of automation, artificial intelligence, and digital tools has changed the way products are designed, manufactured, and distributed. The global pandemic painted a clear picture of the importance of resilience and adaptability to manufacturers when their suppliers were unable to deliver goods or services. One such example is the Dubai Silicon Oasis (DSO), which acts as a high-tech ecosystem for promoting innovation in manufacturing (Mahanta1 and Lele 2022). In DSO, companies are urged to integrate advanced technologies, including automation and artificial intelligence, as tools for improving productivity efficiency and flexibility (Madichie 2010). This case illustrates how the United Arab Emirates (UAE) aligns technological readiness with industrial policy on a large scale. The story is, However, the situation differs for every manufacturing firm.

1.2. Current situation

According to Leinonen, Poesche, and Kauranen (2018), technologically prepared countries and businesses not only improve their global competitiveness but also generate innovation ecosystems that push social growth. Furthermore, in an era where sustainability and efficiency are top priorities, it is critical to understand how technological readiness affects environmental practices in manufacturing is critical (Haddad et al. 2021; Hu, Xu, and Chen 2023). The manufacturing

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industry is currently in a fix, whereby it must embrace the latest technology and develop resilience against interruptions. Since then, digitalisation has led to a change in which businesses must be agile and technologically ready to stay competitive. For example, Tesla's technological readiness has not only enabled it to remain the leading manufacturer of electric cars, but also navigated supply chain disruptions (Mubarik and Khan 2024) better than most conventional car manufacturers. During the pandemic, Tesla was able to rapidly adapt its software and supply chains, whereas other producers faced huge delays (Chervenkova and Ivanov 2023). Not all manufacturing companies perceive this way, although many small- and medium-sized manufacturers find it difficult to adopt advanced technologies due to limited resources and expertise. This gap makes it urgent for these firms to explore ways through which they can improve their technology preparedness levels and resilience to survive in an increasingly crowded market space. In Al Ain, Strata Manufacturing, a high-tech composite aerostructure plant, was an early adopter of digital manufacturing technologies (Haberly 2016). The adoption of automation and AI by Strata is aimed at increasing competitiveness in the aerospace industry. This case shows how technological readiness can improve industrial performance and resilience in the UAE. For instance, big firms such as Strata lead the way, while smaller ones are still grappling with resource limitations that hinder their uptake of these technologies due to a lack of skills. Consequently, there is an urgent need for strategies that can help these businesses become technologically ready to have a more robust manufacturing landscape nationwide.

1.3. Research gap

The prevailing literature extensively covers manufacturing benefits from the adoption of technology; however, there remains a critical gap in understanding how technological readiness specifically promotes resilience, particularly in relation to unforeseen disruptions, such as the COVID-19 pandemic. For example, challenges experienced by Boeing during the pandemic, compounded by its prior technological problems with 737 Max, illustrate the complexities of maintaining resilience amidst a lack of technological preparedness (Junnila 2024). The struggles at Boeing highlight that it is not enough to adopt new technologies, but they must be fully integrated and supported by the necessary organisational structures and processes. The symbiotic link between technical readiness and economic advancement emphasises the importance of this topic (Ali et al. 2022).

1.4. Plan to address gap

This study seeks to address this research gap by providing a hybrid review using bibliometric analysis as well as a conceptual framework. This approach offers more insights into the relationship between technological readiness and resilience within the manufacturing industry, thus providing important directions for future research and practical applications. This study seeks to contribute to scholarly debate and policy making attempts to affect the manufacturing sector's future globally by illuminating these complicated processes.

The foundations underlying the idea of technological readiness are examined in the following sections of this study. To navigate this complex landscape, our study employed a hybrid review (bibliometric analysis techniques and conceptual review). Utilising tools such as the VOS viewer software (Van Eck and Waltman 2014), bibliometrix package in the R software (Aria and Cuccurullo 2017), and Scopus database (Paul et al. 2021), we delivered an exhaustive map of the research terrain of technology readiness in the manufacturing sector. Our work unravels publication patterns and research themes by shedding light on gaps in the existing literature and paving the way for future research.

1.5. Research questions

Notably, this study revolves around four pivotal research questions (RQs) that aim to provide an exhaustive understanding of the current state of research on technology readiness in the manufacturing sector: RQ1. What is the annual trend in technology readiness in the manufacturing sector? RQ2. What are the most prominent themes and topics in technology readiness in the manufacturing sector? RQ3. What is the most promising conceptual framework for future technological readiness in the manufacturing sector? RQ4. What are the future avenues for technology readiness in the manufacturing sector?

2. Methodology

This study employs a hybrid review based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol (Moher et al. 2015; Page, Moher and McKenzie 2022). A hybrid review was based on a formalised protocol. Our dual-pronged methodological approach encompasses bibliometric analysis (Mukherjee et al. 2022) with a subsequent conceptual framework, thereby providing a level of objectivity, transparency, and replicability that lends credibility to the analytical process (Donthu et al. 2021; Kraus et al. 2022; Paul et al. 2021).

2.1. Selection

At the *identification* stage, we employed a strategic search query in Scopus at the outset. Specifically, the search string comprised the terms *Technology readiness*, "manufactur*, and resilience* in the Scopus Database (Paul et al. 2021). This query was executed in September 2023 and identified a pool of 459 articles. We used the period from 2005 to 2023, which resulted in 440 articles.

Transitioning to the *screening* stage, a rigorous subject (engineering/computer science/business management) came out with 357 articles, journals (articles/review, conference) gave 118, and language (English) filtration provided 114 articles. In the *eligibility* stage, we undertook a comprehensive reading of the 114 full texts and eliminated those that failed to occupy a central narrative. Consequently, 77 articles were included in the final analysis. For the *inclusion* stage, a well-defined set of 77 articles (see Figure 1) directly addressing

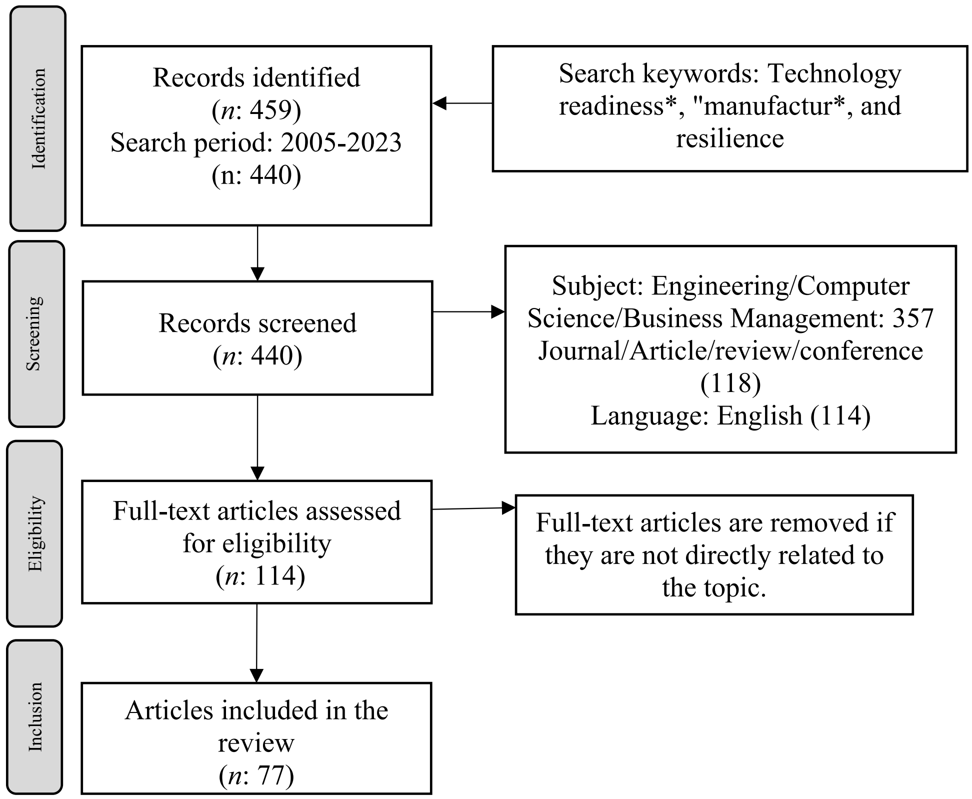

Figure 1. Study flow diagram.

technology readiness and the manufacturing sector were subjected to extensive bibliometric analyses, which we elaborate on in the subsequent section.

2.2. Analysis

We employed several bibliometric analytical techniques to analyse articles on technology readiness in the manufacturing sector. *First*, we performed a performance analysis using the bibliometrix package in the R software (Aria and Cuccurullo 2017). *Second*, we conducted science mapping using VOSviewer software (Van Eck and Waltman 2014) to unpack the significant themes and topics in technology readiness in manufacturing sector research. The threshold for keyword inclusion was set at a software default with a minimum of three occurrences. *Third*, we constructed a cartographic map using the bibliometrix package in R software (Aria and Cuccurullo 2017). The threshold for keyword coverage was set at the package default of a maximum of 53 out of 835 keywords when the threshold was maintained at a minimum of three occurrences.

3. Results

3.1. Descriptive analysis

3.1.1. Publication trend

Figure 2 illustrates these three phases from 2005 to 2023. In 2010, the industrial sector experienced a considerable increase in technological preparedness. Automation and robots have become less expensive and have increased precision and speed. Government programmes and commercial funding have boosted research and development and supported innovation. Workforce training activities guaranteed that staff could properly utilise new technology. These innovations constitute a watershed moment in manufacturing, increasing efficiency, competitiveness, and environmental sustainability (Jones et al. 2012; Reinhart and Schindler 2010).

In 2015, we again witnessed an increase in the rise of 5 publications. AR and VR have been increasingly employed in training and design simulations, respectively. Manufacturing execution systems for cloud-enhanced process visibility (M. B. Jones et al. 2015; Landahl, Raudberget, and Johannesson 2015). Since, 2020 there has been a significant increase in publications because the COVID-19 epidemic has accelerated the use of technology in the industrial industry. The pandemic compelled businesses to rethink their operations and discover strategies to retain production in the face of lockdowns and supply chain interruptions. Manufacturers are compelled to use digital communication and collaboration solutions as a result of the requirement for distant work (Makki and Xie 2020). While the COVID-19 pandemic caused enormous obstacles, it also drove fast technological adoption in manufacturing. The need to adapt to changing working circumstances, assure supply chain resilience, and sustain productivity has resulted in increasing technological preparedness, which has transformed the sector (Guamán-Rivera et al. 2022; Sargam and Gupta 2022).

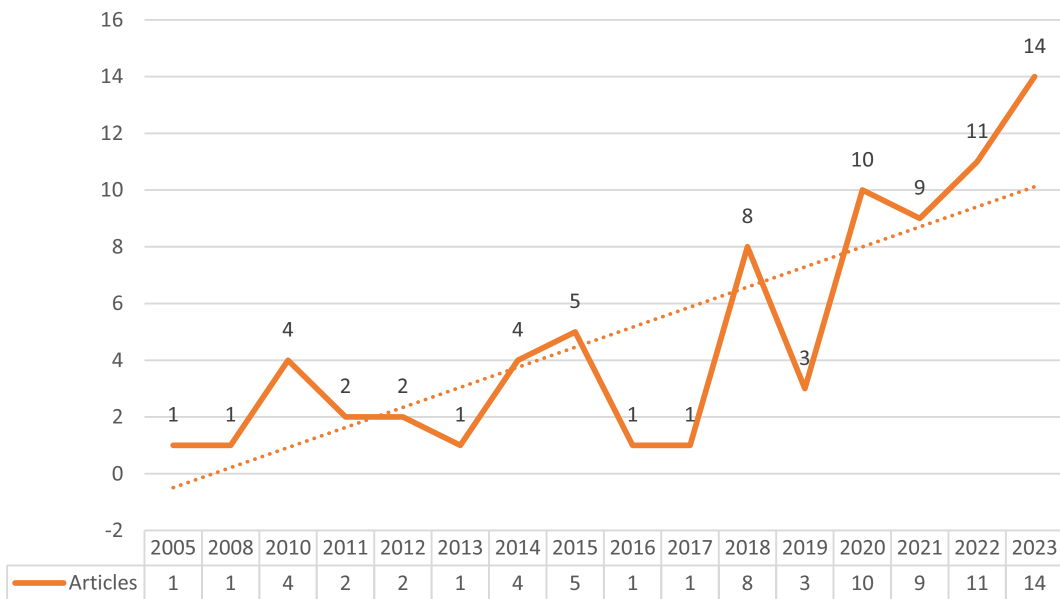

Figure 2. Yearly publication.

3.2. Themes, thematic evolution and clusters

3.2.1. Thematic evolution based on cartographic representation

A thematic area comprises a collection of themes developed throughout distinct sub-periods. Each period produced two distinct types of strategic diagrams to examine the most prominent themes. In the first diagram, the size of the sphere corresponded to the number of publications associated with each theme. Conversely, in the second diagram, the number of citations received for each theme determines sphere size. The 18 years were divided into two subperiods: [2015–2016] and [2016–2023]. By choosing 2015 as the cut-off year, scholars can monitor the progression of thematic areas before and after the inception of the Sustainable Development Goals (SDGs) (Iizuka and Hane 2021). This facilitates the juxtaposition of prominent research themes, providing valuable insights into how global priorities and research emphasis have evolved in light of the aforementioned global agenda.

To map the evolving landscape of technology readiness in the manufacturing sector for both subperiods, 2005–2015 and 2016–2023, we employ a cartographic representation that utilises two critical metrics: Callon's centrality and Callon's density. Drawing from network theory, Callon's centrality gauges the degree of interactions among topics, whereas Callon's density measures the internal cohesiveness of individual topics (Callon et al. 1983). This dual-metric approach bifurcates the topical landscape into four distinct quadrants: motor, niche, declining or emerging, and basic.

Figure 3 presents a thematic map for the subperiod from 2005 to 2015. The only motor theme in this sub-period was *manufacture*. The emerging and declining theme is *decision-making*. The basic themes include *technology readiness*, *industrial research*, and *technology readiness levels*.

3.2.1.1. Motor Theme. Motor topics are the pulsating heart of the field, dictating the overall rhythm, and setting the beat for every other research endeavour. Manufacturing and technological preparedness are inextricably intertwined, which determines the forefront of research. For efficient manufacturing, manufacturers must be prepared to accept upcoming technologies such as Industry 4.0, IoT, and AI (Birkel and Müller 2021; Broday 2020). Manufacturers can enhance quality control, reduce downtime, and optimise production processes using AI technologies, including robotics, predictive analytics, and machine learning. For example, AI predictive maintenance systems can anticipate equipment failures in advance, thereby minimising the expense of disruptions (Liu et al. 2022).

Furthermore, AI-driven automation has revolutionised factory floors by facilitating more precise and consistent production, increasing throughput, and reducing waste (Arinez et al. 2020). By optimising inventory levels and predicting demand trends, the integration of AI also enables wiser supply chain management, thereby reducing costs and guaranteeing timely delivery (Liu et al. 2022). This integration improves efficiency, lowers costs, and ensures long-term practices. Understanding and increasing preparedness in manufacturing are critical as global markets expand, boosting innovation and competitiveness in the sector (Ghobakhloo and Iranmanesh 2021).

3.2.1.2. Emerging or Declining Theme. Emerging or Declining Themes are those in a field that change quickly, and topics that are becoming popular or losing popularity show the dynamics of the field. In the manufacturing industry, decision making is crucial, especially regarding technological readiness. Decisions on whether and how to embrace, integrate, and optimise cutting-edge technologies can be particularly challenging for manufacturers. By making well-informed decisions, businesses can better ensure that their investments in new technology help them meet their goals and remain competitive (Kastensson and Johansson 2011).

3.2.1.3. Basic Theme. Basic themes are essential components constituting the foundational parts of the discipline. Industrial

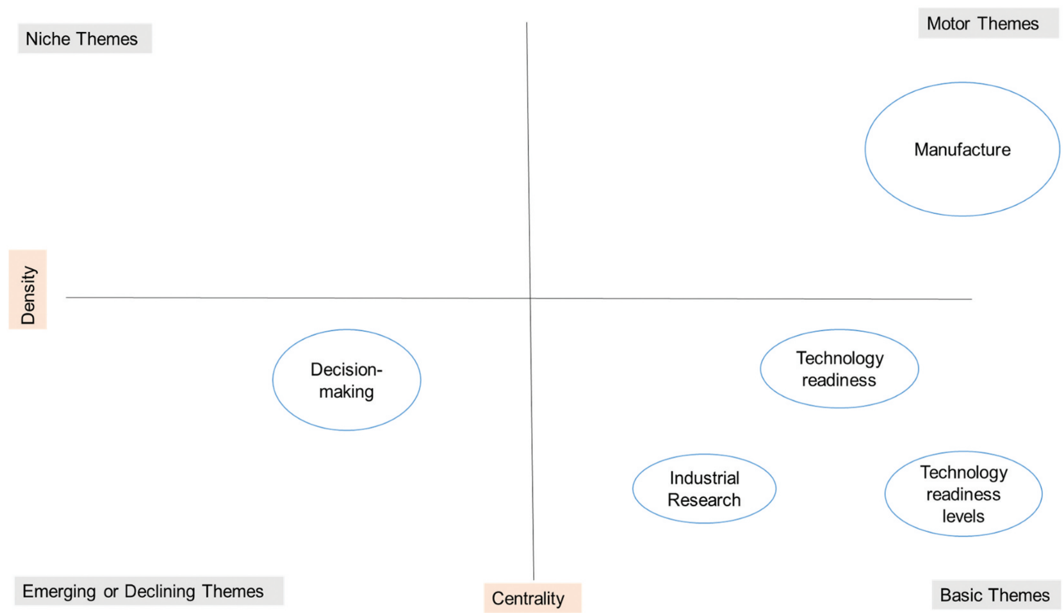

Figure 3. Thematic map for sub-period: 2005–2015.

research is critical in manufacturing because it drives innovation, improves processes, and ensures worldwide competitiveness (Madison et al. 2015). Manufacturers may create cutting-edge technologies, improve product quality, and optimise manufacturing procedures via research. Industrial research promotes breakthroughs that drive economic growth and position manufacturing businesses as innovators (Madison et al. 2015). The manufacturing industry relies heavily on Technology Readiness Level assessment, which determines the maturity of technologies before integration. Its evaluations are crucial for developing the industrial scene, encouraging innovation, and ensuring that the sector remains competitive (Zutin et al. 2022).

Figure 4 depicts the thematic map for the sub-period from 2016 to 2023. The motor themes in this sub-period included gas emissions, additives, and supply chains. The emerging or declining themes are the manufacturing process and life cycle. The basic themes include industry, robotics, manufacturing, and technology readiness.

3.2.1.4. Motor theme. Blockchain technology plays a pivotal role in guaranteeing transparency and security within the supply chain, enhancing the efficiency of transactions, and mitigating the potential for fraudulent activities. Advanced supply chain management practices result in heightened operational effectiveness, decreased expenditure,

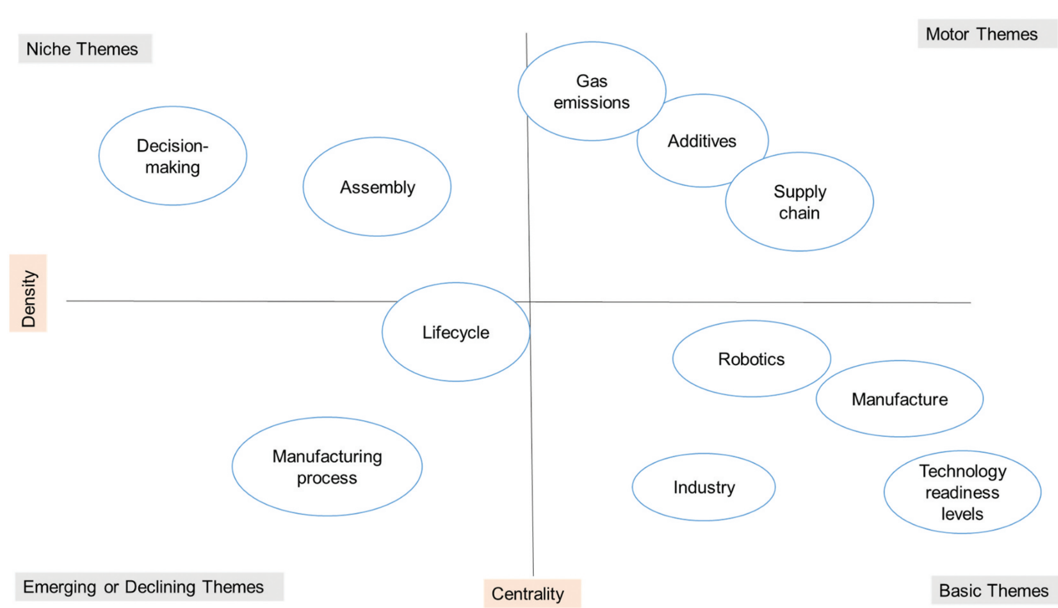

Figure 4. Thematic map for sub-period: 2016–2023.

and enhanced levels of customer contentment (Ahmed, Islam, and Qureshi 2023; Ward et al. 2018). Furthermore, the advent of technological readiness in additive manufacturing has brought about a significant transformation in production processes. This technology reduces material waste and enables the creation of intricate geometries, thereby nurturing the creation of novel product designs (Revfi et al. 2020; Zutin et al. 2022). However, the issue of greenhouse gas emissions is also encompassed within the scope of technological readiness. Advanced manufacturing methods, including utilising green energy-powered factories and implementing eco-friendly materials, contribute to the mitigation of the carbon footprint (Sargam and Gupta 2022).

3.2.1.5. Declining or emerging theme. Companies frequently spend time on research and development throughout the early phases of a product's life cycle, resulting in the introduction of new technologies. The progression from human assembly methods to robotic automation in the car sector exemplifies this link. These technologies have evolved and become industry standards, demonstrating the complicated relationship between product lifecycles and manufacturing technology readiness (Fundin 2005; Schwabe, Erkoyuncu, and Shehab 2020).

3.2.1.6. Niche theme. Assembly procedures become increasingly complex and efficient as technology progresses, directly influencing product development and market readiness. Higher degrees of technological preparedness allow the use of sophisticated assembly technologies. As a result, the progress in assembly techniques is inextricably linked to technological preparedness, promoting faster, more precise, and cost-effective production processes (Ferreira, Biesek, and Scalice 2021; Sanderson et al. 2019).

3.2.1.7. Basic theme. As a cutting-edge technology, robotics substantially affects a company's preparedness to embrace and deploy innovative ideas. Higher degrees of technological readiness suggest that robotic technologies have matured, making them more accessible and simpler to integrate into the production processes. As these technologies grow, so does their readiness, prompting firms to use them for jobs ranging from assembly to packing. Incorporating mature robotic systems improves the overall technical preparedness of the industrial sector, simplifies processes, and enhances efficiency (Perez-Grau et al. 2021; Sanderson et al. 2019).

3.2.2. Keyword analysis map

The exploration of key themes and topics in the domain of technology readiness in manufacturing readiness was pivoted on a sophisticated keyword co-occurrence analysis conducted using VOSviewer software (Figure 5) (Van Eck and Waltman 2014). The threshold for keyword inclusion was set at the software default with a minimum of three occurrences, which led to the selection of 53 out of 835 keywords. The interpretation of the results from this analysis was guided by a three-tiered sensemaking framework, scanning, sensing, and

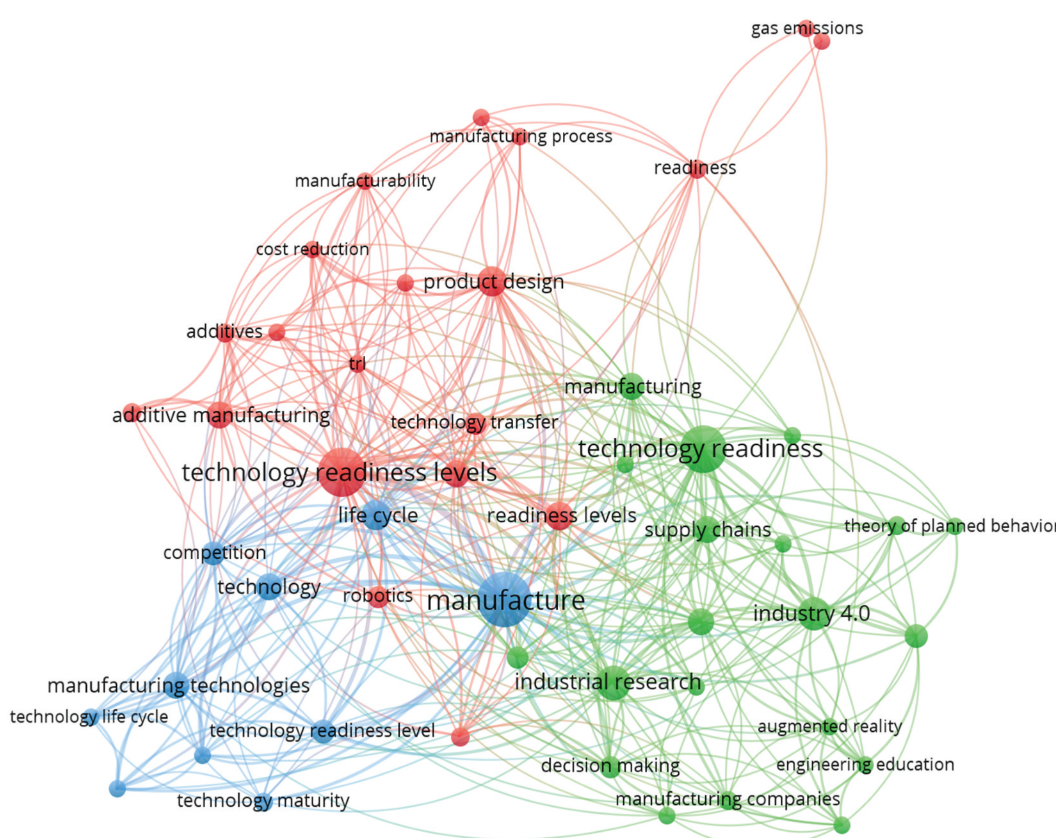

Figure 5. Keyword co-occurrences analysis network map.

substantiating, as articulated by Lim and Kumar (). Three overarching clusters of interest have emerged: *Advanced sustainable manufacturing techniques, Smart Manufacturing Strategies, Tech Competition and Lifecycle Assessment in Manufacturing*.

3.2.2.1. Cluster 1: (Red) Advanced sustainable manufacturing techniques.

Cluster 1 consists of 20 keywords consisting *3d printers, 3d printing, additive manufacturing, additives, cost engineering, cost reduction, gas emissions, greenhouse gases, manufacturability, manufacturing process, product design, product development, readiness, readiness levels, risk assessment, robotics, technology development, technology readiness levels, technology transfer and technology readiness level (TRL)*.

The integration of 3D printing, additive manufacturing, and robots is critical for improving production cost efficiency. These technologies work together to simplify manufacturing processes, eliminate waste, and reduce labour costs (Lianos et al. 2020). According to Gradl et al. (2023), 3D printing and additive manufacturing allow for the layer-by-layer fabrication of complicated components while maximising material utilisation. When combined with these technologies, robotics provides precision and speed in production, significantly lowering the costs associated with human labour. Moreover, the adaptability of these technologies facilitates fast prototyping and just-in-time manufacturing, thereby obviating the need for extensive stockpiles (Klahn et al. 2020). The integration of operations not only leads to a decrease in operating expenses but also enables producers to promptly address market needs, thereby securing a competitive advantage. The effective amalgamation of 3D printing, additive manufacturing, and robotics facilitates the enhancement of operational efficiency, resulting in cost reductions across diverse domains within the industrial sector (Guamán-Rivera et al. 2022).

Emission reduction, technical preparedness, and improved sustainable manufacturing methods are all closely related. Manufacturers are increasingly embracing sustainable techniques, as the need to address climate change has become more pressing. By reducing waste, energy use, and environmental effects, cutting-edge sustainable manufacturing strategies, including lean manufacturing, circular economy ideas, and eco-friendly materials, can drastically lower emissions (Haddad et al. 2021; Leinonen, Poesche, and Kauranen 2018).

3.2.2.2. Cluster 2: (Green) Smart Manufacturing Strategies.

Cluster 2 consisted of 20 keywords comprising *augmented reality, automation, decision making, design/methodology/approach, engineering education, industrial research, industry 4.0, manufacturing, manufacturing companies, manufacturing industries, manufacturing sector, success factors, supply chain, supply chains, sustainable Development, technology acceptance model, technology adoption, technology readiness, theory of planned behavior* and *virtual reality*.

The addition of Augmented Reality (AR), Automation, and Sustainable Development to Industry 4.0, will transform everything. AR enhances maintenance, worker training, and product creation, resulting in increased efficiency and fewer errors. Automation, propelled by artificial intelligence and automata, increases output while decreasing waste and resource consumption (Leinonen, Poesche, and Kauranen 2018). Production systems have become increasingly intricate, flexible, and interlinked. This is because several uncertainties and interdependencies exist in manufacturing, making it highly nonlinear and stochastic. In recent years, breakthroughs in Artificial Intelligence technology, such as machine learning, have provided a lot of hope for how artificial intelligence (AI) will revolutionise manufacturing through better analytic tools for processing large quantities of industrial data, popularly referred to as Big Data (Arinez et al. 2020). Sustainable Development in Industry 4.0 entails employing eco-friendly methods, managing resources responsibly, and minimising environmental impact (Haddad et al. 2021).

The interplay between these technologies is evident in their cumulative contributions to the advancement of sustainability. The implementation of augmented reality (AR) technology in maintenance processes has been shown to effectively minimise downtime, leading to an extended lifespan of the equipment and a reduction in waste generation (Scott et al. 2020). Automated systems can enhance energy efficiency and mitigate emissions by aligning them with sustainability objectives. Furthermore, intelligent automation systems guarantee accurate resource allocation and reduce excessive output and avoidable waste (Bakar et al. 2021; Leinonen, Poesche, and Kauranen 2018). In smart factories, augmented reality (AR) interfaces play a crucial role in providing guidance to workers, thereby ensuring adherence to energy-efficient procedures. This, in turn, leads to a reduction in mistakes and minimises material loss.

3.2.2.3. Cluster 3: (Blue) Tech Competition and Lifecycle Assessment in Manufacturing.

Cluster 3 contained 10 keywords: *competition, industry, life cycle, manufacture, manufacturing technologies, maturity assessment, technology, technology life cycle, technology maturity*, and *technology readiness level*. The technology life cycle covers the phases of a technology from its inception to its eventual demise, whereas the term ‘technology maturity’ refers to the stability, dependability, and efficacy of that technology. According to Schwabe, Erkoyuncu, and Shehab (2020), early in a technology’s life cycle, manufacturing organisations invest heavily in R&D to enhance their technical maturity. Mature technologies are standardised, trustworthy, and economical. Manufacturing companies use proven technology to increase productivity, reduce costs, and improve quality (Cavalheiro, Ratchev, and Summers 2013; Wanner et al. 2021).

Moreover, understanding the technology lifecycle assists manufacturers in forecasting market trends and enables strategic planning for technology adoption and phasing out. For example, early stage robots in the advancement of factory automation are expensive and restricted (Perez-Grau et al. 2021). However, as technology advances, more economical and adaptable robotic systems have emerged, revolutionising various sectors. The maturity and life cycle of technologies significantly impacts manufacturing sector plans and decisions. To remain competitive and efficient, businesses must connect their technology adoption with their life cycle stages (Genaidy and Karwowski 2008).

4. Conceptual framework

The manufacturing sector is a critical component of global economies, and its resilience in the face of various disruptions, such as supply chain interruptions and technological advancements, is crucial. This conceptual framework was developed based on existing studies (Aboelmaged 2014; Adebanjo et al. 2023; Naseebullah et al. 2011) to provide a comprehensive understanding of how technological infrastructure, innovation culture, and supply chain integration interact within the manufacturing industry. This framework is designed to explore the dynamic relationships between these critical factors and their collective impact on an organisation's ability to withstand challenges, adapt to technological changes, and remain competitive in a rapidly evolving environment. The framework integrates these two key concepts to understand how technology readiness contributes to resilience in the manufacturing sector resilience (Moscato et al. 2022).

Figure 6 uncovers the interplay between *technology readiness* and *resilience* in the manufacturing sector. It emphasises the role of technology adoption, digital literacy, and data management as key components of readiness while considering various *digital ecosystem enablers*, *resilience dimensions*, and *moderating factors*. These outcomes encompass *competitive advantage*, *economic and operational performance* and *adaptability to technological change*. This *feedback loop* ensures that the manufacturing sector remains dynamic and responsive to evolving challenges, ultimately enhancing its resilience in an increasingly complex and technologically driven environment.

4.1. Technological infrastructure

The fundamental component of this framework is technological infrastructure, which is of utmost importance in the manufacturing industry. Prior studies (Goswami and Daultani 2022, Naseebullah et al. 2011) have consistently emphasised the critical significance of technological infrastructure in bolstering an organisation's resilience. Communication networks, digital tools, advanced manufacturing equipment, and data management systems were included. Research has shown that organisations with strong technological infrastructure can effectively address market disruptions and technological advancements (Cavalheiro, Ratchev, and Summers 2013; M. Jones et al. 2012; Ward et al. 2018). This technological infrastructure facilitates innovation and technological adaptation by providing the support necessary for organisations to swiftly adjust to changes.

4.2. Innovation culture

Numerous studies (Islam 2010; Leinonen, Poesche, and Kauranen 2018; Schrage 2014) have provided support for the notion that innovation culture constitutes an essential element encircling technological infrastructure. It embodies an organisation's collective mindset, values, and practices concerning innovation. Landahl, Raudberget, and Johannesson (2015) opine that firms that cultivate an environment that promotes and supports progress are more inclined to utilise their technological infrastructure to successfully enhance resilience. According to Andersson et al. (2018), an innovation culture fosters the development of novel concepts, execution of experiments, and introduction of new technologies. Nurturing this culture within an organisation is critical for ensuring that its workforce is in harmony with its technological prowess and actively embraces novel tools and processes.

4.3. Supply chain integration

The outer layer of the framework emphasises supply chain integration, an area well-documented in the literature (Ward

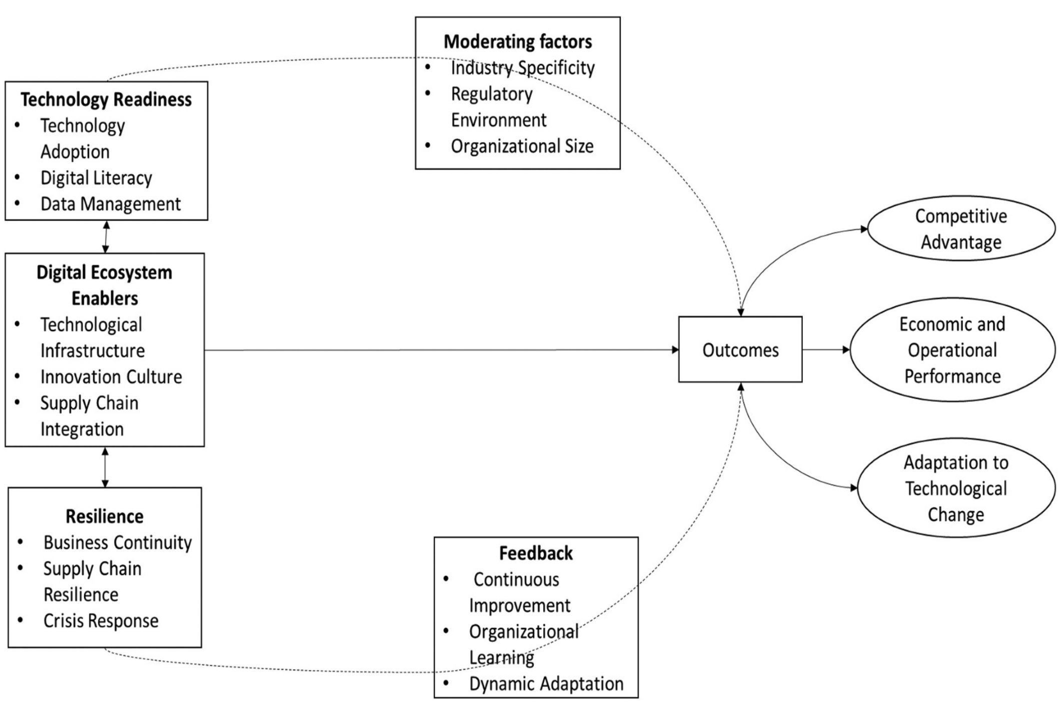

Figure 6. Conceptual framework.

et al. 2018). Supply chain integration involves coordinating and collaborating with suppliers, partners and customers. It is recognised for its critical role in enhancing an organisation's responsiveness and adaptability. Studies (Adebanjo et al. 2023; Genaidy and Karwowski 2008) have shown that tightly integrated supply chains facilitate the seamless flow of information and resources, reducing lead times and increasing flexibility. This, in turn, supports an organisation's ability to effectively manage disruptions and changes.

The interconnectedness of these elements, as highlighted by various studies (Naseebullah et al. 2011; Ullah 2020; Ward et al. 2018), is a key feature of this framework. The strength of technological infrastructure influences an organisation's innovation culture, which, in turn, affects its ability to harness technology for supply chain integration. Conversely, a well-integrated supply chain can enhance an organisation's technology readiness, reinforcing its overall resilience.

5. Future research agendas

This section presents eight future research fronts derived from thematic discussions, consisting of thematic evolution and keyword analysis.

5.1. Resilience enhancement through supply chain integration

Further investigation of the state of technology readiness within the manufacturing industry presents an abundance of prospects for intellectual growth. An area of inquiry that warrants further examination is the significant influence of digitisation and blockchain technology on the technological proficiency and overall competitiveness of organisations functioning under the umbrella of Industry 4.0. This may entail analysing the implementation and assimilation of blockchain-based systems and digital solutions (Ahmed, Islam, and Qureshi 2023), to clarify the impact of these developments on the adaptability and preparedness of manufacturing organisations in a technologically dynamic environment.

Furthermore, forthcoming research must emphasise the degree to which small and medium-sized enterprises (SMEs) are prepared to adopt innovative technologies. SME representation in the manufacturing sector is significant, and readiness to adopt state-of-the-art solutions is of utmost importance. Scholars may investigate the factors that impede or promote the adoption of technology by small and medium-sized enterprises (SMEs), thereby illuminating the potential contribution of such factors to sustainable development. Comprehending how small and medium-sized enterprises (SMEs) can influence sustainability in the manufacturing sector is critical for fostering environmentally conscious and inclusive technological advancement (Bettoni et al. 2021; Ghobakhloo and Iranmanesh 2021).

5.2. Technology readiness and sustainability in additive manufacturing

Given the significance of technology readiness in additive manufacturing, this research agenda delves into the relationship between technology adoption in 3D printing and its impact on reducing material waste and designing sustainable and environmentally friendly manufacturing processes (Alrubaye and Fantoni 2023; Guamán-Rivera et al. 2022). Future researchers can provide valuable insights into the manufacturing sector by understanding how technological readiness can enhance sustainability. Future researchers could examine the influence of digitisation and blockchain on competitiveness and technological competence within the framework of Industry 4.0. Furthermore, it is recommended that future studies investigate the extent to which small and medium-sized enterprises (SMEs) are prepared to implement new technologies and their potential contribution to sustainable Development

5.3. Advanced robotics and its impact on technology readiness

The primary focus of the proposed research agenda is the revolutionary impact of advanced robotics on the manufacturing industry. There is a need for a comprehensive examination of the significant influence that increased levels of technological preparedness in robotics can have on the simplicity of integrating and deploying them across diverse production processes. It is crucial to examine this intricate correlation, as it may result in significant enhancements in operational effectiveness and financial savings, which is consistent with the findings of Madison et al. (2015) and Naseebullah et al. (2011). Given the ongoing transformation of the manufacturing sector brought about by Industry 4.0, and automation, it is critical to fully grasp the complex relationship that exists between the preparedness of autonomous technologies and the robustness of manufacturing processes (Shakur et al. 2024). Acquiring such knowledge is essential for manufacturers seeking to navigate and prosper in the dynamic technological landscape. Hence, this research agenda aims to provide significant perspectives on the future of manufacturing by examining the interconnection between sophisticated robotics, technological preparedness, and overall durability of this critical industry domain.

5.4. Life cycle management and emerging manufacturing technologies

This research agenda aims to examine how the life cycle of manufacturing technologies affects manufacturing organisations' decision-making procedures. A thorough analysis is required to comprehend how technologies develop and advance through their discrete life-cycle stages of life cycles (Fundin 2005; Schwabe, Erkoyuncu, and Shehab 2020), ultimately resulting in their adoption as benchmarks within the industry. A comprehensive understanding of the complex correlation between technology life cycles and readiness is crucial, as it can provide manufacturing companies with invaluable insights that influence strategic decisions regarding the implementation of new technologies. Through an in-depth examination of the intricacies of technology life cycles, future scholars can illuminate the pivotal moments when technologies transform from emerging innovations to established industry-wide solutions. By recognising this, manufacturing organisations can enable themselves to better coordinate their technology adoption strategies with the distinct stages of a technology's life cycle. As a result, they can maintain a competitive edge, demonstrate adaptability, and be adequately equipped to navigate a perpetually changing technological environment.

5.5. Satellite technology and manufacturing assembly processes

The research agenda outlined herein emphasises the rapid advancements in manufacturing assembly processes facilitated by satellite technology. Future researchers can examine the degree of preparedness exhibited by satellite-based assembly technologies and exhaustively evaluate their extensive consequences on product development and market readiness (Perez-Grau et al. 2021). A comprehensive understanding of the significance of satellite technology in assembly is imperative in contemporary technologically advanced and globalised environments. By reducing lead times, improving precision, and streamlining processes, satellite-based solutions can render manufacturing more agile and responsive. Furthermore, this research agenda recognises the criticality of satellite technology concerning product development given its substantial impact on the time required to bring a product to the market and its level of competitiveness. Through an examination of the ramifications of satellite technology on assembly processes, future researchers can seek to provide manufacturing organisations with the means to enhance their operational efficiency and technological preparedness in a market that is becoming more competitive.

5.6. Technology readiness and the impact on small and medium-sized enterprises (SMEs)

The primary emphasis of this research agenda is the preparedness of small and medium-sized manufacturing enterprises (SMEs) to implement new technologies. Future researchers could investigate the complexities of technology adoption readiness levels among SMBs, focusing on the opportunities and challenges unique to this sector. SME participation in the manufacturing sector is growing in importance, frequently catalysing innovation, adaptability, and economic expansion.

The adaptability is a notable attribute that can substantially influence an industry's overall resilience and competitiveness. The ability of entities to rapidly adopt and incorporate nascent technologies has the potential to transform entire industries and impact more extensive patterns of sustainable development. Examining the preparedness levels of technology adoption among small and medium-sized enterprises (SMEs) and their impact on the resilience of the manufacturing sector is critical to fully harnessing the sector's capabilities.

6. Conclusion, implications, limitations

This study embarked on an ambitious journey to critically assess the current landscape of technology readiness in manufacturing sector literature. We scrutinised a compendium of 77 scholarly articles using rigorous review methodology. This meticulous examination created both a keyword co-occurrence network and a topical map, serving as cartographic tools for scholars and practitioners navigating this burgeoning field. Our data suggest that the new decade of change (from 2020 onwards) marks a seminal period in technology readiness in the manufacturing sector. The COVID-19 pandemic compelled businesses to rethink their operations and discover strategies to retain production in the face of lockdowns and supply chain interruptions. Manufacturers were compelled to use digital communication and collaboration solutions because of the requirement for distant work. Unexpected events, such as the COVID-19 pandemic, cause huge disruptions in the activities of firms and lead to many enterprises revaluating their operations and looking for ways to increase efficiency and resilience. However, whether intelligent manufacturing has enhanced flexibility and adaptation during the COVID-19 pandemic (Xi et al. 2024). Worldwide epidemics have caused production limitations in manufacturing. Owing to lockdowns, numerous businesses faced interruptions and could not continue with their production. During such disruptive instances, resilience within the production system becomes critical, because it determines the overall survival of a company. In this regard, Lerch et al. (2024) showed that modern technologies, such as AI, enhance organisations' proactive and reactive capabilities, making them more resilient against disruptive events, thereby leading to increased resilience.

From the cartographic map and keyword co-occurrence analysis, we unveiled trending, nascent, and specialised research areas within technology readiness in the manufacturing sector, revealing the intellectual structure and thematic focus of the existing scholarship. Specifically, they highlighted areas such as *robotics, technology readiness level, supply chain, industrial research and assembly*. The clusters show the importance of *Advanced sustainable manufacturing techniques, Smart Manufacturing Strategies, Tech Competition and Lifecycle Assessment in Manufacturing.*

The presented conceptual framework draws from existing studies (Aboelmaged 2014; Adebanjo et al. 2023; Naseebullah et al. 2011) to offer a comprehensive understanding of the dynamic interplay between technological infrastructure, innovation culture, and supply chain integration in the manufacturing industry. Eight future research agendas offer promising avenues for further exploration. These include investigating the impact of digitisation and blockchain on manufacturing organisations under Industry 4.0, understanding the technology readiness levels in additive manufacturing, exploring the role of advanced robotics in enhancing technology readiness, examining the influence of technology life cycles on decision-making in manufacturing, scrutinising satellite technology's role in manufacturing assembly processes, and assessing the technology readiness of small and medium-sized manufacturing enterprises (SMEs).

6.1. Implications

The study's findings provide significant implications that offer valuable insights for manufacturing sector administrators and decision makers. This study places significant emphasis on the implementation of technological solutions as a means to improve production operations. Previous studies have established that incorporating cutting-edge technology can enhance operational effectiveness (Smith 2024). It is recommended that managers perform cost-benefit analyses and pilot testing to aid in forming well-informed decisions concerning deploying particular technologies.

Additionally, this research emphasises the significance of ensuring that investment strategies follow the organisation's technological preparedness.. When an organisation receives a lower technology readiness score, it may be imperative to make incremental investments in infrastructure and training before deploying sophisticated technological solutions.

An additional crucial implication concerns the cybersecurity protocols. Consistent with the research's emphasis on investigating cybersecurity concerns in the manufacturing industry, executives must give precedence to all-encompassing cybersecurity protocols. The importance of taking proactive steps to safeguard confidential information and proprietary rights. To mitigate potential cyber threats, it is imperative that managers allocate resources to cybersecurity training, implement encryption mechanisms, and upgrade security systems consistently.

Furthermore, this study emphasises the importance of implementing a technology readiness strategy centred on consumers. Satisfying market and consumer demand should take precedence in the context of technology adoption. This suggests that by leveraging technological advancements to improve product quality, customisation, and delivery efficiency, businesses can substantially increase customer satisfaction and strengthen their positions in the market. Therefore, managers are encouraged to prioritise technologies that support these customer-centric objectives. Research on technological preparedness in the industrial sector sheds light on the critical theoretical perspectives. It extends the Technology Readiness Index methodology by providing detailed insights into its application and adaptation to a particular industrial environment. Second, by presenting the conceptual framework in Figure 6, this study adds to the resilience – technology readiness paradigm in the manufacturing sector by elaborating on the complex interplay between manufacturing processes, organisational structures, and external technology environments. Third, it contributes to absorptive capacity by demonstrating how organisations with better technological preparedness effectively absorb and integrate external knowledge. This study lays the groundwork for future research on technology adoption, innovation dispersion, and organisational adaptability in dynamic industrial environments.

6.2. Limitations

Several significant limitations of this study should be considered in future investigations. This study's temporal restriction, which only includes publications published until September 2023, is one of its main limitations. Considering the rapid development of industry and technology, this timeline can miss the essential advances that have occurred recently. Extending the publication date range to include the most recent findings may be prudent.

A second restriction is related to the choice of databases. Although Scopus is a reputable source of systematic reviews, using this database may result in bias. There could have been original research and papers in other databases that were not included in our study. Future studies should consider using different databases to conduct a more thorough literature evaluation to lessen this constraint. Another constraint area was the threshold for keyword inclusion in the keyword analysis map. Specific important but less commonly used terms with relevance to the area were omitted because the threshold was set at three occurrences. Future research may provide a broader view of keyword analysis from a more inclusive perspective.

A significant restriction is the need for qualitative data. The main data source of this study was quantitative information, such as citation analysis and publication numbers. Although these measurements offer insightful information, qualitative data such as expert interviews or content analysis of articles would provide more in-depth knowledge of the subtleties involved in the field of manufacturing technological preparedness. Further studies utilising qualitative methodologies may improve the comprehensiveness of these findings. Finally, a limitation of this study is its generalisability. Within the parameters of the study, the conclusions and conceptual framework were extrapolated from the selected publications. It is advisable to use caution when extrapolating these findings to the entire manufacturing sector given that different industries may have various needs and features. Subsequent investigations must go deeper into the particularities of technological readiness and resilience that are unique to each sector.

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Data availability statement

The data that support the findings of this study are available from the corresponding author, [Seema Bhardwaj], upon reasonable request".

Author's contribution statement

1. Dr. Kiran Nair: Writing – original draft, Methodology.
2. Seema Bhardwaj: Writing – original draft, Visualisation, Data curation.
3. Sreejith Balasubramanian: Supervision.
4. Mahima Misra: Writing – Proof-reading.
5. Ritika Chopra: Original Draft and Formal analysis.

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