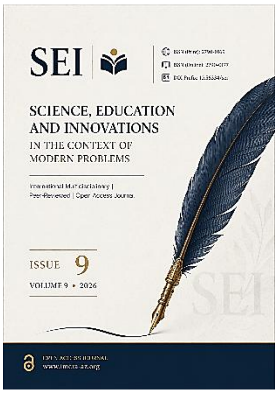

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REVIEW ARTICLE

Unlocking Industry 5.0: Addressing Challenges and Harnessing the Power of Digital Twin Technologies

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Abstract

A new era in industrial innovation, Industry 5.0 places a strong emphasis on human-technology cooperation to create systems that are resilient, sustainable and effective. Digital Twin (DT) technology is essential to this shift because it generates dynamic, real-time digital copies of physical assets and processes, improves operational efficiency, permits predictive maintenance, and offers useful information for well-informed decision-making. The dual facets of DT applications in Industry 5.0 overcoming obstacles and optimizing potential are examined in this paper. The adoption of DT technology is hampered by a number of obstacles, such as high implementation costs, cybersecurity risks, data interoperability problems and a lack of qualified personnel, despite its revolutionary potential. Through a thorough examination of empirical data and industry case studies, this study pinpoints these obstacles. It looks at doable answers like creating affordable technology, encouraging cooperation across industries and improving data security procedures. The study, however, emphasizes DT's unrealized potential in promoting human-centric automation, facilitating resource optimization and propelling Industry 5.0 sustainability initiatives. Industrial processes can achieve previously unheard-of levels of innovation, adaptability and resilience by utilizing advanced analytics, artificial intelligence, and the Internet of Things (IoT). The results of this study highlight the need for workforce upskilling, regulatory frameworks, and strategic investments to fully reap the benefits of DT technology. Policymakers, business executives, and researchers seeking to leverage DT's potential in meeting Industry 5.0 objectives will find this paper to be a valuable resource.

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1. INTRODUCTION

The emergence of Industry 5.0 represents a transformative evolution in industrial development, moving beyond the automation-centered paradigm of Industry 4.0 toward a more human-centric, sustainable, and resilient industrial ecosystem. While Industry 4.0 primarily emphasized the integration of cyber-physical systems, the Internet of Things (IoT), big data analytics, and advanced automation technologies, Industry 5.0 repositions human creativity, expertise, and decision-making at the core of industrial value creation. This new industrial vision seeks to establish a balanced collaboration between humans and intelligent technologies, enabling organizations to achieve higher levels of productivity while simultaneously addressing social well-being, environmental sustainability, and long-term resilience.

The growing complexity of global markets, increasing environmental concerns, and the demand for adaptive manufacturing systems have accelerated the need for technologies capable of supporting the objectives of Industry 5.0. In this context, Digital Twin (DT) technology has emerged as one of the most promising technological enablers of the next industrial revolution. A Digital Twin is a dynamic virtual representation of a physical asset, process, system, or environment that continuously exchanges data with its real-world counterpart throughout its lifecycle. By integrating real-time data, advanced analytics, artificial intelligence (AI), cloud computing, and IoT infrastructures, Digital Twins provide organizations with unprecedented visibility into operational processes and facilitate data-driven decision-making.

The strategic importance of Digital Twin technology extends across a wide range of industrial sectors, including manufacturing, healthcare, transportation, energy management, logistics, and smart cities. Through real-time monitoring, predictive maintenance, process simulation, and performance optimization, DT systems enable organizations to improve operational efficiency, reduce costs, minimize downtime, and enhance product quality. Furthermore, the ability of Digital Twins to simulate complex operational scenarios allows decision-makers to evaluate potential outcomes before implementing changes, thereby reducing uncertainty and improving organizational agility.

Despite these significant advantages, the widespread adoption of Digital Twin technology remains constrained by several technological, organizational, and economic challenges. High implementation costs, interoperability issues, cybersecurity vulnerabilities, data governance concerns, and shortages of skilled professionals continue to hinder effective deployment across many industries. Moreover, as Industry 5.0 increasingly emphasizes human-centric innovation, organizations must address not only technological integration but also workforce development, ethical considerations, and regulatory requirements associated with advanced digital systems.

Given the growing importance of Digital Twin technologies in shaping future industrial ecosystems, a comprehensive understanding of both their opportunities and limitations has become increasingly necessary. Therefore, this study aims to examine the role of Digital Twin technology in supporting the transition toward Industry 5.0 by identifying key adoption challenges, exploring major application areas, and highlighting the technological, organizational, and societal benefits associated with DT implementation. By synthesizing current academic and industrial knowledge, the study contributes to a deeper understanding of how Digital Twin technologies can facilitate sustainable, resilient, and human-centered industrial transformation in the era of Industry 5.0.

2. LITERATURE REVIEW

The purpose of this review is to examine the barriers to implementing Digital Twin applications and the opportunities they present for Industry 5.0 development.

Evolution and Core Principles of Digital Twin Technology

Since its initial applications in aerospace, DT technology has grown to become a vital instrument in numerous industries. According to Grieves (2014), who first introduced the concept, it is a virtual representation of a physical entity that exchanges data with its real-world counterpart. The three primary components of the technology are its digital and physical components and the data communication system that links them. Together, these components enable real-time monitoring, predictive analytics and system optimization (Fuller et al., 2021). In recent years, DT's applications have expanded due to the integration of AI, ML, and IoT, making it a crucial part of Industry 5.0 (Tao et al., 2019).

Contributions to Industry 5.0

Industry 5.0 signifies a shift away from automation-focused procedures and toward systems that put sustainability and human-machine cooperation first. Romero et al. (2020) demonstrate how DTs support this shift by promoting human-centric innovation: DT systems can simulate real-world scenarios, enabling human operators to make well-informed decisions while preserving system efficiency; DTs allow for mass customization in manufacturing, enabling production to be in line with individual customer needs without compromising efficiency and DT technology in conjunction with collaborative robotics enhances human-machine interaction, thereby increasing industrial safety and productivity.

Barriers to Adoption

Despite its benefits, a number of barriers keep digital twins from being widely adopted. High implementation costs remain a significant barrier, especially for small and medium-sized enterprises (SMEs) (Kritzinger et al., 2018). The initial costs are often greater than the perceived benefits of modern sensors, computing infrastructure and trained personnel. Furthermore, issues with data interoperability impede the seamless integration of DT systems with modern technologies. Businesses find it difficult to fully utilize technology due to inefficiencies brought on by non-standardized data transmission protocols, according to Tao et al. (2019). Cybersecurity issues also pose a significant risk since systems are becoming more interconnected, which leaves them vulnerable to possible intrusions.

Advancing Sustainability and Resource Optimization

DT is crucial to accomplishing sustainability goals in Industry 5.0. By providing real-time monitoring and predictive analytics, DT systems can minimize waste and optimize resource utilization. Fuller et al. (2021) found that DTs can reduce manufacturing energy use by identifying inefficiencies in real-time. In a similar vein, DTs assist the energy sector in integrating renewable energy sources by forecasting changes in energy demand and modeling grid performance. These apps help global efforts to reduce carbon emissions and achieve sustainable development goals. Additionally, because DT systems can simulate environmental effects, businesses can adopt greener practices without compromising efficiency.

Need for Workforce Upskilling and Collaboration

Personnel with the requisite abilities to manage intricate systems and understand data insights are required for the successful adoption of DT technology. But there is a significant skills gap, particularly in areas like AI, IoT and advanced analytics. Workforce training and upskilling are crucial to closing this gap. Industry and academia working together can significantly help address this challenge. Collaborations across industries are also required to foster innovation and offer standardized frameworks. Kritzinger et al. (2018) state that by reducing costs and promoting information sharing, these collaborations can speed up the adoption of DT technology.

3. METHODOLOGY

This study employs a qualitative review-based research design to examine the role of Digital Twin (DT) technology in facilitating the transition toward Industry 5.0. The research is based on a comprehensive analysis of existing scholarly literature, industry reports, and conceptual studies addressing the opportunities, challenges, and future prospects of Digital Twin applications in industrial environments.

A narrative literature review approach was adopted to synthesize current knowledge regarding the integration of DT technologies with Industry 5.0 principles, including human-centricity, sustainability, resilience, and intelligent decision-making. Relevant literature was identified through searches conducted in major academic databases, including Scopus, Web of Science, Google Scholar, IEEE Xplore, ScienceDirect, SpringerLink, and Taylor & Francis Online. The search process utilized combinations of keywords such as “Digital Twin”, “Industry 5.0”, “Human-Centric Manufacturing”, “Artificial Intelligence”, “Internet of Things”, “Smart Manufacturing”, “Sustainability”, and “Industrial Metaverse”.

The inclusion criteria focused on peer-reviewed journal articles, conference proceedings, book chapters, and authoritative industry reports published primarily between 2019 and 2025. Earlier foundational studies were also included where necessary to explain the evolution and theoretical foundations of Digital Twin technology. Sources lacking academic credibility or sufficient methodological transparency were excluded from the analysis.

The collected literature was examined using thematic content analysis. The identified studies were systematically categorized into four major themes: (1) technological and organizational barriers to Digital Twin adoption, (2) operational and strategic applications of Digital Twin technologies, (3) industrial and societal benefits associated with Digital Twin integration, and (4) future opportunities and challenges in the context of Industry 5.0. Comparative synthesis techniques were employed to identify recurring patterns, emerging trends, and research gaps across the reviewed literature.

The methodological approach enables a comprehensive conceptual understanding of how Digital Twin technologies contribute to Industry 5.0 objectives while highlighting the challenges that must be addressed to facilitate broader industrial adoption. The study does not involve primary data collection; therefore, no ethical approval or human subject participation was required.

4. Barriers to Digital Twin Adoption in Industry 5.0

- **Technological Barrier**

Infrastructure scalability, data management and system integration are the three main issues that must be addressed in Industry 5.0 to overcome technological barriers to the adoption of DT. One of the biggest challenges is integrating DT technologies with legacy systems because many industries still use outdated hardware and software that are incompatible with modern IoT devices and cloud platforms. To overcome this, organizations need to invest in middleware solutions or update their infrastructure to guarantee seamless communication and interoperability (Tao et al., 2019).

- **Organisational Barriers**

Organizational resistance to change, a lack of skilled workers and a lack of leadership support are common obstacles to the adoption of DT in Industry 5.0. Many businesses, especially those in traditional industries, face cultural resistance when implementing innovative technologies like digital twins. Employees' mistrust of automated technologies or fear of losing their jobs could hinder the adoption process (Santos et al., 2020). Overcoming this challenge requires retraining programs that allow employees to work together with these cutting-edge technologies and clear communication about the benefits of DT.

- **Financial Constraints**

Financial constraints are one of the main barriers to the widespread adoption of DT technologies in Industry 5.0. The initial setup costs for DT systems, which include hardware, software and infrastructure can be prohibitive for small and medium-sized businesses (SMEs) that do not have the necessary funds (Brettel et al., 2014). The need for a large investment in modernizing or replacing outdated equipment to integrate DT technologies with existing legacy infrastructure adds to the financial burden. Continuous operating and maintenance costs like cloud services, data storage and cybersecurity measures can also put a strain on an organization's budget (Tao et al., 2019).

5. Making the Most of Industry 5.0's Digital Twin Applications

a) To enhance the operational efficiency

To maximize the potential of DT applications in Industry 5.0 and increase operational efficiency, organizations need to focus on automation, real-time analytics and streamlining data flow. By adding IoT sensors and advanced data analytics to the DT ecosystem, businesses can monitor performance in real time, identify inefficiencies and make data-driven decisions that improve processes (Tao et al., 2019). By using AI and machine learning algorithms, digital twins can predict maintenance needs, enhance production schedules and even simulate various scenarios to identify the most efficient operating pathways (Santos et al., 2020).

b) To maximize the potential of sustainability in Industry 5.0

By encouraging resource efficiency, environmentally conscious behavior, and long-term financial gains, sustainability is crucial in Industry 5.0 for maximizing the potential of DT applications. It assists businesses in reducing resource waste and their carbon footprint by facilitating real-time monitoring and optimization of material consumption, waste management and energy usage (Tao et al., 2019). By simulating various production scenarios, businesses can discover more sustainable practices like reducing emissions or using less energy, without compromising quality or performance (Santos et al., 2020).

c) To humanise the digital Twin: Industry 5.0

Human-centric applications in Industry 5.0 significantly increase the potential of DT technologies by fostering a collaborative environment where humans and machines work together to optimize performance and creativity. Unlike earlier industrial revolutions, where automation often replaced human labor, Industry 5.0 places a strong emphasis on human intellect, creativity, and decision-making in addition to cutting-edge technology like DT. By integrating human input into the DT models, organizations can make better decisions that balance efficiency with human values like safety, well-being and ethical issues (Santos et al., 2020). Businesses can alter their workspaces and processes to lessen accidents and physical strain by, for example, modeling worker ergonomics and safety scenarios using digital twins.

d) **To optimizes the supply chain management**

Supply chain optimization in Industry 5.0 makes full use of the potential of DT technologies by enabling end-to-end visibility, real-time decision-making and predictive insights that increase efficiency and reduce costs. By allowing companies to create a virtual model of their entire supply chain, including suppliers, production processes, logistics and inventory control, digital twins provide a comprehensive view of their operations (Tao et al., 2019). By adding real-time data to these models, businesses can monitor inventory levels, track product flow, and anticipate disruptions like delays, supply shortages or logistical bottlenecks. This gives them the ability to make proactive changes (Santos et al., 2020). Predictive analytics, aided by digital twins, further enhances supply chain efficiency by forecasting shifts in demand, optimizing manufacturing schedules and reducing excess inventory.

e) Future potential of digital twin technology

For Industry 5.0, digital twin technology holds great promise for advancing supply chain optimization, sustainability, human-centered design and operational efficiency. As Digital Twin technologies advance, they will leverage AI and real-time data to facilitate more accurate simulations, predictive maintenance and resource optimization, all of which will reduce costs and enhance automation. DT will be essential to sustainability's attempts to reduce its adverse environmental effects by optimizing energy use, controlling waste and advancing the ideas of the circular economy.

6. Assessment of Societal and Industrial Benefits of Integrating Digital Twin Technology

The integration of DT technology into industrial systems provides substantial social and industrial benefits by enhancing innovation, efficiency, sustainability and resilience. These advantages align with the broader goals of Industry 5.0 and have the potential to transform a variety of sectors, such as manufacturing and healthcare.

- **Industrial Benefits**

Operational Efficiency: Digital twins offer real-time monitoring, predictive maintenance and process optimization in industries like manufacturing and energy, which reduce downtime and increase output (Tao et al., 2019). Sustainability: The technology encourages sustainable practices and reduces its adverse environmental effects by optimizing resource utilization, reducing waste and improving energy efficiency (Tao et al., 2019). Innovation and Quality: By facilitating quicker prototyping, digital twins enhance product design and quality while accelerating time-to-market (Zhang et al., 2020). Supply Chain Optimization: By providing real-time data and simulation capabilities, digital twins reduce lead times, enhance logistics and boost supply chain resilience (Brettel et al., 2014).

- **Benefits to Society**

Employment Creation: By creating new jobs in data science, artificial intelligence, and system integration, the use of digital twins advances a knowledge-based economy (Santos et al., 2020). Healthcare and Public Services: By improving patient care, streamlining hospital operations, and improving city planning, digital twins improve infrastructure and public health (Brettel et al., 2014). Environmental Impact: By optimizing resource usage and industrial processes, digital twins help reduce carbon footprints and promote sustainable practices across industries (Zhang et al., 2020). Safety: By providing real-time hazard monitoring and predictive risk management, it enhances workplace safety and reduces accident rates in high-risk industries (Santos et al., 2020).

Table 1. Major Barriers to Digital Twin Adoption in Industry 5.0

Barrier Category	Key Challenges	Implications for Organizations	Representative Sources
Technological Barriers	Legacy system incompatibility, infrastructure scalability issues, data integration complexity	Reduced interoperability, implementation delays, increased technical risks	Tao et al. (2019)
Organizational Barriers	Resistance to change, lack of skilled personnel, limited leadership commitment	Slow adoption, employee dissatisfaction, lower innovation capacity	Santos et al. (2020)
Financial Barriers	High implementation costs, infrastructure modernization expenses, ongoing maintenance requirements	Limited accessibility for SMEs, delayed digital transformation initiatives	Brettel et al. (2014); Tao et al. (2019)
Human Capital Barriers	Shortage of AI, IoT, and analytics expertise	Reduced operational effectiveness and inability to exploit DT capabilities	Kritzinger et al. (2018)
Cybersecurity and Data Risks	Vulnerability to cyberattacks, privacy concerns, cloud-related risks	Operational disruptions, loss of trust, regulatory challenges	Santos et al. (2020)

Table 2. Strategic Applications of Digital Twin Technology in Industry 5.0

Application Area	Core Functions	Expected Outcomes
Operational Efficiency	Real-time monitoring, predictive maintenance, process simulation	Reduced downtime, improved productivity, optimized resource allocation

Sustainability Management	Energy optimization, waste reduction, environmental impact simulation	Lower carbon footprint, enhanced sustainability performance
Human-Centric Manufacturing	Ergonomic assessment, workplace safety modeling, collaborative decision-making	Improved employee well-being, safer working environments
Supply Chain Optimization	End-to-end visibility, demand forecasting, inventory management	Greater resilience, reduced logistics costs, improved responsiveness
Smart Decision Support	AI-driven analytics, scenario simulation, risk prediction	Faster and more accurate strategic decision-making
Product and Process Innovation	Virtual prototyping and testing	Accelerated innovation cycles and reduced development costs

Table 3. Industrial and Societal Benefits of Digital Twin Integration

Dimension	Benefits	Long-Term Impact
Industrial Performance	Predictive maintenance, process optimization, quality improvement	Enhanced competitiveness and operational excellence
Supply Chain Resilience	Real-time monitoring and disruption forecasting	More robust and adaptive supply networks
Sustainability	Efficient resource utilization, reduced waste, energy optimization	Contribution to Sustainable Development Goals (SDGs)
Innovation Capacity	Faster product development and digital transformation	Increased technological leadership
Employment and Skills Development	Creation of new roles in AI, IoT, analytics, and DT management	Development of a knowledge-based economy
Healthcare and Public Services	Improved patient care, hospital optimization, smart city planning	Better quality of life and public service delivery
Occupational Safety	Hazard prediction, risk monitoring, accident prevention	Safer workplaces and lower operational risks
Environmental Protection	Reduction of emissions and resource consumption	Greater environmental sustainability

7. Challenges and Limitations of Digital Twin Technology

Although DT technology has the potential to completely transform a number of industries, a number of barriers and limitations prevent it from becoming widely used. One of the biggest challenges is the high cost of implementation, which includes expenses for sensors, data infrastructure, hardware, software and trained staff. These costs may limit access to DT technology, making it unaffordable, particularly for SMEs. Another major barrier is "data interoperability issues." Because different industries rely on different systems and data formats, a lack of defined protocols for integrating data streams often results in inefficiencies, decreased system compatibility and increased implementation complexity.

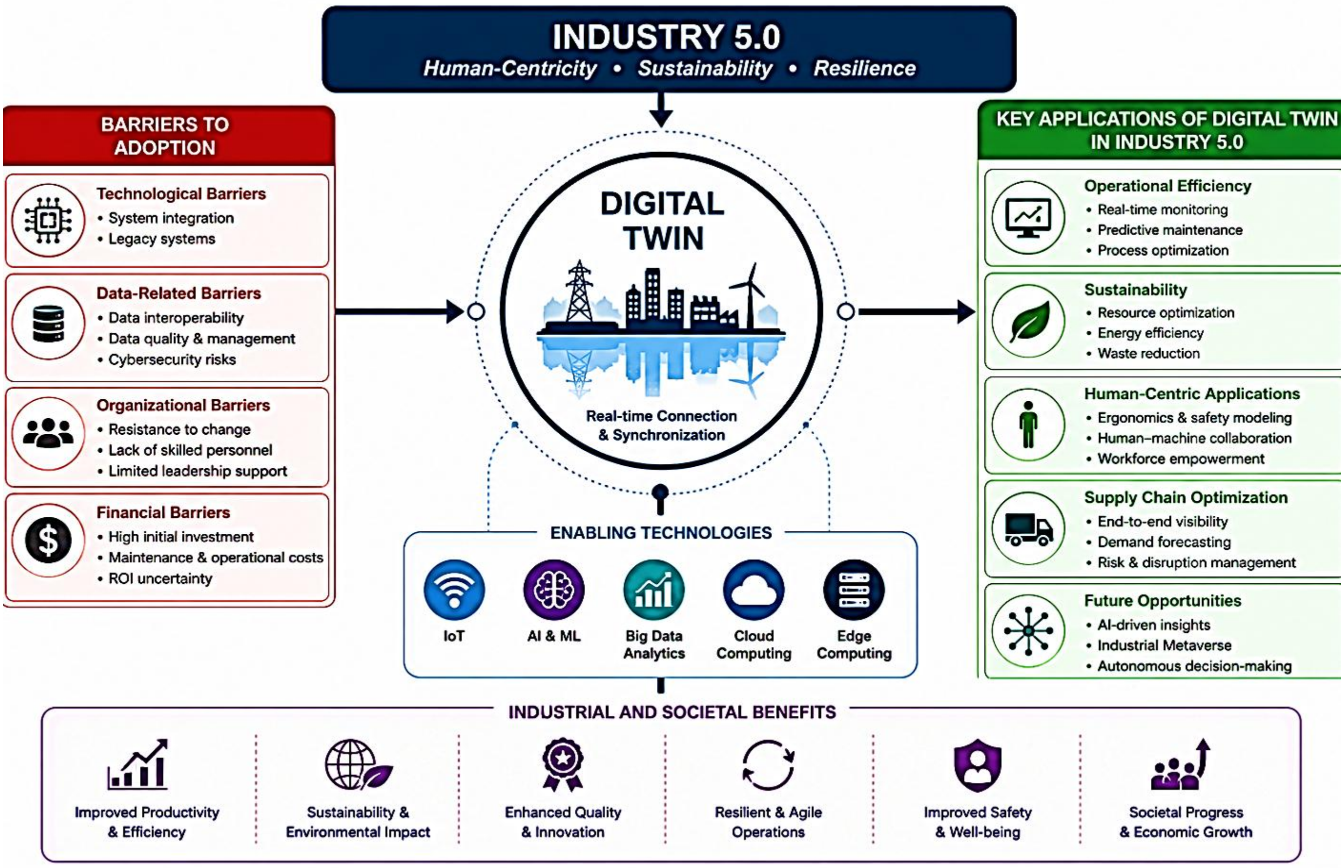
Cybersecurity risks are yet another significant barrier. DT is vulnerable to cyberattacks because of its heavy reliance on cloud computing, the IoT, and data sharing between digital and physical systems. These risks could jeopardize information in the private sector and disrupt essential operations. Another major obstacle is the lack of skilled workers with knowledge of advanced analytics, IoT and AI, particularly in areas with little access to advanced technical training. Without a skilled workforce, industries struggle to effectively implement and manage DT systems.

Another disadvantage of DT technology is its scalability. When scaling DT systems from single-use apps to enterprise-wide usage, which requires a large investment and resources, organizations usually find it difficult to achieve consistent performance across all systems. Lastly, there are ethical and environmental issues with the massive amounts of data collection and energy used to run DT systems. Reducing the carbon footprint of computational infrastructure and safeguarding data privacy are two important areas that still need work. Legislators, corporate leaders and researchers must collaborate to develop cost-effective solutions, enhance cybersecurity, standardize data standards and finance workforce development to get past these challenges.

8. KEY FINDINGS FROM THE LITERATURE

The literature reviewed in this study highlights the growing strategic importance of Digital Twin (DT) technologies in supporting the transition from Industry 4.0 to Industry 5.0. While Industry 4.0 primarily focused on automation, connectivity, and data-driven manufacturing, Industry 5.0 introduces a broader vision centered on human-centricity, sustainability, resilience, and collaborative intelligence. The findings indicate that Digital Twin technology serves as a critical enabler of these objectives by facilitating real-time monitoring, predictive analytics, intelligent decision-making, and enhanced interaction between physical and virtual environments.

Figure 1. Conceptual Framework of Digital Twin Integration in Industry 5.0: Barriers, Applications, and Societal Benefits



Source: Developed by the authors based on Tao et al. (2019), Santos et al. (2020), Attaran and Celik (2023), Barata and Kayser (2024), Leirmo (2024), and the synthesized findings of the present study.

One of the most significant findings concerns the diverse applications of Digital Twins across industrial sectors. The reviewed studies demonstrate that DT technologies are increasingly used for predictive maintenance, production optimization, quality control, supply chain management, energy efficiency, and product lifecycle management. These applications contribute to improved operational performance, reduced downtime, lower maintenance costs, and enhanced organizational agility. Furthermore, Digital Twins provide organizations with simulation capabilities that allow potential risks and operational scenarios to be evaluated before implementation, thereby supporting more informed strategic decisions.

The literature also reveals that Digital Twins play an important role in advancing the human-centric principles of Industry 5.0. Unlike previous industrial paradigms that prioritized automation and machine efficiency, Industry 5.0 emphasizes collaboration between humans and intelligent systems. Digital Twins enable the development of safer workplaces, support ergonomic assessments, facilitate worker training through virtual environments, and enhance decision-making processes by providing real-time insights. As a result, DT technologies contribute not only to productivity improvements but also to employee well-being and organizational sustainability.

Another major finding relates to the contribution of Digital Twins to environmental sustainability. Numerous studies indicate that DT-enabled systems support resource optimization, waste reduction, energy management, and carbon footprint minimization. By continuously monitoring operational processes and identifying inefficiencies, organizations can improve environmental performance while maintaining competitiveness. These capabilities align closely with global sustainability objectives and the broader goals of Industry 5.0.

Despite these benefits, the reviewed literature identifies several challenges that continue to hinder large-scale adoption. The most frequently reported barriers include high implementation costs, integration difficulties with legacy systems, cybersecurity vulnerabilities, data governance concerns, and shortages of specialized expertise. Small and medium-sized enterprises (SMEs) are particularly affected by financial and technical constraints that limit their ability to implement advanced Digital Twin infrastructures. Furthermore, organizational resistance to change and insufficient strategic planning remain significant obstacles in many industrial contexts.

The literature further suggests that the future development of Digital Twin technologies will be strongly influenced by advances in Artificial Intelligence (AI), the Internet of Things (IoT), Big Data Analytics, cloud computing, and the emerging Industrial Metaverse. The integration of these technologies is expected to increase the accuracy, scalability, and intelligence of Digital Twin systems, enabling more adaptive and resilient industrial ecosystems.

Overall, the reviewed studies consistently indicate that Digital Twin technology represents one of the most important technological foundations of Industry 5.0. Its ability to integrate technological efficiency with human-centered values, sustainability objectives, and organizational resilience positions Digital Twins as a transformative tool for the future of smart manufacturing and digital industrial ecosystems.

9. CONCLUSION

The findings demonstrate how DT technology supports environmental sustainability by enabling resource efficiency and promoting the use of renewable energy sources, thus adding societal benefits to the research. It encourages human-centric innovation through mass customization, improved workplace safety and improved human-machine collaboration. The report also emphasizes the value of DT in addressing societal issues like healthcare efficiency, urban planning and infrastructure development, all of which collectively improve quality of life and ensure equitable access to technological advancements. By bridging the gap between technology and human values, which DT supports, Industry 5.0's objectives are to create more inclusive and sustainable industrial systems.

In conclusion, DT technology is essential to the development of Industry 5.0 and provides a host of industrial and societal benefits. To overcome adoption barriers and fully utilize this technology, industries must prioritize cybersecurity, form partnerships, and invest in workforce development. Therefore, DT technology promotes sustainable development, economic inclusion, and an enhanced standard of living while also acting as a catalyst for societal advancement and an instrument for operational efficiency. By combining advancements in technology with human-centered values, DT technology can help create a more sustainable and peaceful future.

10. DECLARATIONS

Author Contributions

Vanshika Thakur: Conceptualization, literature review, methodology development, data interpretation, writing of the original draft, and manuscript preparation.

Snigdha Chowdhari: Literature review, thematic analysis, data collection from secondary sources, visualization, and manuscript editing.

Dr. Gosala Raju: Supervision, conceptual guidance, critical review, validation of findings, and final approval of the manuscript.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical Approval

This study is based exclusively on published literature, secondary data sources, and publicly available documents. It did not involve human participants, animals, personal data collection, or experimental procedures. Therefore, ethical approval was not required.

Data Availability Statement

All data supporting the findings of this study are derived from publicly available academic publications, industry reports, and secondary sources cited within the article. No primary dataset was generated during the course of this research.

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