Materials Circular Economy (2025) 7:20
https://doi.org/10.1007/s42824-025-00176-7

REVIEW

Transitioning from Industry 4.0 to Industry 5.0 for Sustainable and Additive Manufacturing of Clothing: Framework, Case Studies, Recent Advances, and Future Prospects

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Received: 28 February 2025 / Revised: 24 March 2025 / Accepted: 26 April 2025

Abstract
Industry 5.0 aspires to enhance human–machine collaboration in the clothing industry by integrating human intelligence with advanced technologies. This review discusses the transition from Industry 4.0, which focused on automation and ethical supply chain management, to Industry 5.0, which emphasizes robotics, the Internet of Things (IoT), and Artificial Intelligence (AI) to enable customized manufacturing, sustainability, and improved worker roles. It also aims to provide a comprehensive overview of Industry 5.0's impact on additive manufacturing in the clothing sector. It figures out the framework of this transition, explores emerging opportunities, and identifies key challenges that can arise. It summarizes the significant opportunities of Industry 5.0 in promoting innovation and productivity within the clothing industry. Observations from successful case studies indicate that clothing bands that embrace Industry 5.0 in additive manufacturing are enjoying the ultimate benefits. Key benefits include mass customization, intelligent resource management for reduced environmental impact, and the production of high-value employments. However, major challenges persist, including the requirements of substantial technological investments, concerns over job displacement, and data security risks. Addressing these challenges requires strategic framework, strong technological integration, and workforce reskilling programs.

Keywords Artificial intelligence (AI) · Internet of Things (IoT) · Industry 5.0 · Sustainable manufacturing · Industry 4.0 · Circular economy · Additive manufacturing · Supply chain management · Textile recycling · Circular fashion

Introduction

The progression of industries across different stages of technological growth has been a defining feature of human civilization. Every stage of the industrial revolution from the first, which was categorized by mechanization and steam power, to the present, which is defined by automation, ethical supply chain management, and AI has altered lifestyles, economies, and communities (Groumpos 2021; S. Kumar et al. 2024a, b). However, the industry is once again set for a significant approach to Industry 5.0, a new age in the industry's history (Ghobakhloo et al. 2023; Nahavandi 2019a). In this regard, the textile and apparel industry, a vital part of international trade and manufacturing, finds itself at a critical crossroads, navigating the transition to Industry 5.0 while facing opportunities as well as challenges (Rahaman et al. 2021; Yang and Gu 2021). Industry 5.0 represents a significant evolution beyond Industry 4.0. It alters the focus from automation and smart manufacturing to human-centric, sustainable, and resilient production systems (Golovianko et al. 2023). It integrates advanced digital technologies with human expertise to enhance sustainability, efficiency, and personalization. Unlike Industry 4.0, which primarily emphasizes automation, robotics, and AI, Industry 5.0 reintroduces human creativity and problem-solving alongside smart systems to create a more balanced, adaptive, and eco-conscious manufacturing ecosystem (Mourtzis et al. 2022; Zizic et al. 2022). In the context of additive manufacturing for clothing, this transition allows for highly customized, on-demand apparel production with minimal waste, addressing sustainability concerns in textile and apparel manufacturing

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Published online: 20 May 2025

(S. Rani et al. 2024). The incorporation of Industry 5.0 technologies enables real-time adaptability in production, where AI-driven design systems work alongside human creativity to develop unique and functional apparels (Donmezer et al. 2023a). Robotics and collaborative robots (Cobots) assist in complex manufacturing processes, ensuring precision while reducing labor-intensive tasks (Addula and Tyagi 2024). Additionally, smart materials and fabrication techniques are being integrated into clothing production, enhancing durability, comfort, and environmental sustainability. Manual skill of weaving and spinning is the foundation of the centuries long history of the clothing industry. Technology has transformed textile manufacturing, creating the way for process mechanization during the 1st Industrial Revolution (Allen 2011). The modern clothing industry is shaped by other developments brought about by later stages of industrialization, including the introduction of synthetic fibers, mass manufacturing methods, and work automation (Sikka et al. 2024). Yet Industry 4.0 also brought with it previously unheard levels of automation and connection, bringing with it the era of digital supply chains, smart industries, and data-driven decision-making (Bertola and Teunissen 2018; Raja Santhi and Muthuswamy 2023a). Textile manufacturers are now able to increase operating efficiency, improve product quality, and streamline manufacturing processes because of these breakthroughs (Sandvik and Stubbs 2019). However, it has also brought with it a new set of challenges for the clothing industry, such as worries about automation taking jobs, cybersecurity threats from linked systems, and upskilling workers to keep up with quickly changing technologies.

The clothing industry is positioned for yet another paradigm transition as the world moves toward Industry 5.0, which is defined by the fusion of human-centric approaches with modern technology like AI, robotics, and the IoT (Akundi et al. 2022; X. Xu et al. 2021a). Unlike earlier industrial revolutions, which frequently emphasized replacing human labor with machinery, Industry 5.0 places a strong emphasis on collaborating with both human and robots to take use of their distinct strengths and increase production and innovation (Önday 2019). This transformation has enormous potential for the clothing industry, providing opportunities to enhance Supply Chain Management (SCM), advance sustainability standards, and improve product personalization (Kazancoglu et al. 2023, 2024a). By combining modern technology, smart textiles that can monitor health parameters, adapt to their surroundings, and improve user comfort can be ensured (Rahaman et al. 2025a, b; Ramasubramanian et al. 2022; Selvasudha et al. 2021). Additionally, the concepts of Industry 5.0 have the potential to expedite the creation of flexible manufacturing procedures, thereby enabling textile manufacturers to promptly adapt to evolving consumer tastes and market demands (Aslam et al. 2020; Saniuk and Grabowska 2023). As the clothing industry adopts Industry 5.0, it can also have to overcome a number of challenges. The biggest of these is having to get rid of outdated systems and infrastructure that can make it harder for new technologies to be adopted. Many textile manufacturers work in settings with antiquated equipment, compartmentalized data systems, and low employee digital literacy (Irfan and Salam 2020). In order to meet these challenges, large sums of capital can need to be spent on technology upgrades, and extensive training programs can be necessary to provide the workforce with the skills needed to succeed in its setting (Acemoglu and Autor 2011; Kukulska-Hulme 2012). In addition, as modern technologies become more widely used, the clothing industry can have to deal with moral and social ramifications (Niinimäki and Hassi 2011). To ensure that the advantages of Industry 5.0 are fairly spread throughout society, concerns about algorithmic bias, data privacy, and the impact of automation on employment can be properly explored and addressed (Martini et al. 2024).

According to existing literature gap, there is still a lack of comprehensive reviews regarding the convenience of incorporating modern technologies like AI, the IoT, and robotics into the clothing sector for Industry 5.0, particularly in relation to sustainable additive manufacturing practices (S. Ahmed et al. 2025b, a; Flores-Siguenza et al. 2022; Maddikunta et al. 2022; Ahmed and Maccarthy 2021; Reino-Cherrez et al. 2023; Safavi Jahromi and Ghazinoory 2025). While the adoption of Industry 4.0 technologies in the clothing industry is growing, there is a lack of detailed case studies on the practical implementation of Industry 5.0. There is still a gap in developing a systematic framework that guides the transition from Industry 4.0 to Industry 5.0, specifically for sustainable and additive manufacturing in the clothing industry, integrating human-centric approaches with digital technologies.

This review paper will explore the transition from Industry 4.0 to Industry 5.0 in the context of sustainable and additive manufacturing of clothing. It will discuss the impact of industrial revolutions on additive manufacturing, emphasizing the transition towards human-centric and sustainable practices in Industry 5.0. It will highlight key technologies for implementing Industry 5.0, such as AI, automation, and robotics, and compare the limitations of Industry 4.0 with the advancements provided by Industry 5.0. Case studies are presented to showcase successful implementations, and recent advances in the clothing industry are discussed. This review will conclude by addressing challenges and proposing future prospects for Industry 5.0's role in textile and apparel manufacturing.

Methodology

For this study, the authors employed a structured and systematic approach to identify, evaluate, and synthesize relevant literature. The primary focus was on Industry 4.0, Industry 5.0 and its transition in the context of sustainable and additive manufacturing of clothing. The steps undertaken to conduct this review are described in the following sub-sections.

Database Selection and Keyword Strategy

An extensive search was conducted using Google Scholar and major academic databases, including Scopus, Web of Science, IEEE Xplore, Science Direct, and Springer Link to ensure a comprehensive collection of relevant literature. A combination of the following keywords and phrases was used:

- Transitioning from Industry 4.0 to Industry 5.0
- Sustainability in clothing manufacturing
- Advancing from linear economy to circular economy
- Blockchain in supply chain management
- Circular additive manufacturing
- Circular business models for clothing
- Textile circularity
- Textile recycling
- Waste management of textiles in a circular economy
- Life cycle assessment of textiles in a circular economy
- Circular fashion
- Human-centric and resilient manufacturing frameworks
- Biomaterials for textiles and apparel
- Textile supply chain management
- Nanotechnology in functional textiles
- Automation in apparel manufacturing
- AI, IoT, and automation in textile industries
- Digital transformation in textiles and apparel
- Smart textiles in Industry 5.0
- Sustainable apparel merchandising
- Circular economy in textiles and apparel
- Eco-innovation in textiles and apparel
- Sustainable production and consumption of textiles

Publisher and Journal Selection

To ensure credibility and the inclusion of high-quality, peer-reviewed sources, the review focused on articles published by leading publishers such as Elsevier, Springer Nature, Wiley, Taylor & Francis, Sage Publishing, IEEE, the American Chemical Society (ACS), and MDPI. Priority was given to Scopus-indexed Q1 and Q2 journals along with relevant conference proceedings.

Eligibility Criteria

Research and review papers published within the last 25 years (2000–2024) were considered with preference given to recent publications demonstrating high impact and citation frequency. After rigorous screening, 465 articles were retained for detailed analysis. The selected papers were assessed based on the following inclusion and exclusion criteria.

Inclusion Criteria

The transition from Industry 4.0 to Industry 5.0 in textile and apparel manufacturing has gained significant attention with research focusing on sustainable and additive manufacturing technologies in apparel production. Studies explore the integration of human–robot collaboration, AI-driven manufacturing, and intelligent automation, which enhance efficiency, customization, and sustainability in clothing production. Additionally, case studies highlight successful applications of Industry 5.0 principles in clothing manufacturing, analyzing real-world implementations that bridge advanced technologies with human-centric approaches. In addition, researchers examined the environmental, economic, and social implications of Industry 5.0 in sustainable apparel production, emphasizing its role in resource efficiency, ethical labor practices, and circular economy models. This growing body of literature underscores the transformative potential of Industry 5.0 in shaping the future of the textile and apparel industry.

Exclusion Criteria

Studies that focus on general industrial automation without direct relevance to the textile and apparel industry are excluded. Additionally, articles containing outdated discussions that fail to align with Industry 5.0 principles are disregarded to ensure the inclusion of only the most relevant and up-to-date research. Papers that lack empirical data or case studies supporting the transition to sustainable and additive manufacturing are also excluded as those do not provide substantial evidence or practical insights into the evolving industry landscape. Duplicated studies from multiple sources are removed to maintain originality and avoid redundancy in the analysis. Exclusion criteria helped to refine the research focus and ensure a high-quality and credible review.

Critical Analysis and Synthesis

Each selected paper was systematically analyzed and summarized using categorization and comparative analysis to ensure a comprehensive review. The findings were organized into key themes to highlight different aspects of the transition from Industry 4.0 to Industry 5.0 in sustainable and additive manufacturing of clothing. Technological innovations such as AI, IoT, robotics, and digital twins were explored for their role in enhancing sustainable clothing production. The review also focused on sustainability and circular economy by assessing environmental impacts, green supply chains, and circular manufacturing models. Additionally, the integration of human expertise with intelligent systems in human-centric and smart manufacturing was analyzed for its potential to improve productivity and product customization. Industrial case studies provided real-world examples of Industry 5.0 implementations in apparel manufacturing that provide practical insights into successful strategies. In the final part, the review identified future challenges and opportunities including existing gaps, potential advancements, and the role of policy frameworks in shaping the industry. The systematic approach ensures that the review presents a comprehensive, evidence-based, and forward-looking perspective. It also provides valuable insights into the evolving landscape of sustainable and additive clothing manufacturing.

Industrial Revolutions in Additive Manufacturing of Clothing

The evolution of additive manufacturing in the clothing industry has been significantly influenced by the progression of industrial revolutions. Figure 1 shows the evolution of the clothing industry over time. From the mechanization of clothing production in the 1st Industrial Revolution to the incorporation of modern technology in Industry 5.0, the clothing industry has been crucial to the historical developments of industrial revolutions.

Industry 1.0

The industrialization of textile manufacturing in the late eighteenth century marked the start of the 1st industrial revolution in Britain. Small workshops or people's houses (the putting-out system) would use hand tools and primitive machines to make textiles before the Industrial Revolution (O'Brien et al. 2012). Manufacturing textiles moved to industries that used water-or steam powered machinery with the arrival of the Industrial Revolution 1.0 (Tomory 2016). The use of machinery like power looms and spinning frames substantially raised output per worker. The spinning of yarn was revolutionized by inventions like the spinning mule, water frame, and spinning jenny, which also increased output and efficiency (Hahn 2016). The power loom development industrialized the weaving process, speeding up the production of textiles and encouraging the construction of industries (Allen 2018).

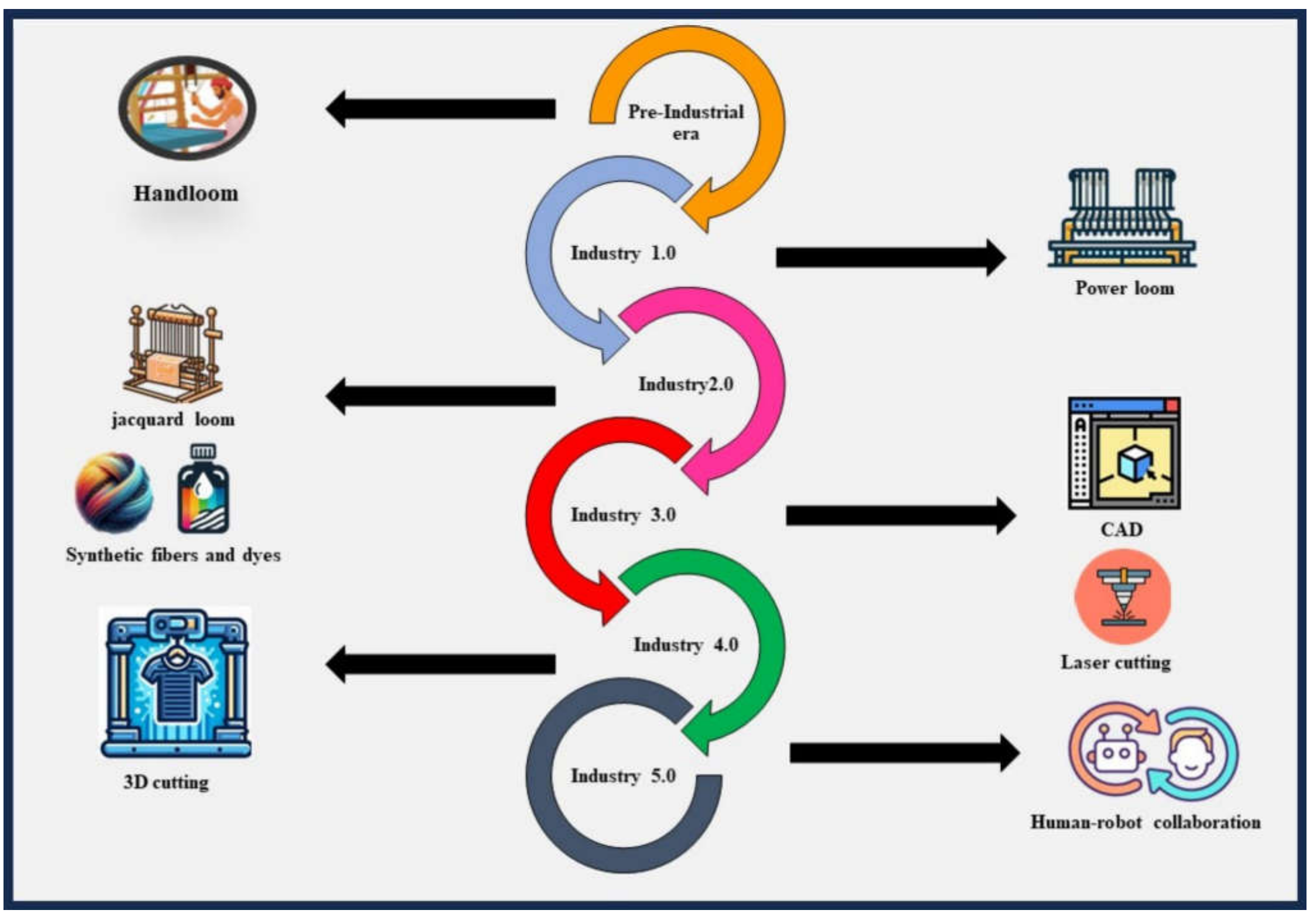

Fig. 1 Chronological developments of the clothing industry

Industry 2.0

Technological developments in the late nineteenth and early twentieth century had taken place in textile manufacturing (Rosenberg 1963). The clothing industry observed initial technological improvements during the 2nd industrial revolution (Mokyr 2001). The extensive use of electricity to power industries was a major breakthrough of the 2nd Industrial Revolution (Zou et al. 2016). Because electricity is more stable and easier to regulate than steam or water, it has largely supplanted older forms of power generation. Textile design and production were changed by innovations like the Jacquard loom, which employed punched cards to regulate the weaving of intricate patterns (Harlizius-Klück 2017). The clothing industry's capabilities were increased by the introduction of synthetic fibers, dyes and chemical processes, which made it possible to produce a greater variety of colors and fabrics (J. Chen 2015; Z. Feng and Rånby 1992; Rahaman et al. 2024a, b).

Industry 3.0

Automation and digitization were brought to the clothing industry during the 3rd industrial revolution. The manufacture of textiles is now more precise and efficient because of the replacement of traditional mechanical methods with computerized looms and knitting machines (Ahmed et al. 2022; Maiti et al. 2022). With the ability to quickly prototype and customize designs, CAD and CAM technology transformed the textile design and pattern-making industries (Sinha 2020). The textile industry has been utterly transformed by the introduction of advanced manufacturing technology including computer-controlled knitting machines, and laser cutting (Si et al. 2022). With the help of these technologies, manufacturing processes can be more precise and flexible, enabling the production of intricate and personalized textile items with reduced waste.

Industry 4.0

Industry 4.0, often known as the fourth industrial revolution, introduced digital technologies and networking to the clothing industry (Burns et al. 2019; Muhuri et al. 2019). The emergence of e-textiles with embedded electronics and sensors allowed for the implementation of features like biometric monitoring, moisture management, and temperature control (L. Da Xu et al. 2018). The manufacturing of textiles was revolutionized by advanced manufacturing processes like 3D printing and additive manufacturing, which made it possible to create intricate structures and forms with little waste (Ahmad et al. 2020; X. Xu et al. 2021a).

Industry 5.0

A new transition in manufacturing is emerging with the advent of "Industry 5.0" which emphasizes the easier combination of human skills and advanced technology (Grabowska et al. 2022). Figure 2 shows the various stages of industrial revolutions in textiles and apparel. Industry 5.0 prioritizes sustainability, resilience, and customization, highlights the collaboration between human creativity and advanced technology. When it comes to additive manufacturing of clothing, Industry 5.0 encourages a transition from mass production to mass customization, allowing items to be produced with little waste. This transformation facilitates localized, on-demand manufacturing, encourages effective resource usage, and lowers overproduction, all of which are in acceptable harmony with sustainability goals. It is seen as a return to fashion design and customization in the apparels and textile industries. Robots and automation help to make certain tasks easier, but human artisans are still needed to make unique, personalized clothing with elaborate patterns that reflect each person's taste (Pinto et al. 2024; Safavi Jahromi and Ghazinoory 2024). In addition to encouraging sustainable acceptable clothing items and decreasing waste through efficient production methods, it promotes sustainable behaviors (Alojaiman 2023; Rahaman and Khan 2024a, b; Zayedul Hasan et al. 2021. In general, the use of Industry 5.0 in the textile and apparel production promotes a revolutionary step towards fashion that is inventive, sustainable and focused on the needs of people. Through modular designs and easier disassembly, additive manufacturing can improve clothing circularity, which emphasizes reusing, repairing, and recycling materials for as long as feasible. Humancentered design, which combines AI, robotics, and additive manufacturing technology can produce high functional and clothing items (Rani et al. 2024). For example, 3D printing can be used to create wearable clothing from bio-based or recyclable polymers that can be decomposed and reused. It deduces the impact on the environment and landfill garbage while promoting a closed-loop fashion business (Hu et al. 2014). Additionally, Industry 5.0 makes it possible for the manufacturing process to be more transparent and traceable, empowering consumers to make ethically sound purchasing decisions.

Concepts of Industry 5.0 from the Point of View of Clothing Industry

Continuing upon the foundations established by Industry 4.0, Industry 5.0 is frequently heralded as the era of human-machine collaboration (Bai et al. 2020; Barreto et al. 2017). It emphasizes the critical role that human workers play in tandem with state-of-the-art technologies. Industry 5.0 aims to achieve a harmonic balance between human creativity,

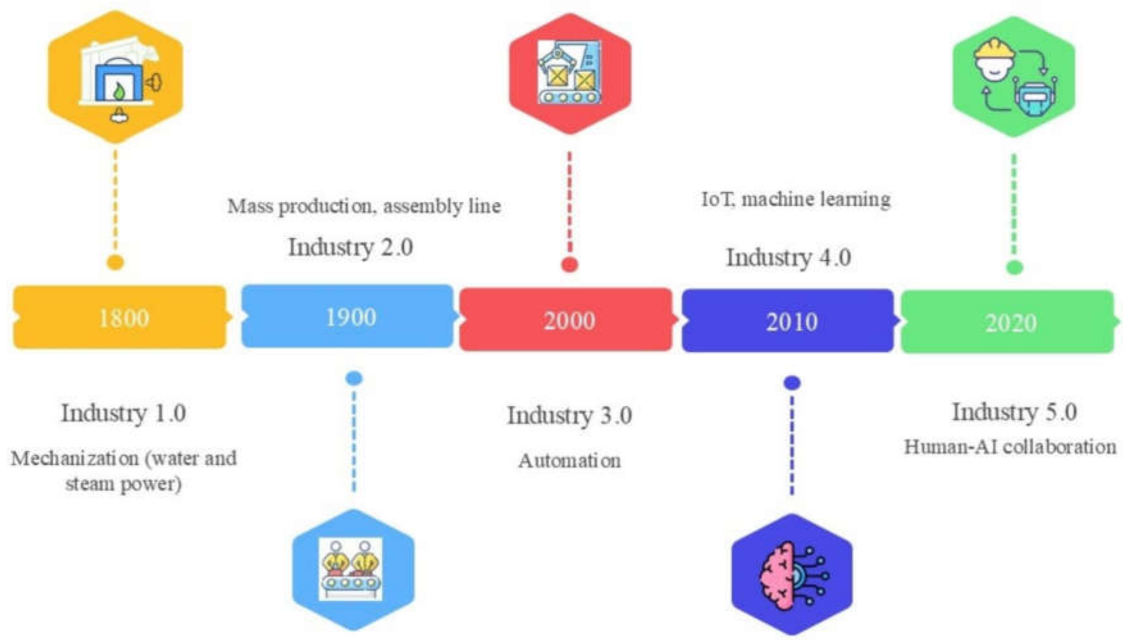

Fig. 2 Different stages of industrial revolutions

intuition, and problem-solving skills, and the capabilities of machines, AI, and robots (Rahardjo et al. 2024). It is in contrast to its predecessors, which were primarily focused on automation and digitalization. Within the clothing manufacturing industry, it involves incorporating intelligent technology like robotics, machine learning, AI, and the IoT into manufacturing processes while placing a fresh focus on human-centered methodologies (Chander et al. 2022; Javaid et al. 2021; C.-C. Wang and Li 2022). Numerous issues confront the clothing industry, from supply chain complexity and environmental concerns to cost constraints and worldwide rivalry (W. A. H. Ahmed and MacCarthy 2021; Villar et al. 2023). Textile manufacturers can maximize productivity, reduce downtime, and optimize production workflows by utilizing IoT-enabled sensors, robotic automation, and AI driven predictive maintenance. Informed decision-making is further facilitated by real-time data analytics, which permits ongoing process enhancements (Tien 2017). Real-time monitoring and control of manufacturing processes are made possible by Industry 5.0 technologies, which also facilitate customization based on industry preferences and ensure adherence to strict quality requirements (Sakare et al. 2023). In order to ensure consistent product quality and enable rapid interventions, advanced analytics algorithms identify variations or flaws early on. In the clothing industry, sustainability has become a top priority, leading to a move toward sustainable procedures and the concepts of the circular economy (Balanay and Halog 2019; Rahaman et al. 2025a, b; Repp et al. 2021a). Industry 5.0 enhances a more environmentally sustainable approach to clothing manufacturing by enabling resource optimization, waste reduction, and energy efficiency through smart manufacturing techniques (Leng et al. 2024). Textile manufacturers need flexible and robust supply chains to adapt quickly to shifting market conditions and reduce risks in a volatile and unpredictable economy. It ensures smooth coordination throughout the whole value chain by enabling supply chain optimization through real-time data interchange, predictive analytics, and smart logistics (Karthik and Gopalakrishnan 2014; Suarez-Visbal et al. 2023). Industry 5.0 enables challenges such as job displacement, and aims to enhance human workers' capacities by giving them access to modern equipment, encouraging systems, and training (Adel 2022). In order to enable the workforce to drive organizational growth and competitiveness, human-machine collaboration develops a culture of innovation, creativity, and continuous learning.

Key Elements and Characteristics of Industry 5.0

The next stage of industrial development, known as Industry 5.0, emphasizes the well-balanced fusion of modern technologies and human knowledge. Industry 5.0 is characterized by a human-centric approach as it emphasizes on the collaboration between human and technology to enhance efficiency and well-being. It is an approach in which people and machines cooperate harmoniously by utilizing one another's advantages and both are key essential components (Bellet et al. 2013). It integrates AI and automation while ensuring that human expertise remains central for decision-making. Additionally, hyper-personalization enables customized production designed to individual preferences using advanced data analytics. Cobots play a significant role in this specific approach as it works alongside human to improve productivity, safety, and precision in manufacturing. It is a kind of cooperation encourages invention, creativity, and problem-solving, which makes it possible to manufacture clothing items to suit specific requirements. Sustainability is another top priority to reduce negative effects on the environment by using sustainable clothing items, energy-saving techniques, and waste management techniques (Brockhaus et al. 2017; Mathew and Spinelli 2025; Pranta et al. 2024). Another characteristic is flexibility, as production processes are built to quickly adjust to shifting consumer tastes and market demands. Various systems and components are interconnected and interoperable, facilitating smooth data transmission and communication and improving productivity and decision-making. Industry 5.0's essential elements are displayed in Figure 3a and the essential characteristics of Industry 5.0 are illustrated in Figure 3b.

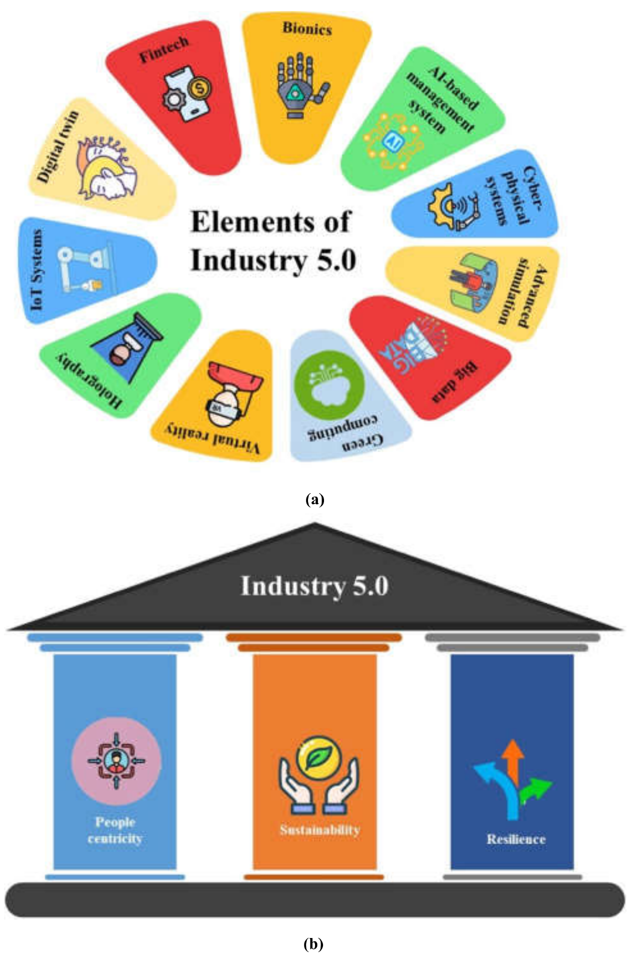

Fig. 3 **a** Key elements of Industry 5.0. **b** Key characteristics of Industry 5.0

Human-Machine Centricity

Industry 5.0 places a strong emphasis on collaboration between humans and machines while acknowledging its own special abilities. It focuses on adapting advanced digital technologies while enhancing easier human-machine interaction (Ivanov 2023). It enhances human-machine collaboration to an advanced level. It transits the focus of manufacturing from system driven processes to human-machine centered approaches. In a sense, this marks a return to the foundational principles of manufacturing while still emphasizing economic and sustainability considerations (Jefroy et al. 2022). The cooperation in the clothing industry means using automation, robotics, and AI to complement human knowledge and abilities rather than to replace them (Monopoli et al. 2025). While machines execute repetitive jobs, human workers supervise and control industrial processes, increasing productivity and efficiency (Modoni and Sacco 2023). AI-driven systems, Cobots, and smart automation encourage productivity can enable the workers to concentrate on creativity, innovation, and quality control (Kazancoglu et al. 2024b). Technologies such as AI-supported customization, Augmented Reality (AR), and digital twins can facilitate personalized clothing manufacturing and streamlined manufacturing. This integration can create a sustainable, efficient, and worker-friendly clothing industry with a total balanced automation with human supervision (Donmezer et al. 2024).

IoT Integration

Through the connection of equipment, sensors, and devices across the apparel manufacturing environment, IoT technologies are essential to Industry 5.0. In Industry 5.0, the integration of IoT in the clothing industry can make personalization, efficiency, and sustainability to the next level. IoT enabled smart textiles can communicate with devices to gather data and allow for the real-time monitoring of production processes, equipment performance, and product quality in the clothing industry (Manglani et al. 2019; Rejeb et al. 2020). Sensors can be integrated into machinery and equipment. It can enable real-time tracking of apparels during the manufacturing process which can remarkably improve supply chain transparency and reduce waste. It ensures constant product quality, reduces downtime, and enables proactive maintenance (Özdemir and Hekim 2018). IoT connected manufacturing systems can optimize production processes, automate adjustments, and improve efficiency that can ultimately pave the way for a more responsive and adaptive clothing industry in Industry 5.0.

Advanced Data analytics

Advanced data analytics plays a pivotal role in enhancing decision making and optimizing processes. Industry 5.0 uses big data analytics and machine learning, among other advanced data analytics approaches, to extract meaningful insights from massive volumes of manufacturing data (Akter et al. 2022). It enables predictive maintenance that can reduce downtime by anticipating equipment failures before the event takes place. Data analytics can be applied to the clothing industry to improve production schedules, forecast maintenance requirements, and find areas for process optimization. Real-time production data analysis enables manufacturers to make well-informed decisions that encourage productivity and cut expenses without meeting any unwanted failures (Kabugo et al. 2020). The combination of advanced data analytics and real time decision making can promote the clothing industry towards a more advanced and smarter operations.

Automation and Robotics

Industry 5.0 in the clothing industry relies heavily on automation and robotics technology to automate labor-intensive and repetitive processes (Wollschlaeger et al. 2017). The integration of Cobots is a key step toward smarter manufacturing systems in the context of Industry 5.0. By utilizing Cobots, manufacturing processes can be enhanced with the minimization of low-value tasks for workers. It can help to focus on more advanced responsibilities that robots struggle with due to task flexibility (Bednar and Welch 2020; Frank et al. 2019). However, a recent study highlighted the factors that influence managers' intentions to adopt Cobots in manufacturing brands, but it did not explore the actual usage stage (Correia Simões et al. 2020). The adaptation of automation and robotics can open endless possibilities for the clothing industry. It can create more efficient and productive industry. Numerous manufacturing operations, including cutting, stitching, and packaging, can be carried out by automated systems with accuracy and efficiency (Gangoda et al. 2023). Automation and robotics speed up production, minimize error rates, and enhance overall product quality while freeing up human labor for more difficult jobs.

Digital Twins

The inclusion of building virtual versions of real manufacturing assets, procedures, and end clothing items, digital twin technology enables manufacturers to model and enhance production processes in a virtual setting (Davila Delgado and Oyedele 2021). This particular technology provides a real-time dynamic model that mimics the operation of physical systems and clothing items. It helps to improve the continuous optimization and troubleshooting without disrupting actual operations (Javaid et al. 2023; Leng et al. 2021). The clothing industry can be particularly beneficial through digital twins as it has the traits to test and simulate process modifications, anticipate potential disruptions, and identify inefficiencies before making physical changes. This test process modifications of digital twins can be implemented, simulate various manufacturing situations, and model production lines (Donmezer et al. 2023b). The capability enables textile manufacturers to simulate the entire production line for better resource allocation, improved quality control, and predictive maintenance strategies. Consequently, manufacturers can significantly reduce waste, increase manufacturing efficiency, and shorten the time required to launch new items which ultimately enhances sustainability and cost-effectiveness in production.

Virtual Reality (VR) and Augmented Reality (AR)

VR refers to a fully immersive, computer-generated environment that allows users to interact with a 3D world with the use of headsets and controllers (Wohlgenannt et al. 2020). On the other hand, AR overlays digital content onto the real world, often viewed through devices such as smartphones, tablets, or AR glasses (Dargan et al. 2023). Both of them allow for interactive simulations and virtual environments that provide workers with hands-on experience without physical constraints. These technologies ensure a safer and more efficient training process (Yazdi 2024). Industry 5.0 is improved by these technologies through the provision of training tools and immersive visualizations for production processes. The clothing industry can be benefitted through AR and VR as it has the potential to provide pragmatic knowledge and experience in the context of different sections of manufacturing. AR and VR can be utilized in the textile business for interactive training simulations, remote maintenance encourage, and virtual product design (Radianti et al. 2020). In clothing manufacturing, these technologies enhance better collaboration, shorten training times, and increase worker safety.

Circular Economy

By maximizing resource use, eliminating waste, and reducing environmental impact, Industry 5.0 encourages sustainability and circular economy concepts in the textile (Senthilkannan Muthu 2019). It highlights sustainability by combining human-centered approaches with advanced technologies, leading to smarter and more sustainable manufacturing processes. In this framework, sustainability goes beyond waste reduction and energy efficiency. As global environmental concerns grow, industries are urged to reduce environmental impact while still maintaining efficiency.

Manufacturers can now use sustainable production methods, recycling, and upcycling to advanced technologies. Textile manufacturers can encourage a more environmentally conscious and sustainable manufacturing ecosystem (Reike et al. 2023). Contemporary waste management practices are increasingly focused on sustainability and eco-friendliness (Nayak et al. 2021; Tareque Rahaman et al. 2021). As a result, circular economy practices are increasingly encouraged in today's industries. Various models have been developed to promote the circular economy, particularly within the manufacturing process. These models are adopted to ensure the sustainability of the clothing industry.

Zero Waste Strategy A zero-waste policy aims to optimize resource efficiency and reduce waste generation throughout the entire manufacturing, consumption, and disposal process (Song et al. 2015). Redesigning clothing items, processes, and systems promotes the efficient use of materials and aims to eliminate waste. The approach focuses on the principles of "reduce, reuse, and recycle" and encourages composting and recycling efforts, along with product repair and reuse programs. The zero-waste policy is in line with Life Cycle Assessment (LCA), reducing textile waste at every stage of production and consumption. It prioritizes resource efficiency by designing durable, recyclable clothing with minimal environmental impact. Diverting waste from landfills through reuse, recycling, and proper disposal helps to reduce carbon emissions and pollution. This strategy enhances a circular economy, ensuring sustainable textile waste management with a small environmental footprint. It works for waste reduction at the source, allowing businesses to reduce environmental impact and better utilize resources. Collaboration among manufacturers, retailers, consumers, and lawmakers is the key to implementing zero-waste policies throughout the supply chain, enabling organizations to reduce environmental hazards and preserve natural resources, advancing toward a sustainable and circular economy.

3R Concept The 3R principle (reduce, reuse, recycle) is essential for advancing sustainability in the clothing industry. It helps to minimize resource consumption, minimize waste production, and repurpose materials, thereby reducing the environmental footprint. Reusing textiles prolongs the life cycle, decreasing the need for new raw materials. Recycling transforms waste fabrics into new clothing items, contributing to a circular economy in fashion. Reducing waste via the 3R approach is a highly effective strategy for promoting sustainable waste management (Mitra and Datta 2014). The environmental impact at each stage of a textile product's life is minimized in alignment with LCA. Recycling and reusing building waste contribute to the achievement of SDGs. These procedures are frequently used to create new clothing items from the significant amounts of waste generated on-site (Schroeder et al. 2019). The strategy holds the potential to revolutionize the approach, reducing the need for exploring natural resources while simultaneously extending the lifespan of landfills. Resources are preserved, and waste treatment costs are reduced (Sarkodie and Owusu 2021). Effective waste management plays a pivotal role in encouraging the circular economy. It focuses on the principles of reducing, reusing, recycling, and recovering materials (Daukantienė, 2023). In 2010, £238–£249 million worth of reusable or recyclable textiles were discarded by residual waste collectors. By recovering just 10% of this, around £25 million in sales could be generated. Textiles for manufacturing clothing contribute significantly to the environmental footprint, accounting for one-third of the waste footprint, three-quarters of the carbon footprint, and the majority of the water footprint in circular business (Okafor et al. 2021; Rahaman and Islam 2021).

Extended Producer Responsibility (EPR) A legislative strategy called EPR transfers the responsibility for managing a product's end-of-life effects from consumers or local governments to the manufacturers. Under EPR, manufacturers are accountable for the entire product lifecycle, including production, collection, recycling, and disposal (Khetriwal et al. 2009). The goal is to create long-lasting clothing items that are sustainable and easy to recycle or dispose of properly. By shifting responsibility to manufacturers instead of consumers or municipalities, it encourages sustainable practices and helps to minimize the environmental impact of clothing items throughout their entire life cycle (Matambo 2021). EPR programs differ in specifics, yet the core concept remains that manufacturers are required to handle the end-of-life consequences of the clothing items through regulations or agreements. These environmental product return schemes encompass items such as electronics, batteries, packaging, and hazardous materials. These serve as an effective mechanism to promote resource conservation, reduce waste, and improve environmental sustainability in product design and manufacturing.

Green Packaging In packaging, the term "green" refers to clothing items that are either manufactured from environmentally sustainable materials or used in a manner that minimizes environmental harm. The goal is to reduce the environmental impact of packaging, starting from the extraction of raw materials to its final disposal. Green packaging efforts include reducing packaging waste through innovative design and optimization, as well as using renewable and biodegradable materials such as paper, cardboard, and compostable plastics (Wandosell et al. 2021). Reducing packaging size and weight to limit emissions associated with transportation is another aspect of green packaging projects (Svanes et al. 2010). Recyclable materials and recycled content are also incorporated into packaging (Motaleb et al. 2024). By adopting these practices, businesses are able to reduce environmental impact. Valuable resources can be conserved, and waste and pollution from packaging materials can be minimized. This approach emphasizes the importance of prioritizing green packaging techniques. Additionally, the demand for sustainable packaging solutions is growing. Green packaging is increasingly preferred by consumers, prompting businesses to embrace more sustainable methods. Reducing the harmful effects of product packaging on the environment, green packaging plays a crucial role in this effort (Pranta et al. 2023).

Lean Manufacturing Lean manufacturing, also known by various terms such as Just in Time (JIT) production. It is a method aimed at improving manufacturing efficiency and minimizing waste. Originating from the Toyota Production System, lean manufacturing focuses on maximizing the use of limited resources to meet consumer demands (Yamamoto and Lloyd 2019). It is firmly based on guiding principles, including, JIT manufacturing, continuous improvement (Kaizen), and pull-based production (Benders and Van Bijsterveld 2000). The key principles of lean manufacturing involve minimizing the risks of overproduction or obsolescence and limiting inventory holding costs. It is centered on delivering clothing items and services to clients, operating on a pull-based system where production is determined by consumer demand rather than schedules or projections. This method allows for more efficient resource distribution and prevents overproduction. It also emphasizes the significance of respecting workers and granting them the autonomy to excel in their roles. The goal of lean manufacturing is to optimize efficiency, reduce waste, enhance quality, and increase productivity. As a result, consumers receive greater value at a reduce cost with a reduced environmental footprint.

Technologies for Implementing Industry 5.0

In the clothing industry, technologies that facilitate Industry 5.0 include Cobots that work alongside human workers to enhance precision and efficiency in tasks such as clothing assembly, quality control, and cutting (Lu et al. 2022a). AI-driven systems help to optimize designs by predicting trends and consumer preferences, while IoT-enabled devices enable real-time monitoring of machinery and inventory, improving workflow and reducing waste (P. Kumar et al. 2022). Industry 5.0's future transitions in the clothing industry are illustrated in Figure **4**. With the arrival of Industry 5.0, which stresses the fusion of innovative technologies and human intelligence, the textile industry is poised for significant change. The study explores the potential and challenges that Industry 5.0 brings to the clothing industry.

Wearable Textiles

In smart and wearable textiles, Industry 5.0 technologies focus on enhancing the interaction between humans and machines for additive manufacturing. It also serves the duty of sustainability and customization. Key technologies include AI and machine learning that enable adaptive functionalities in fabrics such as monitoring vital signs, adjusting temperature, and detecting environmental conditions (Chinnappan et al. 2017). Textiles with integrated sensors and microelectronics allow for the development of smart clothes for sports, wellness, and medical applications (Mondal 2008). These textiles can monitor physiological factors including body temperature, heart rate, and activity. Wearable technology gives wearer hands-free access to information and connectivity by being incorporated into clothing for communication, navigation, and entertainment reasons (Y. Zhang et al. 2023a, b). Cobots work alongside humans to enhance production efficiency and customization. At the same time, blockchain technology ensures traceability and transparency in the textile supply chain. These technologies combine to drive the transformation of e-textiles and it make them more personalized, sustainable, and interactive, paving the way for the next era in wearable technology (W. A. H. Ahmed and Maccarthy 2021).

Antimicrobial and Self-Cleaning Textiles

In the context of antimicrobial and self-cleaning textiles, several technologies are playing a pivotal role in its implementation in additive manufacturing. The application of nanotechnology is central as it allows for the incorporation of antimicrobial agents such as silver (Ag) nanoparticles or copper oxide (CuO) into textile fibers (J. Ghosh et al. 2025; M. Khan et al. 2024; Rahaman and Khan 2024a, b). These nanoparticles exhibit excellent antimicrobial properties and actively prevent bacterial growth and enhance the lifespan of textiles (Momotaz et al. 2024). Incorporating self-cleaning and antibacterial properties to textile surfaces through the application of nanotechnology and photocatalytic coatings can minimize odor accumulation, increase hygiene in apparels, and reduce the need for frequent washing (Hosen et al. 2024; M. S. H. Khan et al. 2025). Implementing self-sanitizing textiles in public transit, medical textiles, and the hospitality industry can help to reduce the spread of infectious diseases and enhance public health results (Saha et al. 2024).

Apparel with AR

Industry 5.0 in additive manufacturing implements with AR can revolutionize design, production, and consumer experience. AR technology allows designers and manufacturers to

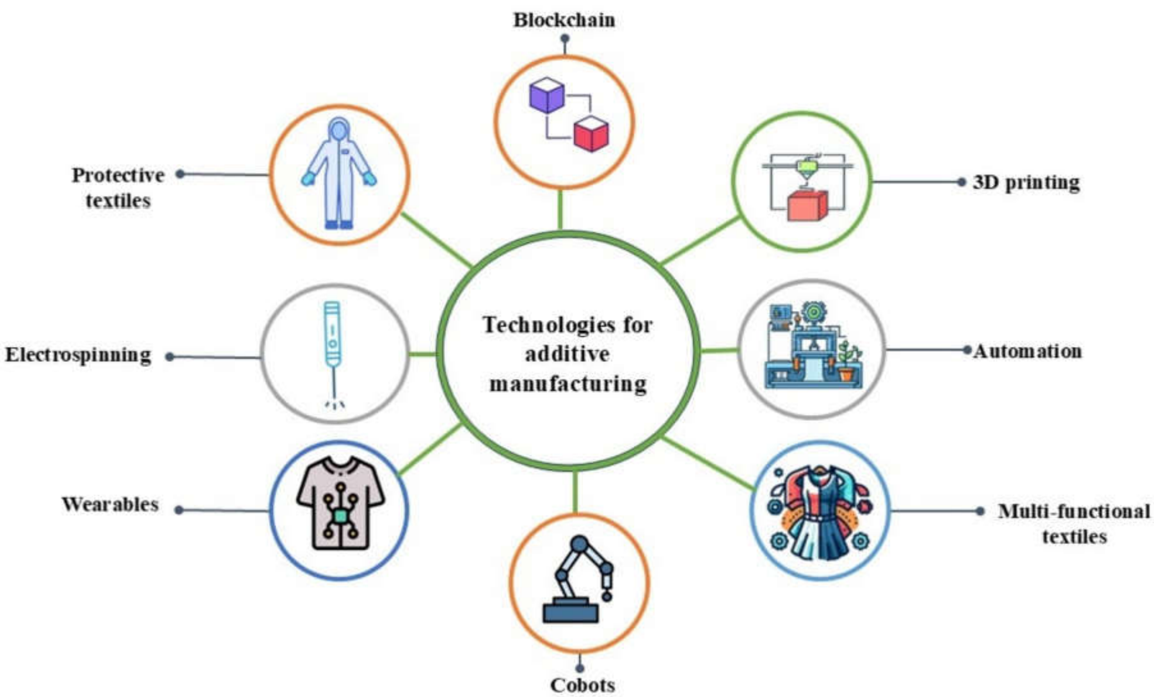

Fig. 4 Technologies for implementing Industry 5.0 in the clothing sector

visualize and simulate apparel clothing items in real-time. It enhances creativity and reduces errors during the prototyping phase (Carmigniani et al. 2011). Consumers can also use AR to try on clothes virtually through apps or in-store displays, providing a personalized shopping experience. In addition, AR can be employed in manufacturing for training purposes where workers can receive real-time guidance and improve efficiency (Berryman 2012). It is being incorporated into apparel and accessories to provide consumers with immersive shopping experiences. It enables them to see things in real time, alter designs, and engage with virtual aspects prior to making a purchase (De Silva et al. 2019). AR features are incorporated into retail settings, fashion shows, and marketing campaigns to improve brand narrative, engage consumers, and close the gap between online and offline purchasing channels.

3D Printing

The use of sustainable materials and sustainable 3D printing technologies also aligns with the Industry 5.0 goals of reducing waste and increasing energy efficiency. These technologies collectively encourage a more human-centric, adaptable, and sustainable approach to additive manufacturing. Customized clothing and accessories are manufactured possible by the use of additive manufacturing technologies, which also help to reduce material waste and enable on-demand production based on specific body measurements and style choices (Dorsey et al. 2022). Adding 3D-printed components to textiles to improve their structural soundness, visual attractiveness, and useful characteristics like complex patterns and varied textures.

3D Knitting

Industry 5.0 in additive manufacturing, particularly in 3D knitting integrates advanced technologies to enhance the production of textiles with a high degree of customization and automation while focusing on human-centric processes (Igarashi et al. 2008). AI is utilized to optimize design processes, predict material behavior, and facilitate real-time adjustments during production (Elahi et al. 2023). Machine learning algorithms can adapt knitting patterns to meet specific requirements that ensure precision and reduce waste (Zulfiqar et al. 2024). Additionally, IoT allows for smart monitoring of machines, providing real-time data for maintenance, performance tracking, and operational efficiency (Soori et al. 2023). Robotics and automation systems are also key components that enable the smoother production of complex, multi-dimensional knit structures with minimal human intervention. Another crucial technology is cloud computing that provides a platform for collaborative design and remote control of manufacturing processes and enhances flexibility in production.

3D Printed Accessories

Industry 5.0 represents a paradigm transition where human intelligence, creativity, and collaboration are integrated with advanced technologies. In the realm of 3D printing, particularly in the production of accessories, Industry 5.0 technologies enable a more personalized, customized, and efficient approach. Key technologies facilitating the transition include advanced AI algorithms for design optimization, which allow for the creation of intricate and functional accessories that ensures individual preferences (Seeber et al. 2020). Cobots play a crucial role in improving production efficiency and precision while working alongside human operators, ensuring both high-quality outputs and reducing physical strain (El Zaatari et al. 2019). Additionally, real-time data analytics and machine learning algorithms can monitor the 3D printing process, optimizing parameters such as temperature, speed, and material usage, resulting in reduced waste and energy consumption.

Multi-Functional Textiles

Industry 5.0 is a new era that emphasizes the integration of human-centric approaches with advanced technologies. It aims to create personalized, sustainable, and innovative clothing items. In the context of additive manufacturing for multi-functional textiles, the transition is enabling the development of highly customizable and efficient textiles with advanced features. Advanced functionalities, including moisture-wicking, thermal management, odor control, and UV protection, are built into clothing to improve comfort and performance in a range of settings and activities (G. Chen et al. 2020). In addition, AI and machine learning algorithms are playing a crucial role in optimizing the design and production processes, ensuring that the textiles are designed to meet specific requirements for applications such as healthcare, aerospace, or sports (Rojek et al. 2025). Textiles with dynamic property adjustments, including stretch ability, breathability, and insulation, in response to variations in the wearer's preferences or the environment (Liu et al. 2020).

Blockchain in SCM

Industry 5.0 represents a significant transition in the way manufacturing integrates human intelligence, creativity, and advanced technologies. In the context of additive manufacturing, Industry 5.0 emphasizes collaboration between human workers and machines to enhance production efficiency, customization, and flexibility. Blockchain provides a decentralized, secure, and transparent system that ensures data integrity and traceability throughout the supply chain (Agrawal et al. 2018). By implementing blockchain in additive manufacturing, businesses can track every stage of the production process from material sourcing to final product delivery.It enhances the reliability of product information, minimizes fraud, and improves accountability. The integration of blockchain with IoT devices further elevates Industry 5.0 by enabling real-time monitoring and secure data sharing, facilitating predictive maintenance and reducing downtime in additive manufacturing systems (P. Rani et al. 2022). By enabling these technologies, Industry 5.0 in additive manufacturing can optimize supply chain transparency, reduce costs, and create more sustainable and resilient production systems.

AI Driven Design

Industry 5.0 focuses on human-centric, sustainable, and intelligent manufacturing. It is revolutionizing additive manufacturing by integrating advanced technologies such as AI for design. AI-driven design in additive manufacturing enables more efficient, adaptive, and innovative processes by enabling machine learning algorithms, generative design, and optimization techniques (Quan et al. 2023). These AI tools can analyze vast datasets, predict material behaviors, and optimize geometries to create structures that are lightweight, durable, and energy-efficient. In this context, AI assists in real-time decision-making helps to create customized, complex clothing items that meet specific user needs and environmental goals. Additionally, AI-powered simulations and predictive analytics can help manufacturers to anticipate issues related to design flaws or production inefficiencies before, further enhancing the quality and sustainability of the final product (Kuzhagaliyeva et al. 2022). The integration of AI with additive manufacturing empowers a easier collaboration between human operators and intelligent machines, ensuring a more adaptive and sustainable approach to product design and production. These advancements pave the way for highly personalized, resource-efficient, and environmentally conscious production in the era of Industry 5.0.

Industry 4.0's Limitations in Light of Industry 5.0

Textile manufacturing’s transition from Industry 4.0 to Industry 5.0 reveals a number of limitations of the former over the latter. The emphasis on automation and technology improvements in Industry 4.0 frequently ignores the human aspect, which could result in the loss of the creativity and artistry that are inherent in the production of textiles (Badri et al. 2018). Flexibility and creativity can be hampered by an over-reliance on automation, which can cause a rift between the personnel and production procedures. Additionally, many manufacturing components work independently, making coordination and data management more challenging, its fragmented systems and lack of interoperability can result in inefficiencies in the apparel manufacturing industry (Dilberoglu et al. 2017). In addition, when it places a strong emphasis on mass customization, efforts are frequently constrained by predetermined constraints, it can be difficult to produce fully customized clothing items at scale (Brun and Zorzini 2009). It can disregard the environmental sustainability of clothing manufacturing in favor of production process optimization over reducing environmental impact. Figure 5 indicates the transitioning limitations of Industry 4.0 over Industry 5.0. By reintegrating human expertise and creativity into the production process, Industry 5.0, on the other hand, solves these shortcomings by enhancing customization, flexibility, and sustainability while utilizing modern technologies to increase productivity and innovation in the textile manufacturing industry (Nahavandi 2019b).

Skill Gap

The demand for a renewed human-centric industrial transition has led to the emergence of Industry 5.0 in which production processes are restructured across structural, organizational, managerial, knowledge-based, philosophical, and cultural dimensions (Carayannis and Morawska-Jancelewicz 2022). The World Economic Forum emphasized that analytical and creative thinking would remain essential in 2023. Employers predict that 44% of employee skills can be disrupted in five years, underscoring the growing need for complex problem-solving (Poláková et al. 2023a). The workforce of Industry 5.0 can be capable of critical thinking, problem-solving, creativity, and technical proficiency (Gürdür Broo et al. 2022). Textile manufacturers need to make investments in employee training and upskilling in order to accommodate the growing emphasis on human-machine collaboration in this new transition. The transition to Industry 5.0 can be hindered when there is a sizable talent gap brought on by the absence of workforce development funding during the Industry 4.0 phase (Poláková et al. 2023b).

Over-Reliance on Automation

One significant drawback of Industry 4.0 compared to Industry 5.0 is its over-reliance on automation and it often leads to a lack of human-centric approaches in production and service industries (Ingaldi and Ulewicz 2019). Industry 4.0 focuses heavily on integrating smart technologies such as IoT, AI, and robotics to optimize production efficiency and reduce human intervention. While automation enhances speed and precision, it also creates challenges such as job displacement, reduced adaptability, and increased vulnerability to system failures (Morkovkin et al. 2020). Industry 4.0 has witnessed a major increase in the use of machine learning and automation, which can result in a decrease in the need for human labor (P. Sahoo et al. 2024). Industry 5.0, however, places a strong emphasis on the value of human creativity and skill in addition to automation. The adoption of Industry 5.0 can be hampered only when the apparel manufacturing industry gets overly dependent on automated procedures while undervaluing human contribution (Longo et al. 2020).

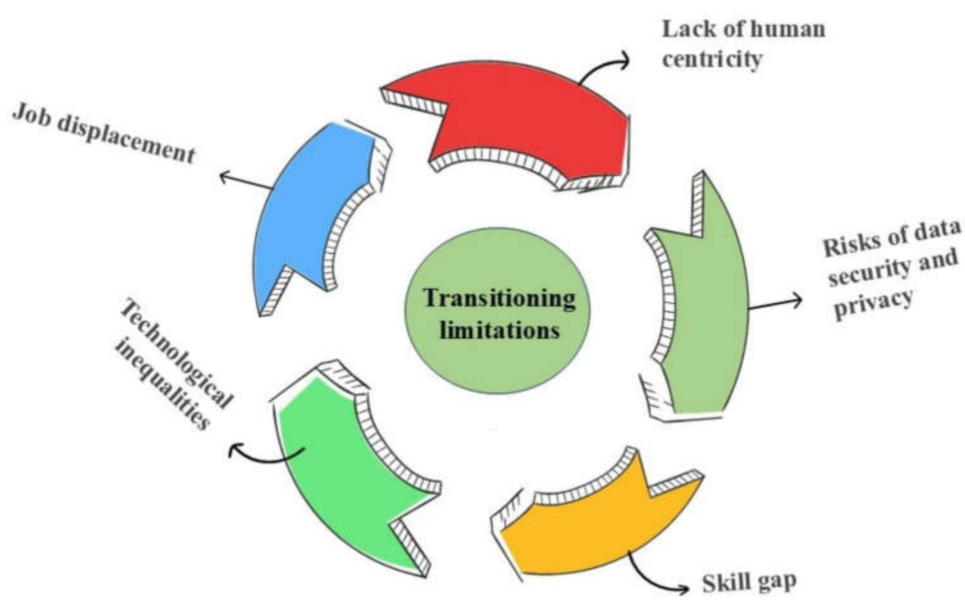

Fig. 5 Transitioning limitations of Industry 4.0 over Industry 5.0

Technological Inequalities

Industry 4.0 heavily relies on automation, AI, and data-driven decision-making and it often leads to a significant gap between technologically advanced nations and those with limited access to digital infrastructure (Gajdzik et al. 2020). Developing countries and small enterprises struggle to keep pace with the rapid technological advancements due to high implementation costs, lack of skilled labor, and insufficient digital literacy (Potočan et al. 2021). Industry 4.0 has resulted in a proliferation of different platforms, technologies, and standards, which has caused technological disparities and interoperability challenges. It can be challenging to accomplish smoother integration and cooperation between humans and machines in clothing manufacturing processes when these issues are not sufficiently resolved in Industry 5.0 (Kasinathan et al. 2022). In contrast, Industry 5.0 emphasizes human-machine collaboration, aiming to bridge the technological inequality by integrating human creativity and personalized production alongside automation. By prioritizing inclusivity, sustainability, and resilience, Industry 5.0 seeks to create a more balanced technological ecosystem that benefits a broader spectrum of industries and societies.

Data Privacy and Security

Industry 4.0 relies heavily on interconnected smart systems, automation, and cloud-based data sharing. It makes industrial operations more vulnerable to cyber threats, data breaches, and hacking. With the extensive use of IoT devices, AI, and big data analytics, large volumes of sensitive industrial and consumer information are continuously collected, processed, and transmitted across digital platforms (Rosin et al. 2020). Industry 4.0's enhanced connection and data interchange give rise to data privacy and security issues. Industry 5.0 promises even more interaction between people and robots, when it is not handled beforehand, can make these issues worse. In Industry 5.0, textile manufacturers can require strong data privacy and cybersecurity protocols to ensure the security and integrity of data generated by both machines and people (Kolesnikov et al. 2024).

Implementation Cost

The transition to Industry 4.0 requires substantial investments in advanced technologies such as automation, AI, IoT, and big data analytics (D. Ghosh et al. 2020). Setting up smart industries involves purchasing expensive equipment, upgrading legacy systems, and integrating digital platforms, all of which require a significant financial commitment (Sezer et al. 2018). Industry 4.0 technologies frequently come with a hefty initial cost associated with infrastructure, equipment, and training. Textile manufacturers can find it more difficult to make the easier transition to Industry 5.0 because of being financially constrained or reluctant to participate in Industry 4.0 because of perceived risks or uncertainty (Raja Santhi and Muthuswamy 2023b). For Industry 5.0 to be adopted in the apparel manufacturing industry, it can be essential to remove financial challenges and show the long-term advantages of the technology.

Interoperability

The interoperability of various hardware, software, and system platforms is a common source of issues for Industry 4.0 deployment. These challenges with interoperability might restrict the efficacy of automation and digitalization initiatives by impeding the smooth integration of technology and data interchange (M. Khan et al. 2023). On the other hand, Industry 5.0's emphasis on human-machine collaboration necessitates a higher level of interoperability across various industrial processes and human laborers and technical systems. Resolving these interoperability issues can be essential to achieving its full potential in clothing production. Otherwise, industries can face issues of fragmented data, inefficient resource utilization, and difficulty in integrating new technologies with legacy systems (Srai et al. 2016). Industry 5.0, in contrast, emphasizes human-centric approaches and seeks to improve the connection between digital and physical worlds through better integration and collaboration between systems.

Human-Centric Focus

While Industry 4.0 has significantly transformed production and other sectors with automation, smart technology, and data-driven processes, it has certain drawbacks, particularly in its human-centric focus (B. Wang et al. 2022). Although Industry 4.0 brought about advances in automation, data analytics, and networking, it frequently places a higher priority on technology than on the participation of people in problem-solving and decision-making processes (Alves et al. 2023). The needs of the textile manufacturing business are better met by Industry 5.0's human-centric approach, as design, aesthetics, and consumer preferences are important factors. The integration of modern technologies and human experience can enable Industry 5.0 to enable more customized and consumer-focused clothing manufacturing processes. It seeks to create a harmonious relationship between humans and machines where humans are not replaced but rather augmented by technology to enhance their roles.

Transitioning from Industry 4.0 to Industry 5.0

The transition from Industry 4.0 to Industry 5.0 represents a significant transition in the way industries operate with a focus on the integration of human-centric values with advanced technology. Industry 4.0 is often characterized by automation, AI driven supply chain management, and the use of cyber-physical systems and IoT. It has revolutionized production processes by enabling smarter, more efficient systems. However, as businesses evolve, Industry 5.0 aims to enhance the role of humans in this technologically advanced landscape, emphasizing collaboration between humans and machines. The components that distinguish Industry 4.0 from Industry 5.0 are illustrated in Figure 6**.** The main distinction remains in the integration of personalized and customized production processes, where human creativity, flexibility, and problem-solving capabilities are harmonized with automation. Industry 5.0 in the clothing industry is a major advancement over Industry 4.0, bringing with it a number of unique features that set it apart from the former. These elements show a trend toward more customization, flexibility, sustainability, and human-machine collaboration.

Human-Centric Manufacturing

Industry 4.0 primarily focuses on the digitization and automation of processes, whereas Industry 5.0 lays more attention on the role that human workers play in the production of textiles (C. Zhang et al. 2023a, b). While Industry 4.0 revolutionized industries through the use of AI, machine learning, and interconnected systems to create highly automated and data-driven environments, Industry 5.0 transitions focus on human-centric collaboration. Instead of simply replacing human workers with machines, Industry 5.0 seeks to integrate human experience, creativity, and domain-specific knowledge with advanced technologies to promote a more flexible, adaptable, and collaborative industrial environment (Lu et al. 2022b). Employees with human ingenuity, problem-solving abilities, and domain knowledge can collaborate with machines to improve industrial processes. The integration of human intelligence with advanced technologies enhances productivity and enhances the development of

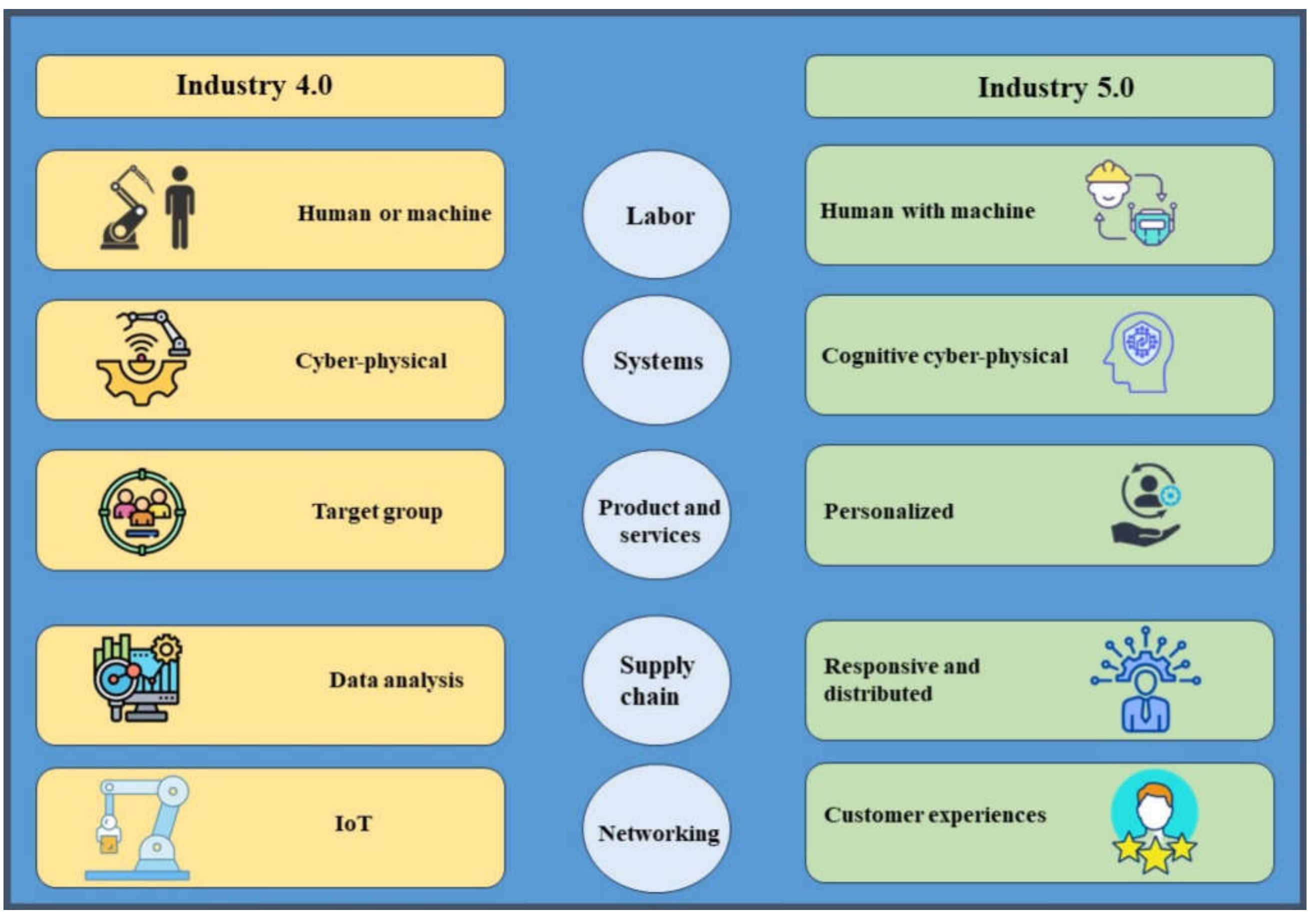

Fig. 6 Drivers of Industry 4.0 and Industry 5.0

more sustainable and customized solutions in apparel manufacturing, leading to a more human-centered approach in the advancement of smart manufacturing technologies.

Integration of Robotics

Industry 5.0 brings Cobots system with active and direct role of human interaction to the clothing industry. In contrast to Industry 4.0's mainly inflexible and segregated automation systems with a minimal and indirect human involvement, Industry 5.0 emphasizes human-centricity, flexible collaboration between humans and machines, and more integrated, adaptive technologies that align with social and environmental values. (Huang et al. 2021). Robots or Cobots work in shared workspaces with human operators to complete tasks that call for dexterity, quickness, or heavy lifting. Cooperative strategy improves textile manufacturing operations' flexibility, productivity, and safety. These human-robot collaborations are particularly advantageous in the clothing industry where intricate tasks and quick responses are often needed. By enhancing flexibility, Cobots can adapt to varying production demands and work in tandem with human workers to ensure higher efficiency and reduced error rates (Faccio et al. 2023). Additionally, this cooperative strategy not only increases productivity but also contributes to improved safety by minimizing the physical strain on workers and allowing robots to handle more dangerous tasks. Integration of human creativity and robotic efficiency marks a significant step towards creating a more dynamic, adaptable, and human-centered apparel manufacturing environment (T. Wang et al. 2024).

Mass Customization

Compared to Industry 4.0, Industry 5.0 allows for higher degrees of personalization and customization in the clothing manufacturing process. Industry 5.0 introduces mass customization, which elevates the concept of personalization that Industry 4.0 established to new heights. Industry 5.0 introduced mass customization that elevates the personalization capabilities that Industry 4.0 introduced by making it possible to create clothing items that are not only individually designed but also mass-produced efficiently (S. S. Kumar et al. 2024a, b). Modern technologies like AI, IoT, and digital twins allow manufacturers to create highly customized clothing items at scale that satisfy specific consumer demands and market trends (S.-E. Lee et al. 2002). With these capabilities, brands can create more individualized clothing items, reducing waste and improving consumer satisfaction. It marks a significant transition from traditional production models where clothing items were often one-size-fits-all, to a more consumer-centric approach that emphasizes flexibility, sustainability, and a deeper connection between manufacturers and consumers (Jin and Muqaddam 2019; Vadicherla and Saravanan 2015).

Sustainable Production

Industry 5.0 places a strong emphasis on sustainability in the clothing industry, setting it apart from Industry 4.0's largely efficiency-driven goals (Rahaman et al. 2024a, b). Industry 5.0 goes beyond Industry 4.0, which focuses on streamlining production processes for economy and efficiency, by incorporating sustainability concerns into all facets of production operations (S. C. Feng et al. 2010). Sustainable production techniques include bio-based materials, 3D printing with recycled fibers, waterless dyeing technologies, and closed-loop recycling systems (F. Ahmed et al. 2024, 2025b, a; Pranta and Rahaman 2024). The integration of AI and big data analytics helps to optimize resource utilization, reducing material waste and energy consumption. Additionally, blockchain technology enhances supply chain transparency, ensuring ethical sourcing and sustainable practices across the production process. It entails reducing the negative effects on the environment, preserving resources, and advancing a circular economy by utilizing sustainable methods and tools.

Flexibility and Agility

The Transition from Industry 4.0 to Industry 5.0 focuses on moving from automation-driven efficiency to a human-centered, adaptable, and sustainable approach with flexibility and agility as key factors. Compared to Industry 4.0, Industry 5.0 encourages more flexibility and agility in clothing manufacturing operations. Industry 5.0 takes flexibility to the next level by enabling quick reconfiguration of production processes and workflows in response to shifting market demands and production requirements (Jafari et al. 2022). Industry 4.0 introduced predictive maintenance and networked production systems. It increases a manufacturer's competitiveness and responsiveness by enabling it to swiftly adjust to new possibilities and challenges. In the context of sustainable and additive manufacturing of clothing, flexibility and agility can allow brands to transition towards localized production, digital fabrication, and responsive supply chains, ultimately promoting a circular economy.

Successful Case Studies of Implementing Industry 5.0

Industry 5.0 focuses on the collaboration between humans and smart technologies and it has seen several successful case studies that highlight its transformative impact on various sectors. Table 1 provides an overview on brands with

Table 1 Brands with successful track records of implementing Industry 5.0

Brand	Adoption level of Industry 5.0	Sustainability impact	Economic viability	References
Patagonia	High—integrates circular economy principles, AI, and robotics	Very high—focuses on waste reduction, using sustainable materials, and carbon footprint reduction	High—strong consumer loyalty, premium pricing, expanding market share in sustainable fashion	Bürklin (2019); O'Rourke and Strand (2017)
Nike	High—uses AI-driven design, sustainable materials, and advanced manufacturing tech	Moderate—aims to reduce carbon emissions and increase recycled materials	High—strong profitability, consumer demand for sustainable innovations	Puterisari (2022)
Adidas	High—3D knitting, robotic manufacturing, and AI-driven production processes	High—uses recycled ocean plastics and sustainable materials, reducing waste and energy	High—popular product lines like Adidas Parley increase consumer demand	Y.-A. Lee (2022)
H&M	Medium—uses AI for trend forecasting and automates some production	Moderate—sustainable lines, but large-scale sustainability is still a challenge	Moderate—pressure on profitability, but sustainable clothing items improve brand perception	Konina (2023)
Levi's	Medium—AI for denim design and water-saving tech in production	Moderate—sustainable cotton, eco-friendly dyeing, and water reduction efforts	High—strong growth in sustainable product lines, attracting eco-conscious consumers	Konina (2023)
Stella McCartney	High—uses sustainable materials and AI for zero-waste production	Very high—mylo mushroom leather and zero-waste practices	Moderate—high-end brand with a focus on sustainability, driving luxury appeal	Sachdeva and Mitra (2024)
Uniqlo	High—robotic stitching and automated systems in production	Moderate—use of sustainable materials like recycled polyester and energy efficiency	High—efficient production processes reduce costs, improving profitability	Sachdeva and Mitra (2024)
Puma	High—AI, 3D printing for customization, and production efficiency	High—focuses on reducing carbon footprint, using recycled materials, and biodegradables	High—growth driven by eco-friendly innovations and strong market positioning	Lim (2024)
Burberry	High—AI and 3D printing for on-demand production and supply chain optimization	Moderate—carbon neutrality efforts and responsible sourcing practices	High—digital and sustainable innovations increase competitiveness	Konina (2023)
Gucci	High—incorporates blockchain, AI, and digital fabrication in supply chains	High—focus on using eco-friendly materials and carbon–neutral goals	High—luxury brand reputation increases economic viability, with sustainability enhancing its appeal	Sachdeva and Mitra (2024)
Tommy Hilfiger	High—AI-driven design, sustainability-focused manufacturing tech	Moderate—works on reducing waste and using more sustainable materials	High—strong consumer base, innovation drives new product demand, and profitability	Lim (2024)
Fendi	High—combines digital fabrication and sustainable materials in production	High—implements responsible sourcing and sustainable design practices	High—luxury brand's focus on sustainability elevates brand value and attracts wealthy consumers	Lim (2024)
Ralph Lauren	High—uses AI for fabric design, robotic production, and sustainable sourcing	High—increased use of organic materials and focuses on ethical sourcing and carbon offset	High—increased brand loyalty and demand for sustainable luxury items increase profitability	Lim (2024)
Chanel	Medium—integrates AI for design and production efficiency, with a focus on high-end items	Moderate—slowly transitioning to more sustainable sourcing and production practices	High—the luxury appeal of Chanel helps it to maintain strong market viability with a focus on sustainability	Lim (2024)
Balenciaga	High—AI and automation for fabric cutting and design, embracing digital trends	Moderate—focus on using eco-friendly materials and reducing energy consumption	High—as a luxury brand, innovation aligns with its appeal, leading to strong consumer demand	Dou (2024)

Table 1 (continued)

Brand	Adoption level of Industry 5.0	Sustainability impact	Economic viability	References
The North Face	High—uses AI to forecast trends and robotic automation in production	Very high—uses recycled materials and aims for carbon neutrality	High—strong market share and increasing consumer preference for sustainable clothing items	De Gauquier et al. (2019)
Reebok	High—integrates 3D knitting and AI for efficient production and sustainable product lines	High—focus on recycled materials, eco-friendly manufacturing processes, and carbon reduction	High—consumer demand for sustainable clothing items encourages strong sales growth	De Gauquier et al. (2019)
Kering	High—uses AI, blockchain, and robotics in its brands (Gucci, Saint Laurent, etc.)	Very high—leading in sustainability initiatives across multiple brands, with a focus on reducing environmental impact	High—strong financial performance due to sustainability-driven luxury appeal	De Gauquier et al. (2019)
Everlane	High—AI-driven SCM and sustainable production tech	Very high—emphasis on transparency, ethical sourcing, and eco-friendly materials	High—strong growth due to focus on sustainability and transparency, which attract eco-conscious buyers	Kim et al. (2021)
Zara	Medium—AI for inventory management and automated logistics	Moderate—introducing sustainable collections and focusing on reducing waste	High—Zara's efficient model allows for sustainable clothing items while maintaining strong profitability	Tokatli (2008)
BOSS (Hugo Boss)	High—uses AI in design and production, focusing on customization and efficiency	High—committed to reducing waste and sourcing sustainable materials for collections	High—strong brand image and sales, bolstered by sustainability-focused collections	Sachdeva and Mitra (2024)

successful track records of incorporating Industry 5.0. The facility demonstrates the potential for a harmonious relationship between machines and human, with workers overseeing complex tasks while the AI handles data-driven decisions. The combination of human involvement and smart technology leads to more resilient, adaptive, and innovative production processes, helping industries to meet the evolving demands of consumers and society. It provided a more personalized and flexible production environment where the workforce was empowered to contribute their expertise alongside automated systems. Some notable examples demonstrate components of Industry 5.0 principles in action, even though specific case studies and best practices in the clothing industry can still be developed.

Suzhou Tianyuan's Sewing Robots

To install completely automated sewing robots in its clothing industry, Chinese textile manufacturer teamed up with SoftWear Automation. These robots increase production and reduce labor costs by sewing clothes without human assistance using computer vision and AI algorithms (Koustoumpardis and Aspragathos 2014). The partnership between industry (Suzhou Tianyuan Garments Company) and academia (SoftWear Automation) shows how modern technologies can revolutionize conventional clothing manufacturing procedures.

Zara's Fast Fashion Trends

The fast fashion brand Zara, incorporated in Spain, is renowned for having an flexible and responsive supply chain that integrates numerous Industry 5.0 principles (Tokatli 2008). Zara uses real-time data analytics to instantly change production and distribution by continuously monitoring consumer preferences, market trends, and inventory levels. With the help of fast fashion business model, Zara can minimize lead times, get rid of extra inventory, and ship stylish clothes to clients much faster than before (Aguilar-Aguilar et al. 2023).

Adidas Speedfactory

In the fashion industry, Adidas has adopted Industry 5.0 to enhance sustainable production. By combining 3D knitting technologies with human creativity, Adidas has been able to produce custom-fit apparels with minimal waste, promoting both sustainability and innovation (Y.-A. Lee 2022). Adidas introduced the SPEEDFACTORY program to incorporate Industry 4.0 and Industry 5.0 ideas into the production of footwear. These facilities use robotics, additive manufacturing, and advanced automation to quickly make bespoke shoes. Adidas provides consumers personalized items while cutting lead times and waste by combining digital design tools with localized production (Galluccio 2022).

Patagonia's Worn Wear Initiative

Patagonia's Worn Wear initiative promotes sustainability by encouraging consumers to purchase used wear, trade in old items, and repair the clothing items, thereby extending their lifecycle and reducing waste. It aligns with the principles of Industry 5.0 as it emphasizes human-centric and sustainable practices, combining advanced technology with environmental responsibility to promote a circular economy and reduce the fashion industry's environmental impact. Although not solely centered around Industry 5.0, "Patagonia's Worn Wear" initiative embraces the fundamental concepts of sustainability and circular economy that are at the heart of the movement (Hepburn 2013; O'Rourke and Strand 2017). Through this program, Patagonia encourages clothing repair, reuse, and recycling, extending the life of their goods and reducing their environmental effect. Patagonia promotes a more sustainable approach to textile consumption and improves consumer interaction by using digital platforms and supply chain transparency (Michel et al. 2019; Rattalino 2018).

Nike's Direct Marketing

Nike has adopted the ideas of Industry 5.0 by placing a high priority on digital client engagement and Direct-to-Consumer (DTC) sales channels. It collects useful information on consumer preferences, behavior, and performance reviews through its mobile apps and NikePlus membership program (Knight and Greenberg 2002). It is able to increase consumer loyalty, streamline inventory management, and personalize product because of its data-driven approach.

Teijin's Digital Transformation

To modernize its textile business, "Teijin Limited," a global chemical, pharmaceutical, and information technology corporation based in Japan, has set out on a digital transformation path. In order to improve product development, manufacturing efficiency, and consumer pleasure, brands use IoT, AI, and data analytics through programs including Teijin Smart Safety, Teijin Smart Meter, and Teijin Smart Color (Kwon 2024). Teijin is positioned as an innovative leader in the global clothing industry due to its dedication to Industry 5.0 principles.

Intelligent Labels from Avery Dennison

With its intelligent label solutions, the world leader in labeling and packaging materials has incorporated Industry 5.0 techniques. Real-time tracking and tracing of textile clothing items throughout the supply chain is made possible by the radio-frequency identification (RFID) and NFC (near field communication) technologies included in these labels (Schaefer and Cheung 2018). Avery Dennison assists textile manufacturers with better inventory control, improved product identification, and streamlined shipping processes by utilizing data analytics and cloud-based technologies.

Recent Advances of Industry 5.0 in the Clothing Industry

Textile manufacturing can adopt Industry 5.0, which requires strategic approaches that combine human innovation and technical integration. Textile and apparel industries need to place a high priority on developing an innovative and ongoing learning culture that provides workers the freedom to accept change and adjust to new technology (A. Arora et al. 2004; Zayedul Hasan, K. M. Ayatullah Hosne Asif, et al. 2021). The textile and apparel Industry's 5.0 recent advances are illustrated in Figure 7. Investing capital into upskilling and workforce training programs can improve workers' digital literacy and provide them with the tools need to collaborate with machines (L. Li 2024). In addition, by using flexible manufacturing techniques, textile manufacturers can react quickly to client requests and market expectations, increasing flexibility and pleasure (Crittenden et al. 2011; Ozdamar Ertekin and Atik 2015). Manufacturing processes can be optimized with minimal environmental effects by combining sustainable practices with modern technology like automation, AI, and the IoT (C. Li et al. 2021; Yildirim et al. 2018). Additionally, encouraging cooperation and joint ventures with tech brands and academic institutions can make it easier to obtain state-of-the art solutions and stimulate innovation in the clothing manufacturing industry (C.-L. Chen 2019). Clothing brands can successfully navigate Industry 5.0 and grab new chances for development, efficiency, and sustainability in the digital age by implementing these strategies.

Cyber-Physical Systems (CPS)

Industry 5.0 represents the next evolutionary stage in industrial development. In the clothing industry, CPS plays a pivotal role by integrating physical processes with digital systems, enabling real-time data exchange and decision-making (Alguliyev et al. 2018). It facilitates more efficient production processes, enhances product customization, and reduces waste. For instance, smart machines equipped with sensors can monitor the quality of fabrics in real-time, adjust manufacturing parameters accordingly, and communicate directly with human workers or other systems to optimize the production flow (S. Sahoo and Lo 2022). In order to

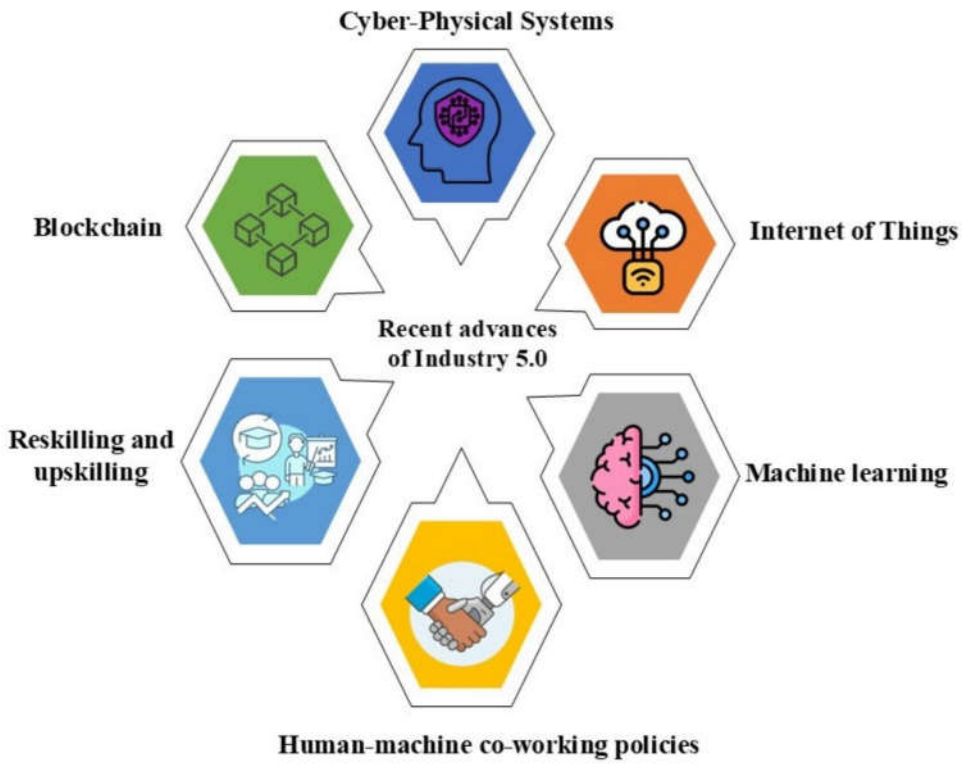

Fig. 7 Strategies for Industry 5.0 in the clothing sector

enable real-time monitoring and control, the implementation of CPS entails integrating digital technology with physical clothing manufacturing equipment. Predictive maintenance is made possible, downtime is decreased, and efficiency is increased by integration of CPS (Jamaludin and Rohani 2018).

Incorporating IoT

In the clothing industry, its integration with IoT has led to transformative advances in both production and consumer experience. Motion, gesture, and position sensors are commonly employed, with accelerometers and gyroscopes being the most frequently used. In some applications, a barometer is utilized to measure altitude (Yin and Sun 2025). Body temperature can be measured using various sensors, such as thermistors or Resistance Temperature Detectors (RTD) (J.-W. Lee et al. 2018). Equipment used in the e-textiles can have IoT sensors integrated to collect information on machine performance, energy usage, and product quality. Through analysis, it can be used to streamline workflows, enhance resource efficiency, and cut down on waste (Manglani et al. 2019).

AI and Machine Learning

Large datasets can be analyzed by AI and machine learning algorithms to find trends, improve production schedules, and forecast equipment faults (S. Arora and Majumdar 2022). AI-driven systems can also improve product personalization through trend and preference analysis (Halepoto et al. 2022). Defects are detected, failure rates analyzed, and control settings adjusted to optimize spinning by AI. Typically, AI analyzes yarn's programmable quality characteristics. A high-resolution camera captures images of yarn flaws, which are then analyzed by a preprogrammed system (Sikka et al. 2024). Over 70% of reported defects larger than 2 m and moving faster than 30 m per minute would be difficult for a human inspector to detect and manage. It is claimed that 90% of defects in plain textiles can be detected using thresholding (Horbovyy et al. 2023). Deep learning was used in another study to automatically detect defects in woven cloth, achieving classification accuracies of 78.1% for holes, 81.6% for stains, 84.7% for selvedge tails, and 74.6% for snarls (Das et al. 2021).

Textile Circularity

The circular economy and sustainability are key components of Industry 5.0 (Repp et al. 2021b). Manufacturers of textiles can use sustainable materials, use less energy and water, and start recycling and upcycling initiatives (Awan and Sroufe 2022). Adopting sustainable practices improves consumer loyalty and brand reputation while also reducing the impact on the environment (Kant Hvass and Pedersen 2019). Intelligent production systems can track a product's lifecycle, optimize its use, and ensure the materials are repurposed at the end of life, thus reducing waste and promoting sustainability (Andrews 2015). It not only minimizes environmental impacts but also opens new avenues for business models focused on apparel repair, upcycling, and leasing, aligning with the principles of a circular economy. The integration of advanced digital systems with traditional human-driven processes promotes innovation and creativity in sustainable fashion, marking a transformative approach for the future of the clothing industry (Di Maio et al. 2017).

Automation

Automation and robotics can increase precision, expedite repetitive jobs, and enhance worker safety in clothing manufacturing processes. Cobots, can increase flexibility and productivity by collaborating with human operators (Fast-Berglund et al. 2016). Automated sewing technologies such as robotic arms with AI-driven vision systems enable complex stitching patterns with minimal human intervention. In Addition, AI-powered robots facilitate real-time quality control by detecting defects and inconsistencies, reducing waste and improving product quality (Manjulatha et al. 2024). Smart industries enable interconnected robotic systems that communicate and adapt to dynamic production demands, ensuring mass customization and on-demand manufacturing. These innovations not only enhance productivity but also contribute to sustainable practices by minimizing material wastage and optimizing energy consumption.

Digital Twins

Digital twins are digital copies of real-world resources, operations, or setups (Donmezer et al. 2023c). Predictive analysis, optimization, and simulation are made possible in the clothing manufacturing process by implementing digital twins. Manufacturers can use this technology to test new concepts, maximize output, and shorten time to market (Donmezer et al. 2023 d). Digital representations allow real-time monitoring, predictive maintenance, and enhanced decision-making through data-driven insights. By simulating production scenarios, digital twins help manufacturers to optimize fabric utilization, reduce waste, and improve operational efficiency. Additionally, in fashion retail, it enable brands to create hyper-personalized shopping experiences by allowing consumers to visualize customized clothing designs before production. It reduces returns and overproduction, contributing to a more sustainable industry (Alkhammash et al. 2022).

Challenges of Implementing Industry 5.0

The transition from Industry 4.0 to Industry 5.0 presents a number of challenges for the clothing industry. It promises sustainability, flexibility, and human-machine collaboration; nevertheless, there are various challenges that can be overcome before it can be applied to the clothing industry. Integrating modern technologies like AI, IoT, and robotics into clothing manufacturing processes while maintaining the industry's traditional manpower and trained workforce is one of the main challenges (Akter et al. 2024; Gabsi 2024; Gangoda et al. 2023). Maintaining product quality and serving niche markets requires striking a balance between automation and the preservation of artisanal skills (Eglash et al. 2020). Additionally, maintaining the sustainability of the clothing industry continues to be a difficult task. To reduce the industry's environmental impact, Industry 5.0 can place a high priority on energy-efficient procedures, sustainable clothing items, and waste management techniques (Rame et al. 2024). Additionally, it is technologically challenging to achieve connectivity and interoperability across various pieces of wear and systems in textile facilities. To secure confidential information and intellectual property, it necessitates investing money on standardized communication methods and strong cybersecurity defenses. In addition, the overall potential of Industry 5.0 in the clothing industry requires addressing the reskilling and upskilling demands of the workforce. Incorporating training programs and placing a strong emphasis on lifelong learning would enable employees to effectively participate in the digital revolution of the industry while maintaining its legacy and workmanship. Main challenges for implementing Industry 5.0 are demonstrated in Figure 8**.**

Reskilling and Upskilling

Industry 4.0 was focused heavily on automation and data-driven processes but Industry 5.0 emphasizes human-machine collaboration that requires workers to develop new competencies in advanced digital tools, AI, and robotics while maintaining their traditional expertise. The rapid pace of technological advancements creates a skills gap, making it difficult for employees to keep up with emerging innovations (Leng et al. 2022). Industry 5.0, which incorporates modern innovations like automation, AI, and data analytics into the clothing industry, heavily relies on reskilling and upskilling. Organizations can invest significantly in training initiatives, promoting a culture of lifelong learning to ensure employees remain adaptable and competitive. However, balancing the cost of upskilling programs with operational efficiency

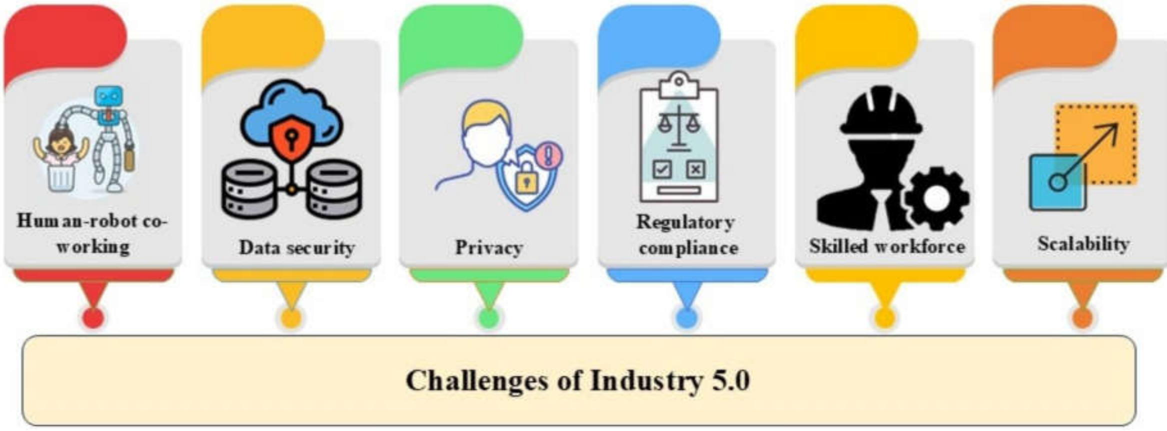

Fig. 8 Challenges of implementing Industry 5.0

poses a financial burden, especially for small and medium enterprises. Without strategic planning and government or industry encourage, the lack of skilled professionals may hinder the full realization of Industry 5.0's potential, slowing down industrial progress and economic growth.

Technological Advancements

The accelerated pace of technological advancements such as AI-driven automation, robotics, and digital twins requires industries to frequently update their systems. It leads to high costs and operational disruptions. Additionally, integrating new technologies with existing industrial setups can be complex as legacy systems can not be compatible with modern solutions. As Industry 5.0 technologies advance quickly, revisions and modifications to skill requirements are inevitable. Workers find it difficult to stay up to date with the latest developments as a result, which calls for constant learning and adaptability. Without proper strategic planning and policy support, industries can struggle to keep up with these technological transitions, potentially leading to inefficiencies, job displacement, and a widened digital divide.

Limitations of Cost and Resources

Upskilling and reskilling employees can be costly, particularly for startups or industries with limited funding. For businesses, one of the biggest challenges is deciding how to fund training programs while still staying profitable. Transitioning to a more human-centric, sustainable, and resilient industrial model requires substantial investment in advanced technologies, training programs, and infrastructure upgrades (Shinge and Shrawankar 2023).

Resistance to Change

Some workers can be reluctant to pick up new skills because they are worried about losing their jobs, feel uneasy using technology, or are unsure of their capacity for adaptation. It can stem from fear of job displacement, uncertainty about their ability to adapt, or a lack of confidence in digital tools. Additionally, organizations may face cultural and structural challenges, where long-established workflows and mindsets hinder the acceptance of Industry 5.0 advancements. Effective leadership, managerial support, and communication are necessary to overcome opposition to change.

Lack of Learning Approache

Unlike traditional education systems that primarily focus on initial skill acquisition, Industry 5.0 demands continuous learning to keep pace with rapid technological advancements and evolving job roles. Industry 5.0 requires a continual improvement and a lifelong learning approach. Organizations can adopt a new culture that empowers workers to grab learning opportunities and take charge of their professional growth. To successfully implement Industry 5.0, industries and policymakers can emphasize the integration of continuous learning initiatives, enhancing a mindset of adaptability and innovation among the workforce.

Cultural Diversity

Industries hire workers with a variety of cultural origins in today's globalized workforce. To achieve inclusion and efficacy, reskilling and upskilling programs can take cultural variations into account and provide training in multiple languages. Cultural differences in learning styles, communication, and workplace expectations can create challenges to effective training programs. Language differences, resistance to change due to deeply ingrained work traditions, and varying levels of technological exposure among employees from different cultural backgrounds can slow down the adoption of new skills.

Job Displacements

The employment of sophisticated robotics in manufacturing processes, together with automation, are key components of Industry 5.0. While automation enhances efficiency, productivity, and precision in manufacturing, it also raises concerns about workforce redundancy. The integration of advanced robotics, AI, and CPS reduces the need for manual labor, particularly in repetitive and routine tasks. It threatens job security for workers who lack the necessary skills to adapt to new technological roles (Badet 2021). Workers in the clothing industry can find it difficult to transition into new positions requiring technological know-how, which could result in underemployment or unemployment.

Initial Investment

Upgrading equipment, infrastructure, and software systems necessitates a large initial investment in order to implement Industry 5.0 technologies. The cost of adoption can be prohibitive for many textile manufacturers, particularly Small and Medium-sized Enterprises (SMEs) which would limit their competitiveness and create a challenge to entry. The integration of advanced technologies necessitates substantial upfront costs for infrastructure, equipment, and training. These technologies also require ongoing maintenance and upgrades, adding to the financial burden. While the long-term benefits of Industry 5.0, such as improved productivity and efficiency, can outweigh these costs, the initial investment can be a challenge for brands with limited capital or those operating in industries with tight profit margins (X. Xu et al. 2021b). Consequently, businesses may hesitate to adopt Industry 5.0 due to the financial uncertainty and risk involved in making such significant investments.

Data Security and Privacy Concerns

To streamline operations and enhance decision-making, Industry 5.0 mostly depends on data collecting and analysis. But also brings up issues with privacy and data security. To safeguard sensitive data from cyber threats and unauthorized access, including consumer information and proprietary designs, textile industries need to invest in strong cybersecurity solutions. The volume and complexity of sensitive information being shared and processed increase significantly. It widespread the integration of smart systems raises concerns about unauthorized access, cyber-attacks, and data breaches that can lead to the exposure of critical business and personal data (Tyagi et al. 2023). Additionally, maintaining privacy becomes even more challenging as organizations rely on data from interconnected devices and human interactions.

Supply Chain Complexity

Industry 5.0 implementation presents significant challenges when addressing supply chain complexity. As Industry 5.0 emphasizes the integration of advanced technologies into the manufacturing process, it complicates the coordination of multiple, interconnected supply chain components (C.-H. Hsu et al. 2024a, b). Textile supply chains can become more complex as a result of the implementation of Industry 5.0 technology. Increased interconnectedness and dependency among manufacturers, distributors, and suppliers increases the likelihood of interruptions brought on by things like supply shortages, traffic jams, or geopolitical concerns. Textile industries need to allocate resources towards supply chain resilience measures in order to minimize risks and ensure uninterrupted operations.

Regulatory Compliances

The clothing industry needs to abide by a number of laws pertaining to labor practices, environmental sustainability, and product safety. Adoption of Industry 5.0 technology can bring up new compliance issues, such as making sure robotics and AI are used ethically or making sure automated manufacturing processes adhere to environmental regulations. The lack of standardized regulations for emerging technologies makes it difficult for industries to ensure compliance across different jurisdictions (Rehman and Umar 2025). To prevent fines and reputational issues, clothing brands need to stay up to date on regulatory developments and modify their operations accordingly.

Sustainability Issues

Industry 5.0 raises questions regarding its potential effects on the environment even as it presents chances for waste reduction and resource optimization. The complexity of managing these technologies in harmony with existing systems can lead to inefficiencies, requiring significant time and resources to overcome. The manufacturing of textiles uses a lot of energy, water, and raw materials, which increases pollution and greenhouse gas emissions. Additionally, there is a need for new standards and regulations to ensure that sustainability efforts align with global environmental goals, which can be slow to develop. Textile industries need to strike a balance between the advantages of automation and sustainable practices in order to reduce their environmental impact and satisfy consumer demand for green clothing items.

Sustainability of Raw Materials

Like other industries, the clothing industry is focusing on Industry 5.0, which aims to produce sustainable and efficient operations by combining sophisticated technologies with sustainability principles. Compared to traditional approaches, eco-friendly materials and processes can have greater upfront prices (Gunay 2013; Karuppusamy et al. 2015). For businesses, particularly smaller ones or those in price-sensitive industries, it can be a major challenge. Locating sustainable resources on a large scale might be challenging. Industries find it difficult to implement eco-friendly clothing items on a large scale because many are still in the early phases of research or have limited availability (Ozlu et al. 2024). Compared to the conventional counterparts, some sustainable materials could not provide the same performance qualities. It can be problematic in industries where durability and performance are essential, like textiles where comfort, strength, and lifespan are vital components (Samanta et al. 2014).

It might be challenging to increase the production of eco-friendly materials and procedures to satisfy the needs of mass manufacturing. One of the biggest challenges in developing sustainable production systems is ensuring that these are scalable and efficient. Even while interest and awareness for sustainable clothing items are growing, some buyers can still place a higher value on performance and cost than environmental sustainability (Chavan 2011). It is still challenging to persuade consumers to purchase environmentally sustainable clothing items, particularly when cost more. Using sustainableeco-friendly raw materials and procedures becomes more difficult when strict environmental standards can be followed. To maintain compliance and maintain their competitiveness, businesses need to manage an intricate structure of rules and standards. A substantial investment in research and development is necessary to create new environmentally sustainable materials and procedures. Industries and fashion brands in fast-paced industries like textiles can find it difficult to satisfy sustainability goals while keeping up with rapid technical improvements (Mu and Yang 2022).

Although sustainable materials have an influence on the environment, recycling and end-of-life disposal procedures also need to be taken into account. Reducing waste generation in textile and apparel manufacturing processes can be achieved by implementing advanced technologies including automation, robots, and AI-driven process optimization (H.-W. Hsu et al. 2024a, b; Senthilkannan Muthu Editor 2020). These technologies aid in waste reduction and increased resource efficiency by streamlining production parameters and cutting down on material inefficiencies. Industry 5.0 makes it possible to embrace closed-loop systems and circular economy practices. Blockchain technology and IoT-enabled tracking systems can improve supply chain traceability and transparency and make it easier to recover and recycle textile materials. Textile manufacturers can optimize product designs and reduce material waste prior to manufacturing by utilizing digital design tools and virtual prototype technology.

Investments in technological progress

In the clothing industry, switching from conventional machinery to Industry 5.0 technologies presents a number of challenges. Industry 5.0 technology, such as IoT sensors, data analytics, and automation systems, cannot be compatible with traditional machinery because of a lack of connectivity and digital capabilities. It can be costly and time-consuming to retrofit or replace outdated equipment to make it compliant. Employees used to operate conventional machinery might not have the knowledge and experience required to operate and maintain Industry 5.0-enabled technology. It is crucial to close the talent gap through reskilling and upskilling initiatives, but doing so can cost money and time. In Industry 5.0 contexts, real-time data necessary for optimization and decision-making cannot be generated or transmitted by traditional machinery. It might be difficult to integrate data from outdated machinery with digital platforms and analytics programs; creative approaches to data collecting and integration are needed. Conventional machinery might be built for particular jobs or procedures, which would limit its capacity to adjust and change course in response to shifting production needs. The focus of Industry 5.0 is agility and adaptability; thus, textile manufacturers need to upgrade their current machinery or make more adaptable equipment purchases to keep up with changing demands. More regular maintenance and repairs can be necessary for older machinery, which could result in more downtime and production delays. In an Industry 5.0 setting, ensuring the dependability and uptime of conventional machinery might necessitate further investing on monitoring and predictive maintenance technologies. For certain textile manufacturers, particularly SMEs with limited funding, upgrading or replacing outdated equipment with Industry 5.0 technologies can be prohibitively expensive. It is quite difficult to strike a balance between the initial costs of investment and the long-term advantages of increased productivity and competitiveness.

Enablers and Future Directions of Industry 5.0 in the Clothing Industry

The clothing industry stands to gain greatly from Industry 5.0, which ushers in a new era of innovation, sustainability, and consumer-centricity. The combination of human ingenuity and advancedcutting-edge technologies presents a noteworthy prospect for the creation of highly personalized clothing items that ensures personal tastes. By working together, humans and machines can create complex patterns and textures using digital technologies like AI and virtual reality. It preserves traditional fashion design while satisfying the needs of contemporary consumers (Barreto et al. 2017). Additionally, it promotes sustainable clothing manufacturing through waste reduction, sustainable raw materials and process adoption, and resource optimization. It is compatible with consumers' increasing desire for sustainableeco-friendly clothing itemsproducts, giving textile manufacturers who practice sustainability a competitive edge. Future advancement areas of Industry 5.0 in the clothing sectore are pointed out in Fig. 9. Industry 5.0 facilitates flexible manufacturing, which enables clothing brands to efficiently generate small-batch or on-demand orders and quickly adjust to market changes. Production systems that are interconnected improve the visibility and responsiveness of the supply chain, simplifying processes and cutting lead times. It provides the clothing industry with the means to innovate, set itself apart, and prosper in a market that is changing quickly, all the while tackling urgent issues like sustainability and customization.

Enhanced Technologies

Production processes are optimized by modern technology like automation, robots, and AI, which results in heightened efficiency. Higher productivity is achieved by completing labor- or time-intensive tasks more quickly and precisely than in the past. Industry 5.0's technological foundations are presented in Figure 10a. AI can predict trends, optimize manufacturing, and enhance SCM (Kazancoglu et al. 2023). AI-driven systems can analyze consumer preferences, allowing for the production of highly customized apparel, while also ensuring efficiency and sustainability in operations. Robotic

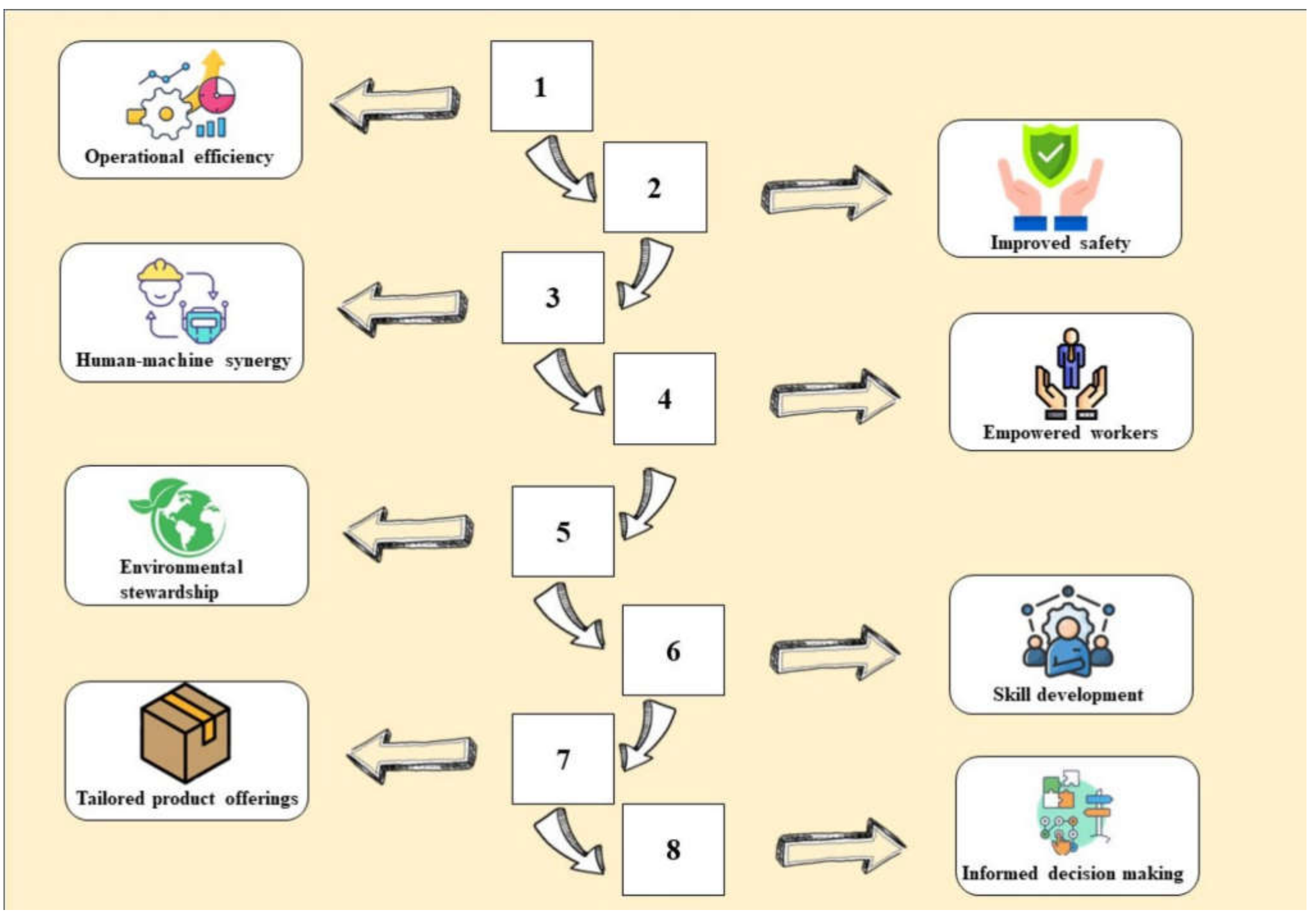

Fig. 9 Research Areas for the Future Advancements of Industry 5.0 in the Clothing Sector

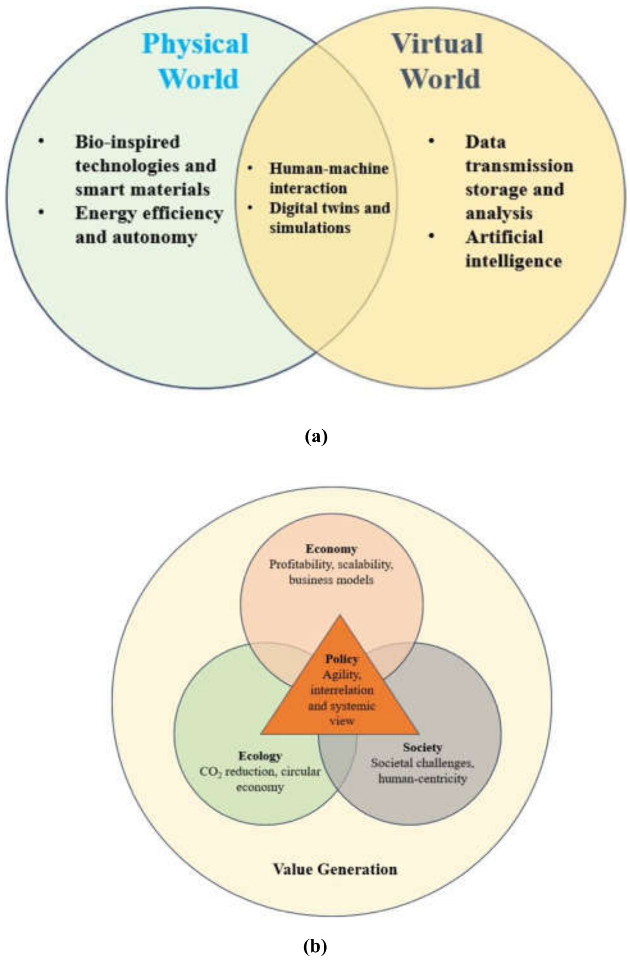

Fig. 10 **a** Technological pillars of Industry 5.0 (X. Xu et al. 2021c). **b** Global perspectives of Industry 5.0 (Celent et al. 2022)

automation is another promising technology that can continue to play a pivotal role in the future of the clothing industry (Barreto et al. 2017). These advanced robots combined with human oversight can perform complex tasks such as cutting, sewing, and finished apparel with precision and speed. It can reduce human error and waste. Alongside automation, 3D printing technology enables on-demand production. It can allow manufacturers to produce prototypes or final clothing items with less waste and faster turnaround times.

Improved Control

Industry 5.0 promises significant advancements in the clothing industry, particularly in the area of improved control over production processes. By integrating advanced technologies, the clothing industry can achieve unprecedented levels of precision and flexibility in manufacturing. It allows for the creation of highly personalized clothing items at scale, enhancing customization options for consumers while reducing waste and optimizing production efficiency (Di Maio et al. 2017). Real-time monitoring of manufacturing parameters is made possible by sensors and AI-driven systems, which enables manufacturers to promptly detect flaws or departures from quality standards (Barreto et al. 2017). It reduces the possibility of defective clothing items entering the market and improves quality control.

Customization

Industry 5.0 is poised to revolutionize the clothing industry by enabling unprecedented levels of customization and individualization. Unlike Industry 4.0, which focuses on automation and efficiency, Industry 5.0 emphasizes the collaboration between humans and machines to deliver more personalized, consumer-centric clothing items (Rahaman and Khan 2024). This transition allows consumers to actively engage in the design process, manufacturing apparels to their specific preferences in terms of style, fit, color, and fabric choice. Industry 5.0 technologies enable clothing items to be customized and personalized. Manufacturers can create items that are specifically adapted to the preferences and demands of consumers due to digital design tools, 3D printing, and digital printing. It increases consumer happiness and enhances brand loyalty (Di Maio et al. 2017).

Circular Economy and Sustainability

As sustainability and circular economy principles become increasingly vital in addressing the environmental impacts of the fashion sector, Industry 5.0 providesoffers solutions that promote resource efficiency, reduce waste, and enhance the durability of clothing items. Through the use of AI and IoT, manufacturers can optimize production processes, minimize material waste, and create smart systems that track apparel life cycles. It can allow for more efficient recycling and upcycling (Rahaman and Khan 2024). Additionally, human-centered approaches enhancer innovation by combining fashion design and design expertise with advanced technologies. In the clothing manufacturing industry, modern technologies help with sustainability goals (Kazancoglu et al. 2023). Digitalization and data analytics, for instance, maximize the use of resources while minimizing waste and consuming less energy. In addition, the environmental sustainability of clothing manufacturing is further improved by the incorporation of sustainable materials and procedures.

Digitalization in Supply Chain

The future of supply chain optimization within Industry 5.0 can involve greater customization, enabling brands to respond more efficiently to consumer demands. By utilizing AI-driven analytics, clothing manufacturers can predict trends, optimize production schedules, and manage inventory more effectively (Barreto et al. 2017). The clothing industry's SCM is enhanced by Industry 5.0 technology. Manufacturers can ensure transparency, efficiency, and regulatory compliance by tracking and tracing materials, components, and finished clothing items across the supply chain with the help of data analytics, blockchain technology, and IoT devices. Additionally, the integration of blockchain for transparency and traceability can ensure ethical sourcing and sustainability practices, meeting the growing demand for environmentally sustainable production. As Industry 5.0 continues to evolve, its impact on supply chain optimization in the clothing industry can enhance more flexible, sustainable, and consumer-centric operations (Di Maio et al. 2017).

Upskilling Programs

As Industry 5.0 integrates advanced technologies with human creativity and intuition, the workforce can require a blend of traditional skills and new technological proficiencies. Adopting modern technologies calls for a workforce with the expertise to run and maintain intricate systems. In order to provide workers with the skills and knowledge necessary to use these technologies efficiently, Industry 5.0 promotes investments in training and upskilling programs. It increases innovation and competitiveness in the clothing industry. Workers can need to adapt to operating and collaborating with smart machines, interpreting data from advanced manufacturing systems, and utilizing new digital tools for design, production, and quality control (Rahaman et al. 2024). Skill development programs can focus on interdisciplinary expertise, combining technical know-how with creativity to enhance innovation in clothing design and production.

Globalization

ClothingTextile manufacturers can now collaborate globally and reach markets more easily due to advanced technologies. Manufacturers and consumers are connected globally through digital platforms, e-commerce, and online marketplaces, which broadens the market and creates growth potential (Rahaman and Khan 2024). Additionally, technologies like virtual prototyping and 3D modeling allow for cross-border collaboration and virtual product development. The global perspectives of Industry 5.0 are displayed in Figure 10b. Globalization and commercialization are two driving forces that shape its future prospects. As the clothing industry continues to expand globally, the integration of Industry 5.0 technologies promises to enhance product customization, improve supply chain transparency, and promote greater collaboration between humans and machines.

Adaptability

Industry 5.0 technologies improve the adaptability and robustness of clothing manufacturingproduction processes. Adaptability also extends to manufacturing, where production lines can adjust quickly to market demands. It has a prospect of reducing waste and improving sustainability (Barreto et al. 2017). By enabling AI and data analytics, clothing brands can forecast trends, optimize inventory, and reduce lead times, ensuring remain responsive to changing consumer needs and environmental factors (Di Maio et al. 2017). Manufacturers can mitigate risks and sustain competitiveness in dynamic business contexts by promptly responding to external factors such as supply chain disruptions, shifting market needs, and other events by enabling real-time data analysis and decision-making.

Predictive Maintenance

As the clothing industry becomes more reliant on automation and smart machinery, predictive maintenance stands out as a crucial aspect of enhancing operational efficiency and minimizing downtime. Industry 5.0 makes predictive maintenance techniques possible for the clothing industry, which minimizes maintenance expenses and equipment downtime (Rahaman et al. 2024). Production uptime and asset usage are maximized by proactive maintenance scheduling, predictive maintenance, and equipment health monitoring provided by IoT sensors and machine learning algorithms. By using sensors, AI algorithms, and machine learning, predictive maintenance systems can monitor equipment in real-time. These technologies can detect anomalies and forecast potential issues before.

Enabling consumer research

Enabling consumer research involves implementing strategies and tools that help businesses gather meaningful insights into customer behavior, preferences, and expectations. The future prospects of Industry 5.0 in the clothing industry lie in its potential to revolutionize consumer experiences by enhancing deeper personalization, greater sustainability, and enhanced interactivity. Textile industries can now provide improved consumer experiences via digital platforms, e-commerce channels, and interactive marketing tools due to Industry 5.0 technologies (Kazancoglu et al. 2023). Virtual try-on experiences, immersive product presentations, and personalized suggestions increase consumer engagement and increase revenue. With AI and machine learning, clothing brands can study consumer data to predict preferences, style choices, and body measurements. It allows them to provide personalized recommendations and made-to-order clothes. It can include using surveys, focus groups, and digital analytics to collect and analyze data directly from consumers (Rahaman and Khan 2024). Additionally, smart textiles and wearable technology, like fabrics with sensors, provide consumers with a more interactive and practical shopping experience, improving both style and comfort.

Global Collaborations

Industry 5.0 promotes global collaboration and connection within the clothing industry, facilitating cross-border alliances, information exchange, and market expansion. Industry 5.0 represents the next phase in the evolution of industrial processes. The synergy between humans and advanced technologies, such as AI, robotics, and automation can lead to the creation of more personalized, sustainable, and efficient manufacturing systems (Safavi Jahromi and Ghazinoory 2024). Global supply chain networks, virtual collaboration platforms, and digital communication technologies make it easier for stakeholders to collaborate, which increases innovation and competitiveness (Pinto et al. 2024). It can enhance the exchange of innovative design ideas, production techniques, and best practices, leading to the development of highly customized, on-demand fashion that ensures diverse consumer preferences.

Data-Driven Waste Management

Through data-driven systems, manufacturers can track waste generation at every stage from fabric cutting to clothing assembly, identifying patterns and inefficiencies. Predictive analytics can then be applied to forecast waste generation. It can allow for more precise resource allocation and waste reduction strategies (Rahaman et al. 2024). Throughout the production process, textile waste can be continuously monitored and analyzed due to Industry 5.0 technologies like IoT sensors and data analytics (Bajic et al., 2023). Manufacturers can find opportunities for waste optimization and reduction by gathering information on waste generation, content, and sources. As Industry 5.0 continues to evolve, it can empower the clothing industry to not only minimize waste but also recycle and repurpose materials more effectively, aligning with circular economy principles and driving the industry toward greater sustainability and resource efficiency.

Closed-Loop Recycling

Industry 5.0 makes it easier to put closed-loop textile waste recycling systems in place. As it develops, closed-loop recycling could play a key role in making the fashion industry more sustainable. Using advanced technologies like AI, automation, and smart materials, clothes can be designed to be recyclable from the start (Kazancoglu et al. 2023). It allow apparels to be taken apart and their materials reused, cutting down on waste and saving natural resources. The recovery of valuable recycling materials is made possible by the efficiency and precision of waste separation enhanced by robotic sorting arms, AI, and advanced sorting technologies. Future technologies might include smart fabrics that can be easily separated and reused, or AI systems that track the lifecycle of apparels, ensuring these are returned to the recycling loop at the end of their use (Hu et al. 2014). This transition would not only contribute to environmental sustainability but also provide new opportunities for innovation, creating a more resilient and eco-conscious industry.

Life Cycle Management

Life cycle management focuses on tracking, assessing, and minimizing the environmental impact of apparels from raw material sourcing to production, distribution, usage, and end-of-life stages. Textile items are tracked and traced from production to end-of-life disposal, due to Industry 5.0 technologies (Rahaman et al. 2024). Transparent and traceable supply chains are made possible by RFID tags, QR codes, and blockchain technology, which also ensures accountability and encourages appropriate recycling and disposal methods. With the rise of Industry 5.0, advanced technologies like AI, IoT, and big data can be the key in improving life cycle management. AI can help design and produce apparels with a smaller environmental impact by predicting the best materials and manufacturing methods (Di Maio et al. 2017). IoT can enable real-time tracking of clothing performance, providing insights into durability and wear. Additionally, blockchain technology can ensure transparency and ethical sourcing, allowing brands to trace sources of textile raw materials, and maintain sustainability standards.

Resource Optimization

In the clothing industry, the future prospects of Industry 5.0 provide significant potential for resource optimization. It encourages a more intelligent, interconnected, and eco-conscious approach to production, where advanced technologies like AI, machine learning, and IoT work alongside human expertise to reduce waste, energy consumption, and raw material use (Ghobakhloo et al. 2023). By optimizing the value generated by textile waste, Industry 5.0 makes resource optimization possible. Textile manufacturers can trade waste materials for recycling or reuse with manufacturers and recyclers using digital platforms and marketplaces. Additionally, Industry 5.0 promotes sustainable practices by facilitating the use of renewable materials, recycling, and reducing carbon footprints, all while maintaining high levels of customization and quality (Nahavandi 2019). The transition toward more personalized and efficient clothing manufacturing can also lead to greater consumer satisfaction, reduced environmental impact, and ultimately, a more sustainable clothing industry.

Conclusions

This review paper has explored the transformative shift from Industry 4.0 to Industry 5.0 in the clothing industry. It analyses the integration of advanced technologies such as robotics, AI, and the IoT to promote sustainable and additive manufacturing practices. The key theoretical implication of this review remains in evaluating the critical role of human-centric approaches in advancing technological integration within the textile and apparel industry. By emphasizing creativity, inclusivity, and collaboration, the study provides a theoretical framework for incorporating human elements in the adoption of Industry 5.0 technologies. From a practical perspective, it provides valuable insights into how the clothing sector can accept Industry 5.0 for increased sustainability, productivity, and innovation. The transition towards a human-centric model presents a significant opportunity for manufacturers and brands to address social and environmental challenges while enhancing consumer engagement and product differentiation. It discusses the practical significance of adopting resilient, flexible systems that encourage continuous learning and development.

Despite ensuring valuable insights, this review has several boundaries. The transition from Industry 4.0 to Industry 5.0 in the context of sustainable and additive manufacturing in clothing is a relatively new and evolving area. As a result, the availability of comprehensive empirical data and longitudinal case studies is very limited which restricted deeper quantitative analysis. Additionally, most of the existing literature are conceptual or theoretical in nature, with few real-world implementations currently documented, particularly in developing countries where the adoption of advanced technologies is still in primary stages. The integration of human-centric and ethical considerations is still under-researched within the specific scope of additive manufacturing in the clothing industry which clearly indicates a gap for future empirical exploration.

Future research should focus on the requirement for further exploration of the specific challenges faced by SMEs in implementing Industry 5.0 technologies and how these challenges can be mitigated through policy or financial incentives. Research should also explore the development of decentralized and intelligent manufacturing models that encourage mass personalization of clothing while adhering to circular economy principles. Investigating the long-term impact of Industry 5.0 on the global textile supply chain, particularly in terms of sustainability and ethical labor practices can be significant for ensuring the successful implementation of the paradigm transition. Research into the integration of digital twins and AI-driven decision-making tools can ensure more accurate production without causing errors and could provide valuable insights into enhancing efficiency, reducing waste, and improving resource management to promote circular economy.

Acknowledgements The authors gratefully acknowledge the support provided by the Department of Textile Engineering, Mawlana Bhashani Science and Technology University, Tangail.

Author Contribution M.T.R.: conceptualization, methodology, data curation, data collection, formal analysis, validation, visualization, writing—original draft preparation, review and editing, content approval, supervision; A.D.P.: conceptualization, methodology, data collection, resources, data visualization, formal analysis, writing—original draft preparation, review and editing; and S.A.: writing review and editing.

Data Availability No datasets were generated or analysed during the current study.

Declarations

Ethical Approval The ethical approval and consent have been obtained where necessary. Where approval has been waived, credit has been given via appropriate citation.

Consent to Participate Not applicable.

Conflict of interest The authors declare no competing interests.

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