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Technologies of Industry 4.0 for the next fashion revolution: A systematic literature review

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Abstract*– Fashion industry has undergone significant changes over time due to the variations on perception, exigencies, and activities of customers around the world. Because of the fluctuating and increasing demand, one of the main concerns of fashion-related activities is pollution, particularly water and air pollution. To that, some technologies from industry 4.0 technologies could be useful for mitigating the negative environmental impact in the fashion industry. Based on this challenge, the article aims to identify the most relevant technological applications of Industry 4.0 to enhance sustainability in production and service processes. To achieve this, two methodologies (PICOC and PRISMA) were used to search and select articles for the research. Through inclusion and exclusion criteria, thirty open-access articles from the Scopus database were chosen. Nowadays, it is known that fashion industry activities represent approximately 8% to 10% of global carbon emissions contributes to industrial wastewater pollution (20%), and generates substantial amounts of waste of materials and energy. Hence, there are various Industry 4.0 technologies that can be combined to improve sustainability in different processes within the fashion industry (textile manufacturing, supply chain management, store management, user experience). After the analysis, it was concluded that technologies such as virtual reality, digital twins, and artificial intelligence, belonging to Industry 4.0, offer a potential solution to mitigate the negative environmental impact of the fashion industry an enrich the customer-business interaction. Further works must explore the benefits and limitations of these technologies, focusing in small and midsize enterprises (SMEs).

Keywords*—fashion industry, industry 4.0, fashion 4.0, artificial intelligence, virtual reality.

I. INTRODUCTION

Industry 4.0 is a term used to describe and relate different tools and techniques that associated cyber-physical technologies, data processing and modern manufacturing process into networks and enable continuous operations. It is known as fourth industrial revolution because it defines a new level of organization and control over product life cycle value chain, with emphasis on customer requirements, costumer experience and stronger competitiveness. The most recent technologies and trends mentioned in the latest investigations are Artificial Intelligence (IA), Internet of Things (IoT), Virtual Reality (VR), 3D printing, advance robotics, digital twins, data analytics and others. In all cases, researchers and entrepreneurs related with these terms look for the development of integrated and intelligent systems able to analyze big amount of data, able to adapt in our changeable world by increasing the flexibility of the process with an efficient resource management [1].

According to Dantas et al. [2], Industry 4.0 is a set of advanced technologies that can establish a positive impact on the environment, because it can reduce the use of energy and materials and promote reuse. On the other hand, the implementation of these technologies can also contribute to the construction of more resilient and sustainable infrastructures, encouraging innovation and achieving the sustainable development goals established by the UN. As mentioned, Industry 4.0 represents a stage of digital transformation that encompasses various industrial companies, taking advantage of technologies such as artificial intelligence, digital twins and virtual reality. Its main objective focuses on improving efficiency and promoting environmental sustainability. Through the development of innovative tools, it seeks to reduce the negative impacts of industrial processes, allowing more efficient waste management and a more responsible use of resources according to sustainable practices.

One of the industries that generate the most pollution is the fashion industry because it is one of the most important resource-demander activities in the world that produces a large amount of wastewater and CO_2 emission. The increasing in clothing consumption is putting the environment at risk, so the industry must take responsibility for its environmental effects and reduce the consumption of water, energy, chemicals, reduce the emissions CO_2 and waste generation. Through the adoption of new materials and business strategies to reduce the negative effects of garment production and consumption [3]–[8]. The implementation of technologies that help to reduce several impacts and provide a better experience for the consumer is a main topic for research. Several studies (Alves et al. [9], Charnley et al. [10], Gu et al. [11], Islam et al. [12]; Jeong & Sohn [13], Lee [14], Noh [15], Pan [16], Sharma et al. [17]; Shi et al., 2021; von der Assen [18]) analyze the use of artificial intelligence in the fashion industry. Different authors have discussed different applications of artificial intelligence, such as optimizing the purchase of sustainable fashion and circular user experience, fashion analysis, business models focused on recycling, fashion design, classification of recycled clothing, prediction and analysis of fashion and retail trends.

On the other hand, other authors [19]–[23] point out that the use of digital twins in the fashion industry offers various applications that contribute to improving efficiency, productivity, safety, sustainability and, at the same time,

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providing greater creative opportunities and flexibility regarding the design and presentation of products. These applications include the digitization of designs and materials, virtual fashion shows and creation of promotional content, as well as the simulation and optimization of processes.

Finally, Casciani et al. [24], Lee [25], Morotti et al. [26], Ricci et al. [27] and Wang [28] consider virtual reality as one of the innovation technologies that can be used in the fashion industry to engage consumers and to provide information about the origins of fabrics and garments. In addition, most of these applications promote personalization and educate consumers about lifecycle of clothes, consumption and disposal of garments, designing sustainable solutions in the field of fashion and optimization of shopping user experience. The technological advances promise to transform the field of the fashion industry and provide original solutions for changing consumer demands, focused on sustainability. Therefore, the objective of this study is to analyze the application of Industry 4.0 technologies in optimization and sustainability of production and service processes. This manuscript summarizes the results on environmental impact, applications, benefits and limitations of industry 4.0 technologies in the fashion industry. Novel technologies will contribute to reduce environmental deterioration caused by fashion industry.

II. Methodology

Systematic literature review aims to determine and evaluate the main technologies related to industry 4.0 employed in fashion industry. A comprehensive bibliometric analysis was performed by using two strategies: PICOC framework and PRISMA methodology. For this work, the authors have followed these guidelines:

- Definition of a research question for the review.
- Systematic search and selection of articles (PICOCT framework and PRISMA methodology).
- Organization and analysis of the collected data.
- Presentation and discussion of the results.

Firstly, the definition of the research question is focused on the main technologies from industry 4.0 employed in fashion and textile industry to enhance the costumer experience or mitigate the environmental impact. The research question is: “What are the industry 4.0 technologies employed for the optimization and sustainability of industrial process and services in fashion industry?” The systematic search started by the definition of the main points using a PICOC framework (P: population or problem, I: intervention, C: comparison, O: outcome, C: context), detailed in Fig. 1. For each point, key questions and related keywords are reported. The “Population” section is referred to the main technologies analyzed for the investigation: “What are industry 4.0 technologies? “Intervention” section collects different terms associated to applications in fashion industry: What are the main technological applications of industry 4.0 in fashion industry. The “Comparison” sections show the main keywords associated with the pros and cons of industry 4.0 technologies: What are the most important benefits and relevant impacts of industry 4.0 technologies in production process and services? “Outcome” section describes the main applications related to industry 4.0 technologies: What are most relevant consequences of industry 4.0 technologies in fashion industry. Finally, “Context” section encloses the investigation in specific sector: fashion industry.

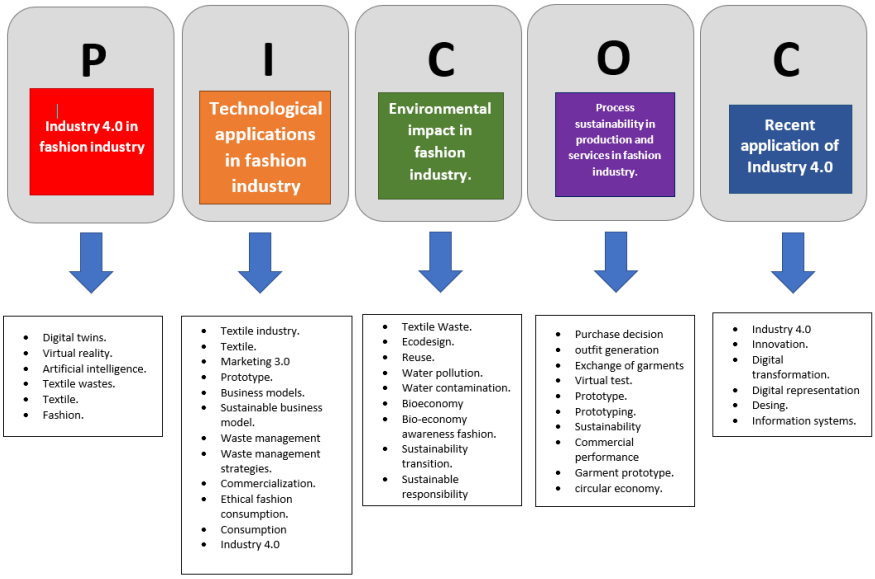

Fig. 1. PICOC framework (components and keywords).

According to the keywords determined in the PICOC framework, the research equation was formulated using Booleans connectors OR y AND as follow for being used in SCOPUS database: TITLE-ABS-KEY ("Digital twins" OR

"Virtual reality" OR "Artificial intelligence" OR "TEXTILE WASTE" OR textile OR fashion) AND TITLE-ABS-KEY (textile OR "textile industry" OR "Marketing 3.0" OR prototype OR "Business models" OR sustainability OR "Sustainable business model" OR "waste management" OR "Waste management strategies" OR "Commercialization" OR "Ethical fashion consumption" OR consumption OR "textile consumption" OR "industry 4.0") AND TITLE-ABS-KEY ("Textile Waste" OR eco-design OR reuse OR "Water pollution" OR bioeconomy OR "Bio-economy awareness fashion" OR "Sustainability transition" OR "sustainable responsibility") AND TITLE-ABS-KEY ("purchase decision" OR "outfit generation" OR "exchange of garments" OR "virtual test" OR "PROTOTYPE" OR prototyping OR sustainability OR "commercial performance" OR "Garment prototype" OR "circular economy") AND TITLE-ABS-KEY ("Industry 4.0" OR innovation OR "Digital transformation." OR "digital representation" OR design OR "Information systems").

As a result, 138 articles were identified after the inclusion and exclusion process, considering that there were no duplicate records. Through the review of titles and/or abstracts, 119 articles were discarded, leaving 19 for full-text evaluation. Of those 19 articles, 2 were not available in their entirety, leaving a total of 17 publications for final evaluation. During the full-text evaluation, 2 articles that were not related to technology 4.0, 6 papers were not related to the fashion industry, and 5 papers did not address the negative environmental effect of the fashion industry were excluded. Thus, only 4 articles relevant to the research topic were obtained. Due to the low number of relevant articles obtained, a new selection of documents was made based on the articles related to the studies previously found (related articles). After searching related articles, 26 documents were added as shown in the PRISMA scheme (Fig. 2).

Table 1. List of criteria of inclusion and exclusion.

Inclusion criteria	Exclusion criteria
- Research articles related to industry 4.0 and fashion industry. - Applications of artificial intelligence, digital twins and virtual reality in fashion industry. - Articles related to innovation in sustainability in fashion industry. - Technologies for optimization of production process and services. - Document type: original articles and review articles. - Year: 2019-2023	- Technologies no related to environmental footprint evaluation. - Traditional technologies applied in fashion industry. - Technologies with no relation with industry 4.0. - Only articles written in English, excluding conference papers, books and letters.

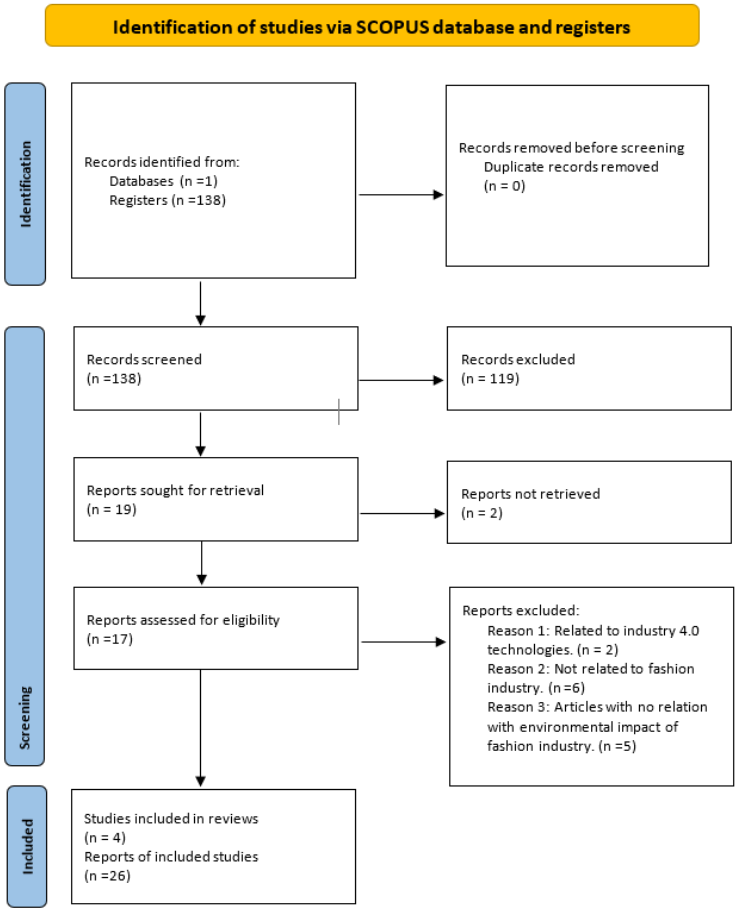

Fig. 2. PRISMA flow diagram for this systematic literature review.

III. Results and Discussion

Fashion plays a notable role in the development of clothing design, manufacturing and marketing. Despite its many positive contributions to the economy, fashion industry presents negative environmental effects due to its activities (Fig. 3). Fashion industry produces approximately 8 to 10% of global carbon emissions [29]. It is estimated that 30% of purchased clothing remains hanging unused in closets, and consumers are throwing away increasing volumes of clothing and, most of clothes residues are incinerated [6], [21], [29]. An equivalent percentage ends up in landfills after being used less than five times (on average), and sometimes clothes are discarded after the first use. In total, 14 million tons of used clothing and textiles are thrown away every year around the world [15]. In addition, Battesini Teixeira et al. [5] reported that only 27% of the clothing produced is recycled or reused. This means that large quantities of products end up as garbage, are incinerated or abandoned in remote locations. At the same time, this industry uses a large amount of water (about 93 billion cubic meters) in the manufacturing process, which contributes approximately 20% of pollution in industrial wastewater [6], [7]. Additionally, chemicals are used during

"wet process" stages such as dyeing, washing, printing and finishing fabrics. Approximately, around 200 tons of water for every metric ton of textiles produced. Therefore, the entire sector is responsible for being one of the main generators of greenhouse gases and wastewater [9].

In another instance, Industry 4.0 technologies can accelerate the industrial transition towards circularity and improve the climate sustainability indicators of this industry. Due to these technologies allow the transfer of real-time data on the status, availability, accessibility, and material and product resources, the fashion industry is taking advantage in sustainably optimize garment design, manufacturing and sales protocols. Some of these technologies include: virtual reality, digital twins, artificial intelligence, IoT, blockchain, CAD, augmented reality, big data, and 3D printing. In Table 2, different technologies from industry 4.0 previous reported in the last 5 years have been summarized. Moreover, Fig. 4 scheme shows how these technologies can work together to promote innovation and digital transformation, adapting to the specific needs and objectives of the industry. Another graph shows the percentage of articles that involve VR, AI and digital twins for this systematic review literature (Fig. 5).

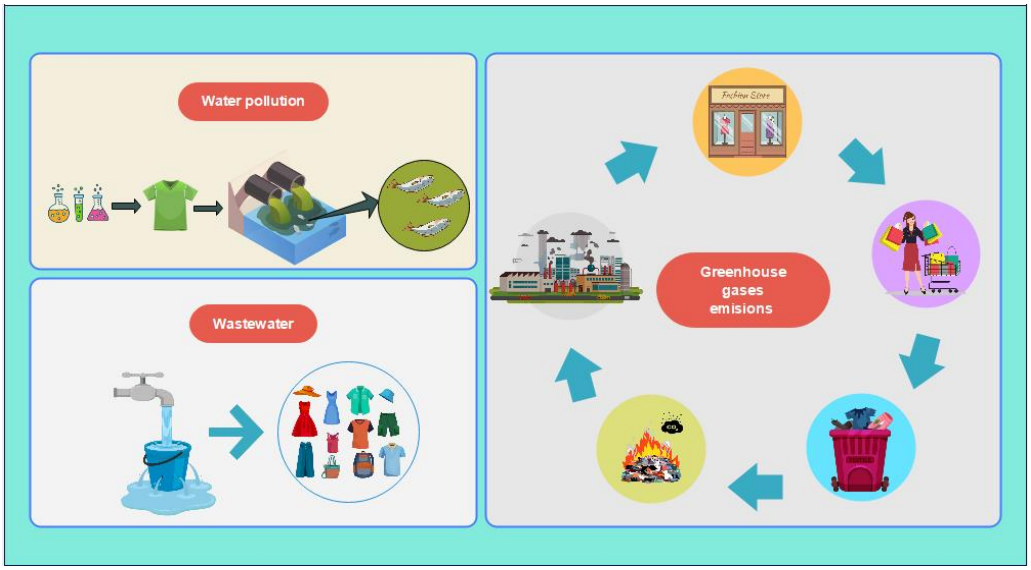

Fig. 3. Examples of environmental impacts of fashion industry.

Table 2. Different technologies of industry 4.0 applied to fashion activities reported in the last five years.

Technology	Application	Main contributions	Reference
Big data with artificial intelligence	Fashion recognition Fashion understanding Fashion application	**Low-level recognition: Employment of fashion images** - Clothing/human parsing: Graphical models, non-parametric models, parselets representation methods, CNN models and adversarial models. - Landmark detection. **Middle-level recognition: Clothing attributions and compact representation for describing people.** - Clothing attribute prediction: Single-task learning, multi-task learning, transfer learning. - Fashion style prediction: Supervised and unsupervised learning. **High-level recognition: fashion retrieval, fashion recommendation, fashion compatibility, fashion image synthesis and fashion data mining.** - Fashion retrieval: cross-scenario retrieval model, interactive retrieval model. - Fashion recommendation: Complementary recommendation model, personalized recommendation model, scenario-oriented recommendation model, explainable recommendation model, generic model. - Fashion compatibility: pairwise compatibility learning, outfit compatibility modeling. - Fashion image synthesis: Pose guided generative model, text guided generative model, virtual try-on model, image transformation model, fashion design model. - Fashion data mining: fashion trends analysis, hybrid analytics.	Gu et al. (2020) [11]
Artificial Intelligence and Big Data	Clothing design	**Intelligent design scheme:** 1. Adaptive fusion docking: The utilization of big data establishes that data resources should be dynamically connected with the needs of customers as much as possible to fully guarantee the level of Shared data and business openness. 2. Open data: The idea of integrating intelligent design into costume design means that more inter-group requirements can be quickly connected to the terminals of software and hardware. 3. Adhere to aesthetic comfort: The purpose of innovative clothing design is always to return to make the human body feel comfortable, happy and beautiful to wear, and the intelligent	Pan (2020) [16]

		selection of materials is the key step of intelligent design. 4. Big data security refers to the protection of data security required by artificial intelligence, as well as the privacy information security of consumers.	
Artificial intelligence	Apparel design	**Application of SEAN (Semantic region-adaptive normalization):** In deep learning, normalization is used to normalize the output of the intermediate layer. Stable learning is possible by forcing the distribution of the output values of the activation function, but a lot of information is lost. Is it possible to modify images by segmentation to visualize an outfit. Additionally, experts can easily prototype ideas and stimulate imagination, which will help in design development.	Yoojin et al. (2020) [30]
Internet of things and deep learning	Recycled clothing classification	It is proposed a recycled clothing classification system with IoT and AI using object recognition. The IoT device consists of Raspberry pi and a camera, and AI uses the transfer-learned AlexNet to classify different types of clothing. To classify the clothing images collected by the recycled clothing image datasets, the CNN used transfer-learned AlexNet. AlexNet used in the experiment was a pretrained CNN written in MATLAB, and deep learning to identify the surrounding objects, which is trained on more than 1 million images and can be classified in real time into 1,000 categories, including keyboards, coffee mugs, pencils, and various animals	Noh (2021) [15]
Artificial intelligence and virtual environments	Sustainable real-time fashion system (RTFS)	Fashion companies in RTFS will be able to use personalization and customization, and the focus will be on how to effectively match the design of clothing to the behaviors and interests of users according to consumers or prosumers. There are five elements to the upcoming RTFS: - Purchase and use products in real time. - Consumers involved in personalization and manufacturing - AI-based interactions (designs, size and style). - 3D-CAD and AI-based products. - Real-time supply chain tracking services.	Lee (2021) [25]
Artificial intelligence	Fashion trend forecasting	The study proposes a data-driven quantitative abstracting approach using an artificial intelligence (A.I.) algorithm. The proposed A.I. model is believed to have the ability to detect fashion attributes from images with some degree of accuracy (around 75%) from static runway images. The proposed A.I. model is also able to discover fashion trends for ZARA's products as com- pared with the forecasting analyses prepared by Vogue to some degree.	Shi et al. (2021) [31]
3D garment CAD	Intelligent Data-Driven System to Recommend Personalized Fashion Design Solutions	**Proposed Data-Driven Interactive Design System Architecture** 1. Prediction of body shape group using biometric profile. 2. Prediction of the most relevant garment fitting style adapted. 3. Identification of the most relevant garment style. 4. Identification of the most relevant fabric (3D CAD tool and Kd-tree algorithm) 5. Radial basis function neural network (RBFNN). The proposed system is directly involved in the process of increasing the proximity between designers, consumers, and fabric manufacturers.	Sharma et al. (2021) [17]
Industry 4.0 technologies	Sustainable textile manufacturing	**Application of Industry 4.0 technologies:** - Smart factory: Technology significance for local textile industry. Energy and waste management. - Cyber-physical systems: Smart decision model. - Internet of services: qualitive analysis, value chain transparency.	Stulga et al. (2022) [1]
Big data and decision-making analysis	Develop a sustainable manufacturing proposal for the industrial textile sector	The implementation of a model of production and industrial systematization focused on Big Data and applied through Power BI software and visualization of Dashboard caused the reduction time among the processing of batches of orders and company's customers.	Araque-Gonzalez et al. (2022) [4]
Virtual Reality	Computer-Aided Garment Design CAD Based on Virtual Reality Model	The computer-aided garment design virtual reality (VR) model for surplus fabric removal and reuse without segmentation of cutting pieces is proposed to improve the efficiency of garment design. CAD computer technology is used to transform the 3D garment into a 2D view of the same garment in the plane.	Wang (2022) [28]
Internet of Things, artificial intelligence, blockchain, augmented reality, and virtual reality	Sustainable development of fashion industry.	**Digitalization in fashion:** The digitalization empowers to visualize the real-time information of smart cloth and other garments on the virtual network. **IoT in fashion:** The designing of smart clothing considers the use of sensors, electrodes, and communication protocol. **AI in fashion:** Trend forecasting, dress recommendation, health prediction. **Blockchain in fashion:** For supply chain track and trace application areas, transaction validation mechanisms and smart contracts.	Akram et al. (2022) [29]
Artificial intelligence	Customer purchasing experience	AI in fashion can join the brands and consumers towards making sustainable choices. The process will bring end- users to hassle-free experience, more optimized garment stock, more household space, a chance to buy more quality while buying less, collaterally leading to less pollution while working with the intent to increase the expected life frame of the garment.	Bolesnikov et al. (2022) [6]
Digitization	Second hand fashion market	Digitization promote innovation in second-hand fashion and digital technologies are driving new ways to exchange and share goods and services, enabling companies to match the supply, and demand for, otherwise underused assets and products. Online platforms have	Charnley et al. (2022) [10]

		played a crucial role in driving the growth of used goods and resale in other consumer goods markets.	
Artificial intelligence	Fashion design creation	Artificial intelligence technology provides sustainable solutions in the fashion industry to increase the productivity of fashion products and decrease unnecessary energy consumption. In this study the authors employed generative adversarial networks (GAN) and a deep convolution GAN (DC-GAN). The results demonstrated that the processes of humans and GANs were similar in creative thinking in high similarity areas. The AI design of a complex system can be effectively used in fashion industry to predict fashion system changes and provide recommendation and co-creation services.	Lee (2022) [14]
Digital twins	Sustainability in fashion industry	In Bacon company, TwinOne 3D software focuses on providing fashion-related technological solutions, creating hyper realistic DTs and presenting lifelike 3D graphics in real time. DT helps to reduce unnecessary use of materials during the prototyping phase (paper drawings, material samples, physical jacket prototypes). In addition, DT processes creates virtual equivalent clothe models. On the other hand, the trend forecasting using AI and DT helps to reduce the overproduction of new clothing items (despite their being sustainable).	Wagner et al. (2022) [23]
3D modeling, virtual and augmented reality (VR and AR), 2- and 3-dimensional (2D/3D) scanning, and digital twinning (DT).	Digital transformation of fashion industry	Opportunities of digitalization: - Dematerialization of the supply chain: Creative exploitation of technologies to modify the way garments are inspired, conceived, perceived and designed. - New B2B and B2C: digital garments and cyber-fitting services, physical garments augmented with VR filters that provide the opportunity for constant updating. - Business model based on network, community, service/experience-oriented: It is related to the opportunity for simultaneous value creation along multiple dimensions of sustainability, in which platform-based services emerge as a new digital BM archetype. - 3D virtual and digital technologies in the design process: The application of 3DVD technologies allows for optimization of traditional production processes, digital made-to-measure, and production-on- demand approaches that are sometimes supplemented by locally-based micro-factory production	Casciani et al. (2022) [24]
Extended reality technologies (virtual reality and virtual assistant)	Fashion communication	The authors proposed e-commerce strategies based on extended reality technologies (XR-commerce). For this, virtual reality applications demonstrated to create immersive experiences simulating the processes typically involved in fashion stores. Additionally, users interacted vocally with voice-assistant Alexa. The findings highlighted the feasibility of x-commerce for fashion retail purposes, ranging from advertising to shopping platform providers.	Morotti et al. (2022) [26]
Digitalization using Technology-Acceptance-Model (TAM) and the Unified Theory of Acceptance and Use of Technology 2 (UTAUT 2)	Management of fashion stores	Digitalization contributes to sustainable resource management with respect to human assets as well as physical assets and energy savings. Digitalization model was developed following these stages: 1.Supporting store technologies: Digital price tags, QR codes, mobile payment. 2.Assisting store technologies: digital changing room, magic mirror, digital shop window. 3.Augmenting store technologies: augmented reality, virtual reality glasses) 4.Autonomous store technologies: self-checkouts, drone or robot retail delivery, robotic inventory management. 5.Artificial intelligence store technologies: in-store cameras that measure consumer reactions to product, inventory management provided by AI-driven demand forecasting.	Von der Assen (2023) [18]
Immersive (IVR) and desktop (DVR) virtual reality	Virtual fashion stores	The study explores whether using Immersive Virtual Reality (IVR) technologies enhances the shopping experience in the fashion industry compared to Desktop Virtual Reality (DVR). For DVR, a desktop computer setup was used to test the shopping experience using a mouse and keyboard for navigation. For IVR, a Head-Mounted Display (HMD), virtual scenes and controllers were employed to allowed navigation while seated on a workstation. The results show that the experience in IVR presents better results in terms of hedonic and utilitarian value and user experience than in DVR.	Ricci et al. (2023) [27]
Reutilization of waste textile fabrics by image processing	Image processing	The implementation of image processing algorithms were achieved by using GNU Octave 6.4 programming environment. The algorithm's effectiveness and applicability could be further enhanced by incorporating innovative technologies such as artificial intelligence, virtual reality, or advanced simulation tools.	Indrie et al. [32]

On the other hand, the study of technologies such as virtual reality (VR), artificial intelligence (AI) and digital twins applied in fashion industry have generated a series of benefits that contribute to promoting sustainable industrialization and innovation despite of consumer barriers. These technologies allow an improvement in the supply chain based on efficiency and transparency [8], [9] which facilitates the monitoring and traceability of products for reducing the risk of unsustainable practices [4]. Furthermore, thanks to the optimization of re-sources, it is possible to reduce costs in the methods of designing, manufacturing and selling garments [22], [33]. The dematerialization of traditional, resource-intensive design practices is another key benefit [24]. Moreover, the incorporation of circular business models focused on recycling and reuse in this industry makes it possible to significantly reduce the environmental and social impact on production and consumption [10], [12], [15].

The application of VR, AI and digital twins also improves factory safety efficiency by facilitating early detection of anomalies and enabling more informed decision-making process [20]. In addition, consumer data management is optimized, which in turn improves the shopping experience by on-line personalizing recommendations and offering products and services with individual preferences [16], [18], [26], [27], [29]. Another benefit of technologies 4.0 is the possibility to forecast fashion trends by analyzing large volumes of data [21], [31]. This allows a more accurate and efficient planning, reducing production times and minimizing the risk of unsold inventory. Therefore, the application of VR, AI and digital twins in fashion establishes a wide range of benefits, from promoting sustainability and innovation, to improving supply chain efficiency, consumer experience and the optimization of design and manufacturing procedures as seen in Fig. 6.

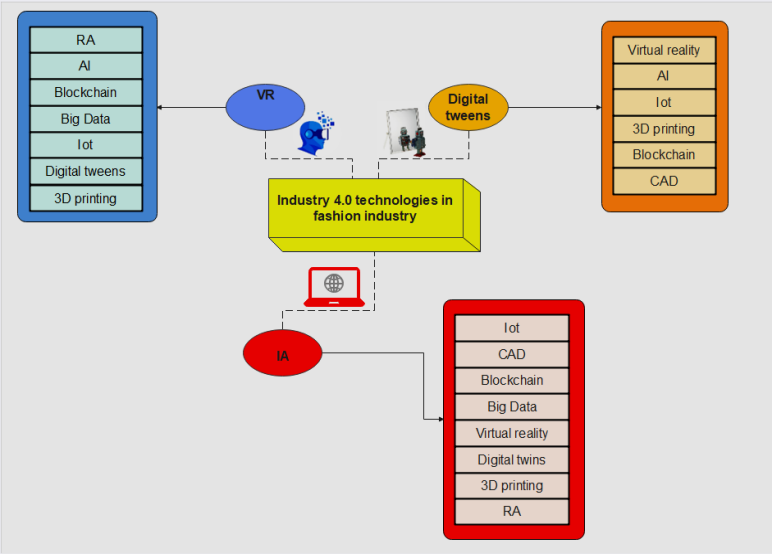

Fig. 4. Relationship between Technologies 4.0 (IA, RV and Digital tweens and relations) and other technologies.

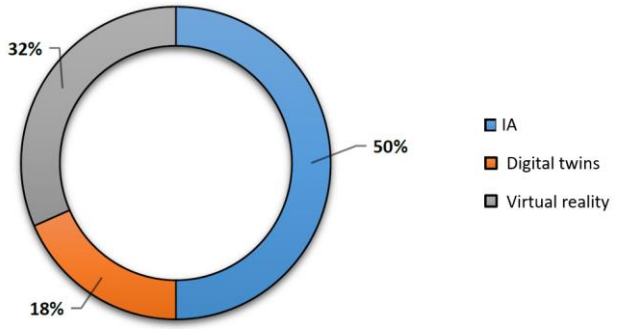

Fig. 5. Distribution of articles about fashion industry and technologies 4.0.

As described above, the applications of these technologies also present certain limitations and challenges that need to be addressed (Fig. 7). First, fashion companies often show resistance to innovation, especially when it involves re-placing existing systems with newer models. This may be due to concerns about costs, implementation time, and the need to change long-standing practices. Additionally, there is a lack of awareness in consumers about how their purchasing behavior impacts on the environment. Despite companies' efforts to adopt more sustainable practices, a lack of education and understanding on the part of consumers can limit demand of sustainable products and hinder the adoption of innovative technologies [1], [6].

From the perspective of the fashion industry, the most significant challenges are the enormous gap between design, production and marketing. The complex and diverse nature of fashion, with multiple actors and interconnected processes, makes it difficult to implement VR, AI and digital twin technologies in an efficient and effective way. Close collaboration and coordination between the different actors in the value chain is required to overcome this fragmentation and maximize the potential of these technologies [11].

Also, Industry 4.0 technologies can prove to be highly effective, environmentally friendly and sustainable compared to traditional technologies in the fashion industry. These digital technologies offer a series of advantages and benefits that significantly improve processes and results at all stages of the fashion value chain. Firstly, 4.0 technologies enable extensive automation and digitalization of garment design, manufacturing and sales procedures. For example, computer-aided design (CAD) software [17], [19], [28], 3D modeling and printing streamlines the design process and allows for more accurate visualization of the garments before their production [24], [25], [28], [29], [33]. Those technological tools reduce time and costs associated with developing physical samples and increases flexibility in creating designs. In addition, technologies 4.0 improve efficiency in the supply chain by facilitating the management and tracking of materials, products and orders at the moment. For forecast the trends and to simulated the processes, digital twins contribute to the continuity of information throughout the product life cycle and their performance by engineering simulations [19]–[23], [33]. Another aspect in which technologies 4.0 surpass traditional technologies is in personalization and customer experience [1], [16], [18], [29]. The application of augmented reality (AR) and virtual reality (VR) allows users to virtually try on clothing and accessories, which increases satisfaction during the purchasing process and minimizes the need for returns. Likewise, the study of big data and artificial intelligence (AI) allow a greater understanding of customer preferences and behaviors [6], [29], [31], which facilitates product customization and more effective marketing strategies. For this reason, 4.0 technologies in the fashion industry offer greater effectiveness in terms of agility, innovation, precision, efficiency, customization and sustainability compared to traditional technologies. These digital tools drive innovation and transformation in the sector, allowing companies to remain competitive in a constantly changing environment and satisfy the increasingly demanding of consumers (Fig.8).

The implementation of technologies such as virtual reality (VR), artificial intelligence (AI) and digital twins in the industry can significantly contribute to improving sustainability in production and service, and reducing the negative environmental impact. First, virtual reality (VR) and augmented reality (AR) reduce the need to manufacture and transport physical samples. This helps to reduce waste of raw material and greenhouse gas emissions related to the production and distribution of physical samples. Secondly, artificial intelligence plays an important role in optimizing design, manufacturing and distribution processes. By studying large amounts of data, AI can identify patterns and trends in product demand, helping companies to produce only the necessary amount of clothing and to avoid excess inventory. This reduces waste and the need to discard unsold products. Finally, digital twins make possible to simulate and optimize different production and service on different scenarios. This helps to identify specific areas for energy efficiency improvement, waste reduction and resource optimization. Additionally, digital twins can provide real-time information on product performance, enabling better decision-making processes regarding repairs, reuse and recycling. The adoption of these technologies, such as virtual reality, artificial intelligence and digital twins, can go a long way in prioritizing sustainability in the fashion industry. These technologies enable more precise and efficient production, reduce material waste, optimize the use of resources, improve the consumer experience and encourage the adoption of circular practices in the value chain. By integrating these technologies into the processes of the fashion industry, it is viable to move towards more sustainable production and consumption. Turner et al. [34] evaluated the integration of some tools and proposed the concept of "dynamic Life Cycle Assessment," which makes data available on material use and potential for recycling. The authors argued that Digital Twins could play an important role in visualizing intelligent product materials that can be recycled and/or reused.

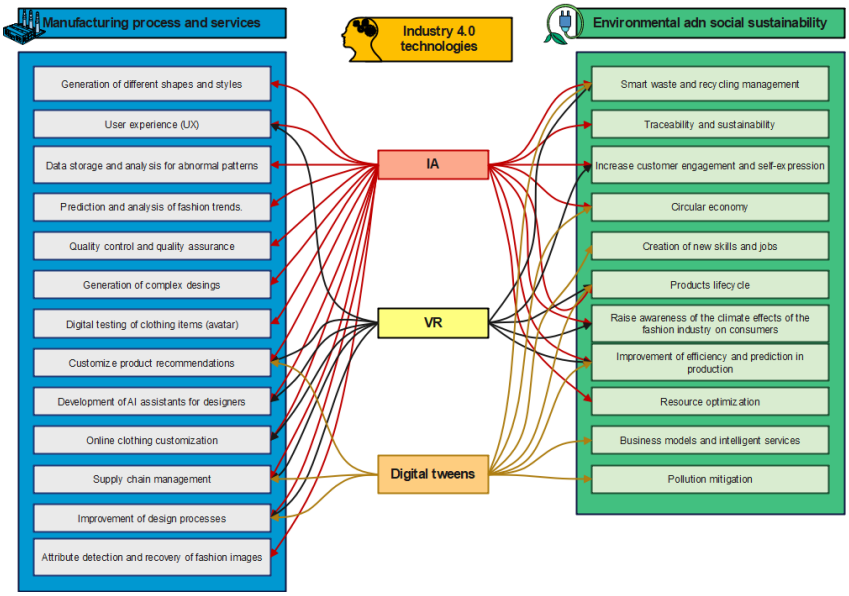

Fig. 6. Benefits of technologies 4.0 in production and service processes and relation with sustainability.

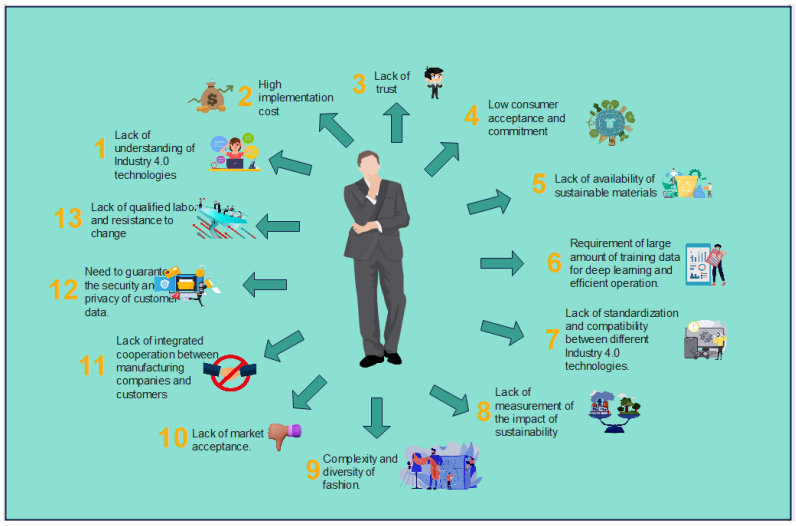

Fig. 7. Barriers for implementation of Industry 4.0 technologies.

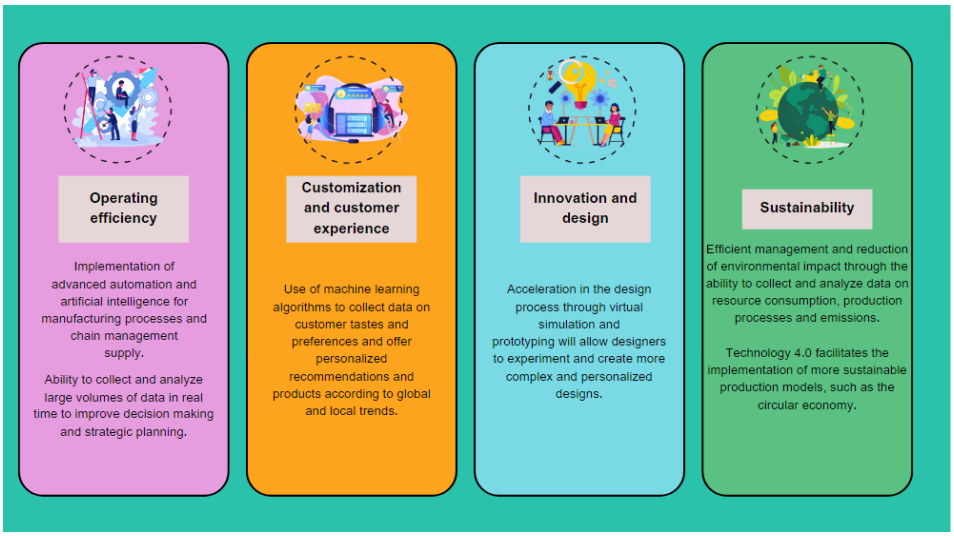

Fig. 8. Improvements in fashion industry due to implementation of Industry 4.0 technologies.

This review article analyzes the main concerns of fashion industry and explores the uses of Industry 4.0 technologies as a potential solution to improve its sustainability. The results reveal that the fashion industry has a significant impact on the environment, contributing to high global carbon emissions and industrial wastewater pollution. Therefore, the use of Industry 4.0 technologies is presented as promising tools to improve sustainability in this sector. These findings are consistent with previous researches that highlight how these technologies can improve the efficiency in the supply chain, optimize resources, reduce costs and improve the consumer experience [1], [2], [6], [14], [28], [29]. Furthermore, compared to traditional technologies, Industry 4.0 technologies offer numerous benefits in terms of agility, innovation, efficiency, customization and sustainability in the fashion industry. For example, the application of virtual reality and augmented reality minimizes the need to manufacture and transport physical samples, digital twins allow real-time management of the supply chain, and artificial intelligence facilitates the study of large volumes of data by optimizing processes. design, manufacturing and distribution. These improvements have also been summarized by Casciani et al. [24] who highlight the importance of strengthening transparency and traceability in the supply chain and the dematerialization of traditional design practices.

Despite the useful tools that technologies 4.0 offer, those technologies also face challenges and limitations in their implementation [21]. The resistance to innovation, especially when it involves replacing existing systems, and a lack of knowledge among consumers about the relevance of sustainability are obstacles that must be overcome. Furthermore, the complexity and diversity of the fashion industry make difficult to implement technologies 4.0, especially because it requires close collaboration and coordination between the different stakeholders in the value chain [11].

According to this review, the use of Industry 4.0 technologies in the fashion industry can be crucial to achieve sustainability and reduce environmental impact. However, greater awareness, collaboration and adoption of these technologies across the fashion value chain is needed. The potential of these technologies to increase efficiency and minimize environmental impact in the fashion supply chain is an important topic. Entrepreneurs must attack the lack of industry research and promote the implementation of novel technologies based on the benefits and opportunities that these technologies offer. More research is needed, especially in the context of sustainable development, to ensure effective implementation and maximize benefits in the fashion industry.

IV. CONCLUSIONS

This research aimed to response of how Industry 4.0 technologies can optimize and improve the processes of fashion industry by keeping in mind the criteria of sustainability in the production and service procedures of the fashion industry. The determination of the main technologies gives lights for reducing the negative environmental impacts in the industry. Regarding the environmental footprint of the fashion industry, it has been shown to be one of the most polluting industries due to the overexploitation of natural resources, high levels of water consumption and energy requirement. Further, CO_2 emissions and the generation of lignocellulosic waste increase the impact of fashion activities. This has led to the need to look for technological solutions that contribute to reducing the environmental footprint. In this way, several technologies used in the fashion industry have been identified, belonging to industry 4.0 such as artificial intelligence, virtual reality, digital twins, among others.

The identified technologies offer significant benefits in terms of transparency, supply chain efficiency, customization and resource optimization. In addition, technologies 4.0 encourage the transition towards circular practices and improve the consumer experience. However, some limitations have also been identified in the implementation of these technologies. The most relevant are: high acquisition and implementation costs, lack of training and specialized knowledge, resistance to change on organizations and lack of acceptance and commitment by consumers. Regarding the

effectiveness of these technologies compared to traditional ones, it has been shown that their implementation can generate significant improvements in terms of environmental sustainability. Industry 4.0 technologies offer more efficient, precise and personalized solutions, resulting in a reduction in negative environmental impact compared to traditional technologies.

Findings reveal that, despite recognizing the value and advantages of these technologies, there is a lack of specific studies and cases in the context of fashion. The implementation of these technologies is at an early stage, and significant challenges in terms of costs, interoperability, and resistance to change remain in the industry. Therefore, this document emphasizes the importance of conducting more research in this field, with a specific focus on the implementation of Industry 4.0 technologies to promote sustainability. Furthermore, the most important stakeholders must collaborate, share knowledge and experience, and overcome technical and organizational challenges to adopt these technologies. Only through jointing efforts a more sustainable fashion industry can be achieved.

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