Periyasamy and Periyasami
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REVIEW

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Rise of digital fashion and metaverse: influence on sustainability

Aravin Prince Periyasamy[1,2*] and Saravanan Periyasami[3]

Abstract

The fashion industry is a lucrative market that generates revenue in the trillions through the production and distribution of clothing, footwear, and various accessories. The apparel industry has experienced a remarkable expansion in the past few years, evidenced by a 100% increase in output between 2000 and 2023. The apparel industry makes a substantial contribution to the negative impacts of biodiversity loss and climate change. The fashion industry's expansion and social and environmental sustainability concerns, catalyzed by digitalization, are propelling it toward a sustainable trajectory. The present review article centers on the primary issues faced by the fashion industry and the utilization of metaverse technologies to tackle sustainability challenges within this sector. The metaverse refers to the amalgamation of physical and digital space within a virtual world, commonly referred to as the metauniverse. The metaverse is a strategy that is anticipated to be employed in fashion e-commerce and retailing, aiming to facilitate consumer decision-making processes, ranging from user experience to customer experience. This approach is expected to confer considerable competitive benefits. This review paper aims to analyze the sustainable impact of the metaverse on the fashion industry and foster discourse among researchers and industry professionals.

Keywords Blockchain, Metaverse, Industry 4.0, Digitization, Sustainable fashion, Fast fashion, Fashion 4.0, Personalization

1 Introduction

The term 'metaverse' was first introduced by Neal Stephenson, a science fiction writer renowned for his novel Snow Crash, in 1992 (Stephenson 1992). According to Stephenson, the metaverse is a vast virtual environment that runs parallel to the physical world, where users engage with each other through digital avatars (Stephenson 1992). By this definition, the metaverse is a virtual three-dimensional (3D) environment where real-world people and things can freely circulate, exchange, and interact with one another (Dwivedi et al. 2022). In fact, the metaverse merges the actual world with the virtual world, providing a way for users to build relationships and friendships through shared experiences (Kim et al. 2023a). In a contemporary society characterized by pervasive interconnectivity, whereby individuals can accomplish a multitude of tasks through a singular device, the metaverse may be regarded as the ultimate frontier in the evolution of other technological advancements, including the internet and e-commerce (De Felice et al. 2023). Despite being in its nascent stages of development, metaverse technology holds the potential to create a network of interconnected virtual and physical worlds, enabling its inhabitants to perform routine activities without the need for physical mobility (Allam et al. 2022; El Archi et al. 2023). Presently, numerous textile and fashion enterprises have adopted a perspective that acknowledges this emerging paradigm, perceiving it as a chance for commercial expansion (Moon et al. 2012). The

*Correspondence:
Aravin Prince Periyasamy
aravin.periyasamy@vtt.fi; aravinprincep@gmail.com
[1] Textile and Nonwoven Materials, VTT Technical Research Centre of Finland Ltd, P.O. Box 1000, 02044 Espoo, Finland
[2] Department of Bioproducts and Biosystems, School of Chemical Engineering, Aalto University, Espoo 02150, Finland
[3] Thuan Phuong Company, Limited (Garments-Embroideries), Ho Chi Minh City, Vietnam

concept of the metaverse has the potential to enhance the capabilities of fashion enterprises by enabling them to engage in various business activities such as buying and selling fashion products, particularly clothing, monitoring activities, gathering information, adjusting forecasts, and delivering services, among others. Consequently, it transforms into a digital replica of businesses actions and existence in the physical world, with boundless potential (Hazan et al. 2023).

The concept of the metaverse was first introduced approximately twenty years ago. In 2021, the concept was gaining momentum and there are proponents who posit that it represents a redefinition of the contemporary internet (Pamucar et al. 2022). The metaverse is a virtual realm that integrates physical reality with digital virtuality in a seamless manner, catering to a multitude of users. The convergence of virtual reality (VR) and augmented reality (AR) technologies has facilitated the possibility of multimodal interactions with virtual environments, objects, and individuals. It has been demonstrated that residing and engaging in professional activities within a digital world, known as the metaverse, is feasible (Joshua 2017; Mystakidis 2022; Dwivedi et al. 2022; Sun et al. 2022). The metaverse comprises seven different technological layers that are utilized to augment user experience and facilitate interactions. The metaverse currently represents a transitional phase towards an unprecedented realm of innovation. The phenomenon under consideration pertains to the prolonged utilization of the internet by individuals belonging to the generation commonly referred to as generation alpha (gen-α). Consequently, the evolution in question is anticipated to manifest itself through two distinct pathways (Park and Kim 2022). The metaverse and its user base hold significant potential for the bridge millennials, generation Z (gen Z), bridge α, and gen-α generation populations. Over the course of the upcoming half-decade, there will be a proliferation of metaverse integration across diverse sectors and for a range of objectives (Zibell 2021). The metaverse has garnered interest and engagement from various generations, as evidenced by prior research (Park and Kim 2022). The generation known as gen Z serves as a crucial touch point for comprehending the process of key generation, and this study aims to comprehensively examine the behaviors of gen Z across various domains (Lettink 2019).

The textiles and apparel industry significantly impacts the global economy in terms of trade, employment, investment, and revenue. The global consumption of textiles has witnessed a surge in recent decades, primarily attributed to the growth in population and an improvement in living standards (Shirvanimoghaddam et al. 2020). Based on projections, the global apparel industry is anticipated to reach a value of 2 trillion dollars by the year 2026, after having been estimated at 1.5 trillion dollars in 2022 (Smith 2022). Simultaneously, the operational procedures within textile supply chains have significant adverse effects on the natural environment. These effects are marked by the extensive consumption of water, the use of chemicals that emit excessive greenhouse gases (GHGs), and the generation of waste (Periyasamy and Militky 2017a, 2020a; Periyasamy et al. 2018a). Furthermore, it is estimated that 85% of textiles are discarded in landfills on a yearly basis (Algayerova 2018). It is possible that a considerable quantity of microplastics is discharged and subsequently deposited in the ocean as a result of laundering textiles (Periyasamy 2021, 2023a, b; Periyasamy and Tehrani-Bagha 2022). The textile and fashion industry has been found to have a notable adverse impact on the attainment of the 2030 United Nations Sustainable Development Goals (SDGs) (Burdea, et al. 2017; Clo Clo 2022; UN Partnership on Sustainable Fashion and the SDGs 2018). As previously mentioned, the clothing industry discharges a lot of contaminated water with harmful chemicals, colors, and additions (SDGs6). The phenomenon of "throwaway fashion" and the adoption of the "take, make, dispose of" approach is likely to undermine efforts towards responsible production and consumption (SDGs12), as well as exacerbate global climate change (SDGs13), marine pollution (SDGs14), and land pollution (SDGs15) (Periyasamy et al. 2018b; Radhakrishnan 2020).

The emergence of the metaverse is engendering a paradigm shift in our understanding and interpretation of the world of fashion. The incorporation of virtual reality (VR) and augmented reality (AR) technologies has enabled unimpeded exploration within three-dimensional (3D) environments (Prieto et al. 2022). The utilization of the metaverse in the digital fashion economy provides designers with the essential means to establish a brand that is environmentally sustainable and to support suppliers that adhere to sustainable practices. This is made possible through the availability of open-source repositories containing digital patterns, materials, and textures, which can be utilized or supplemented by designers. Furthermore, original designers are entitled to receive royalties when their work is employed. Presently, fashion brands predominantly employ digital fashion as a marketing tactic to garner interest in their merchandise. In 2021, the Helinski fashion week transitioned to a fully digital format, resulting in a significant reduction in the carbon footprint of each attendee from 137 kg to 0.66 kg (Hausse 2021). Research has indicated that digital fashion weeks exhibit a higher degree of environmental sustainability compared to conventional fashion shows. This is primarily attributed to their ability to mitigate overproduction, optimize time management, and minimize resource consumption (Hausse 2021). This has led to a significant reduction in water consumption, with an estimated 3,300 L of water saved, and a 97% decrease in carbon dioxide emissions (Hausse 2021).

The metaverse has the potential to foster innovation in the realm of sustainable fashion. The convergence of the physical and digital realms is occurring concurrently with the emergence and advancement of various technological frameworks such as fifth generations (5G) telecommunications, blockchain, non-fungible tokens (NFTs), and other infrastructures, alongside the evolution of VR/AR and other virtualization technologies (Park and Lim 2023).

The current infrastructures exhibit a high degree of fragmentation and lack of cohesion, spanning from fashion brand to manufacturing, supply chain, distribution, retailing, and ultimately, the end consumer (Noris et al. 2021; Nobile et al. 2021; Di Leo et al. 2023). Hence, the decomposition of stated structures is facilitated through the utilization of digital infrastructure assessment (DIA), digital asset management (DAM), Product lifecycle management (PLM), and Bill of material (BoM). The digitalization process is being facilitated by the increasing computational power, rendering capabilities, and memory capacity of the computer industry. Upon closer examination, it becomes apparent that what is commonly referred to as digitalization is a process of digitation, to a certain level. Conversely, digitalization pertains to the utilization of digital technologies to revolutionize commercial procedures and establish novel business frameworks. Industries that are well-versed in these technologies are increasingly adopting PLM and software as service (SaaS) to enhance transparency for stakeholders using charts and graphs that provide information on what, where, and when (Safari et al. 2015). The management of the DIA and DAM processes is typically undertaken by the BoM team and is incorporated into the digital brands of the supplier. On the other hand, PLM, and Life Cycle Assessment (LCA) are managed by the manufacturers (Periyasamy et al. 2017b; Liu et al. 2020). However, the traceable future of the supply chain and its associated background remains largely ambiguous and difficult to discern. These depths require special permissions and sharing objectives among them is uncommon. This infrastructure facilitates more efficient communication and requires fewer workers to do a given task. Because of the delay in receiving this data, real-time fashion is now out of reach, and it is not a case of precision marketing. However, the true economic gain can only be realized by speeding up the process of enhancing operations and services.

This article represents the initial endeavour to consolidate the possibilities of metaverse integration in the field of sustainable fashion. This article aims to explore the potential impact of digital technologies such as metaverse, digital transformation, blockchain, AR, and VR on the fashion industry's sustainability. Specifically, it will examine how these technologies may address existing challenges and shape the future of the fashion metaverse.

2 Implementation of a metaverse in the Fashion industry

Comprehending the impact of the metaverse on ecological sustainability is significant. There exist two perspectives regarding the metaverse, one of which is characterized by a digitally native outlook. This viewpoint is held by conscientious consumers who prioritize sustainability and social justice. Such individuals anticipate a digital-first approach, given the malleability, adaptability, and customizability of digital content. This approach has a significant potential for enabling product personalization and hyper-personalization. Personalization of digital products enables hyper-personalized brands and retailers to leverage consumer data to meet their expectations. The provision of clearly delineated data feeds pertaining to style, trend, and color facilitates precise manufacturing processes that are informed by data (Karunakaran et al. 2023). This phenomenon motivates retailers to promptly cater to the needs and demands of their customers. According to a study, there is a global overproduction rate of 27% in the conventional fashion industry (Rauturier 2022). Garments that are overproduced bear minimal distinctions from pre-existing merchandise stocked in retail establishments, except for marketing tactics and branding (Fashinza 2023). This text discusses the storage and economic implications associated with inventory cases. In the context of sustainability, it is imperative to not only examine the various aspects such as processes, chemicals, fibers, landfills, and biodegradation but also to consider the sustainable allocation of space and financial resources within the economy (Niinimäki et al. 2020; Klepp et al. 2020).

Consider a hypothetical scenario where a network of interlinked communities is present in a hyper-alternative virtual and AR environment, enabling individuals to convene, engage, and enjoy recreational activities. The metaverse is poised to exert a noteworthy influence on the realm of fashion, with self-presentation remaining a crucial facet of this virtual world, much like it is in the physical world (Joy et al. 2022). The metaverse is characterized by the absence of the rules and restrictions that regulate our everyday existence, thereby obviating the necessity of conforming to established conventions. The elimination of variables such as geographical proximity and limited consumer bases is expected to bring about a transformation in our perception of apparel, as fashion becomes more widely accessible. The significance of metaverse components is paramount in the context of Industry 4.0 (Jon Radoff 2021). Industry 4.0, according to McKinsey, is the digitization of the manufacturing industry, with integrated sensors in almost all product components and production equipment, omnipresent cyberphysical systems, and analysis of all pertinent data (Gregolinska et al. 2022). The metaverse necessitates the utilization of subsequent technologies for its realization in the fashion industry and they are,

- Virtual/augmented and mixed reality devices.
- Computer & devices with high network connectivity
- Machine learning (ML)
- Artificial intelligence (AI)
- Machine vision
- Volumetric scanning and 3D modelling
- Blockchain, NFT, Cryptocurrency which enables digital property and payments
- Internet of Things (IoT)

2.1 Virtual, augmented, and mixed reality devices

Currently, the fashion industry is expanding its reach through the utilization of AR and VR technologies, leading to the emergence of a multiverse (Berryman 2012; Rauschnabel et al. 2022a, b). AR/VR tools enable customers to observe the liner content of products in metaverse. The aforementioned tools are designed to offer a comprehensive, hands-on, and engaging encounter with the merchandise and its accompanying components (Cipresso et al. 2018; Rauschnabel et al. 2022a). These innovations will integrate tangible and digital encounters, thereby obfuscating their demarcations. The tools offered by retail stores in the Metaverse are expected to be both engaging and utilitarian. It is imperative that all creations are generated in a digital format to allow for subsequent digital modifications, revisions, and reconceptualization's (Cipresso et al. 2018). This will afford consumers a greater array of customizable options, enabling them to procure unique fashion items that are tailored to their individual preferences, ranging from personalized fashion to hyper-personalized fashion.

2.2 Computer power and infrastructure

The establishment of a robust infrastructure is crucial for the seamless and uninterrupted operation of metaverse while ensuring minimal latency within the network. The network's stringent latency requirement can effectively reduce the delay time for typical internet usage. The Meta platform necessitates the utilization of 5G/6G or Wi-Fi connectivity and cloud-based storage. Furthermore, the incorporation of high-performance GPUs assists in reducing network strain during data retention or collection processes. The storage and rendering of digital duplications or creations necessitate consolidation onto a single computing device or electronic device. The transfer and connectivity of digital products between different device locations and meta spaces is a crucial aspect that requires consideration (Peng et al. 2022).

In the fashion industry, consumers often visit stores, on-demand digital marketplaces, and online retail platforms to peruse and purchase apparel, with each option presenting distinct benefits and drawbacks. While customers have the opportunity to verify the fit of items in physical stores prior to purchase, this is not always feasible in the realm of e-commerce. In fact, customers often bear the responsibility for sizing and fit concerns in online shopping, leading to a high rate of returns that may not be sustainable. In the context of e-commerce, it has been noted that a significant proportion of products, ranging from 34 to 46%, are returned as a result of issues pertaining to fit, size, and color (Berthene 2019). The metaverse is constructed using various technologies, including VR/3D, which is anticipated to have a significant impact on the infrastructure of the metaverse. The utilization of virtual reality (VR) headset technology has the potential to benefit e-commerce brands and retailers by facilitating customer support and creating customer touch points and impressions.

2.3 AI and machine learning

The integration of machine vision, encompassing computer vision and extended reality (XR), constitutes a pivotal technological component in establishing the fundamental framework of the metaverse. Visual data obtained from optical displays and video players are analysed to derive advanced insights, which are subsequently presented to users through various devices, including smart glasses, smartphones, and head-mounted devices. Computer vision enables XR devices to analyze and comprehend user activities by leveraging visual-based meaningful information on the garments. The users are able to navigate through 3D maps and engage with virtual fashion within the metaverse by means of their avatars. Machine learning (ML) is a branch of artificial intelligence that involves the utilization of algorithms to construct a model that can enhance its performance through experience and data analysis. This process involves the conversion of existing data into training and testing data, which is then used to create statistical models. Based on these models and the available data, ML algorithms can make predictions and validate their accuracy against the testing data (Huynh-The et al. 2023). The acquisition of data plays a crucial role in forecasting customer expectations, thereby guiding the direction of fashion. Conventionally, designers would visit various stores and catwalk shows, while influencers would post on social media and celebrities would analyze outfits of different brands, all with the aim of identifying white space to showcase their own brand's products (Certilogo 2023). In the advanced stage of e-commerce, searches are conducted through images or text, and the number of touchpoints is transformed into valuable data. The ML algorithm facilitates customer interaction with data through a unique identifier, enabling it to comprehend customer expectations regarding color, fit, and material touch and comfort (i.e., in the case of textiles). The algorithm then recommends a suitable model to the customer and offers alternative methods for providing expectation models to brands or firms. Metaverse offers the advantage of consolidating data from various sources, including entertainment, social media, search engines, product displays, and public opinion. Metaverse is a platform that enables bidirectional interaction between creators and brands. It offers fundamental products that serve as the foundation for user and customer engagement. Through this platform, users and customers can interact with these products, data, and engage in the cultivation and harvesting of fashion.

2.4 Volumetric scanning and modelling

The process of 3D scanning involves the utilization of a laser to capture the dimensions of an object or surface in a 3D space. A laser scanner is commonly utilized for this purpose due to its inclusion of a specialized sensor capable of capturing intricate contour features of an object or surface. The process of creating a three-dimensional depiction of an object or surface through computer graphics is commonly referred to as 3D modelling, as documented in sources (Danckaers et al. 2019; Wang et al. 2021). Volumetric scanning has emerged as a viable solution to address fit-related challenges in the web2 fashion or online retail industry. The rate of returns in this sector is significant, with more than 30% of returns being attributed to sizing issues. Volumetric scanning technology enables accurate measurement of the human body, thereby reducing the likelihood of ill-fitting garments being purchased and subsequently returned (Daanen and Psikuta 2018).

Currently, it is possible to generate a personalized digital representation of oneself through the utilization of volumetric scanning technology within mobile applications (Jain et al. 2018; Wholeland 2022). The utilization of an avatar facilitates access to the metaverse and enables the selection of various physical attributes such as skin tone, facial features, and skin type. This phenomenon presents a novel prospect for designers and consumers to generate their own merchandise for exchange within the meta realm, encompassing items such as apparel, adornments, or gaming implements. Digital fashion assumes a pivotal role in this context (Joy et al. 2022). Since 2019, companies based in Amsterdam that specialize in fabricating clothing have been engaged in the development of digital-only fashion and the establishment of a creator economy for the metaverse (Wholeland 2022). The practice of virtual production is being utilized to facilitate the advancement of the fashion industry. The utilization of software as service (SaaS) platforms such as CLO (Clo) and Browzwear (Browzwear 2023) has facilitated the development of digital fashion tools, thereby enhancing productivity in the production of digital goods. Digital content possesses the inherent qualities of being editable, modifiable, customizable, personalized, and hyper-personalized. The Software as a Service (SaaS) applications are designed to generate and segment each component of clothing using engineering terminology, and subsequently store this data (Sun et al. 2007). The preparation of the metaverse involves the integration of fractioned, engineered, digital elements and components with ML through artificial generative intelligence (AGI) (Baidoo-Anu and Owusu Ansah 2023; Korzynski et al. 2023). Facilitate a platform for end-users to engage in co-creation activities utilizing text-to-image models, prompt modules, image-to-image interruption models, and voice-to-image models. The utilization of AGI is expected to significantly expedite the process of metaverse digital asset creation, thereby assuming a pivotal role in this domain. The deceleration of AI advancements is attributed to the clearance of regulatory and policy measures.

2.5 Blockchain, NFTs, Cryptocurrency which enables digital property and payments

The metaverse relies on the blockchain as a foundational platform. The metaverse is a digital realm where virtual currency is essential for conducting transactions such as buying, selling, and trading, thereby establishing a digital economy. The phenomenon is being referred to is commonly known as meta economy or meta money, as documented in the source (Malik et al. 2022). As such, it can be argued that both cryptocurrency and NFTs hold significant importance within the context of the digital economy (Vidal-Tomás 2022a). The integration of cryptocurrencies such as Bitcoin or Ethereum into the novel blockchain railways yields a mechanism that facilitates the transportation of digital data while conferring ownership. Within this universe, individuals have the ability to engage in various activities such as acting, learning, shopping, trading, and traversing between different metaverse spaces. Notable instances of metaverse blockchains include Minecraft (Minecraft 2022), Roblox (Roblox 2023), Sandbox (Sandbox 2023), Decentraland (Decentraland 2023), and Somnium (Somnium 2023). NFTs are digital designs that are created by designers and creators. These designs can take the form of images, wallpapers, avatars, clothing, skins for gaming, or even dresses for fashion shows. NFTs are traded based on their individual value within the metaverse space. Digital companies are being accused by brands such as Nike, Adidas, and Gucci, among others, of enabling creators to mint NFTs. The utilization of digital economic behavior results in a reduction of physical currency circulation, thereby decreasing the need for printed money in the physical world (Vidal-Tomás 2022a). These digital-to-physical (D2P) and physical-to-digital (P2D) technologies offer platforming for use in manufacturing in the real world; data integration in this context will lead to Industry 4.0 or Fashion 4.0 (Tigar 2022).

2.6 Internet of Things (IoT)

The Internet of Things (IoT) is currently exerting a significant impact on the fashion industry, surpassing initial expectations. The essence of IoT lies in the convergence of individuals and commodities, thereby facilitating ease of use for end-users, enterprises, producers, and vendors (Segura 2018). Numerous organizations are currently seeking a solution that can effectively balance sustainability and overall production (Environment in Geneva 2023). It has been suggested that a meticulously crafted IoT solution may be the precise answer to this challenge (Akram et al. 2022). The metaverse, facilitated by AR and IoT, is poised to set a novel standard for work and cooperation, enabling businesses to function with increased velocity and magnitude.

It is imperative to achieve a comprehensive understanding of the IoT within this particular framework, alongside its utilization within the metaverse and its interconnectivity with AR. The device in question is a sensor that captures and identifies bodily movements, such as those of the hand and eye, to generate dependable data. The potential for enhancing the traceability and identification of physical garments, akin to a passport, can be further augmented through the utilization of IoT and hyper-vision cloud computing. The Digital Product Passport (DPP) has been included in the EU's sustainable and circular textiles strategy as a key objective (Jahnz 2022). This initiative has been proposed as part of the Eco-design for sustainable products regulation for the textile sector (European Commission 2022). The DPP is a mechanism employed to retain and disseminate pertinent data during the entire lifespan of a textile product (Fig. 1a). The provision of information is costless and can be electronically retrieved via a data carrier, including but not limited to a QR code, an NFC chip, or an RFID tag (Adisorn et al. 2021; Walden et al. 2021). The party is responsible for disseminating the information pertaining to the product being introduced to the market is the economic operator. The potential implementation of the DPP in the textile industry through a decentralized approach is currently under consideration by the European Commission (European Commission 2022). As a result, certain industry leaders have taken the initiative to develop DPP concepts. Several privately-owned enterprises, such as TrueTwins, EON, Niaga, Circular Fashion, and AURA Blockchain, have developed and effectively tested DPP models for the textile industry. Some of their collaborators comprise prominent brands such as H&M, Zalando, and Prada (Simon 2022).

For instance, EON engage in collaborative efforts to create IoT passports, also known as CircularID™, for clothing items (2022a). The CircularID™ Protocol is a prevalent standard utilized for the digital identification of clothing items within the context of the circular economy (Manufy 2022). The implementation of this approach is expected to facilitate the alignment of pre- and post-sales monitoring, minimize the amount of waste deposited in landfills, and encourage conscientious consumption, as depicted in Fig. 1b. The implementation of a digital passport can aid in the identification of products and comprehension of their constituent materials and components, such as fiber content, composition, process, reusability, and the proportion of virgin versus recycled materials. This, in turn, can simplify the task of preserving these products in optimal condition, enabling multiple lifecycles and facilitating more efficient, expedient, and cost-effective reuse and recycling processes. This technology has the potential to facilitate the implementation of circular textile and circular fashion practices. The digital identification system contributes to the UN's sustainable development goals. Specifically, SDGs 8 aims to promote sustainable economic growth and ensure decent work for all, while SDGs 9 seeks to foster innovation and promote sustainable industrialization. SDGs 12 addresses sustainable production cycles, while SDGs 13 takes immediate action on climate change. Additionally, SDGs 14 aims to ensure the conservation and sustainability of the marine environment, and SDGs 17 focuses on the implementation and reinvigoration of the global partnership for sustainable development (2018; Algayerova 2018).

Nike has obtained patents for cryptographic digital assets to secure their retail products on the blockchain (Andon and Pham 2021). They have also partnered with RTFTK and cryptokicks internet of adaptive apparel footwear (IoAAF)-2021, as well as developing intelligent electronic shoes (IES) in 2019 (Nike Inc 2019). The aforementioned patents are poised to revolutionize the

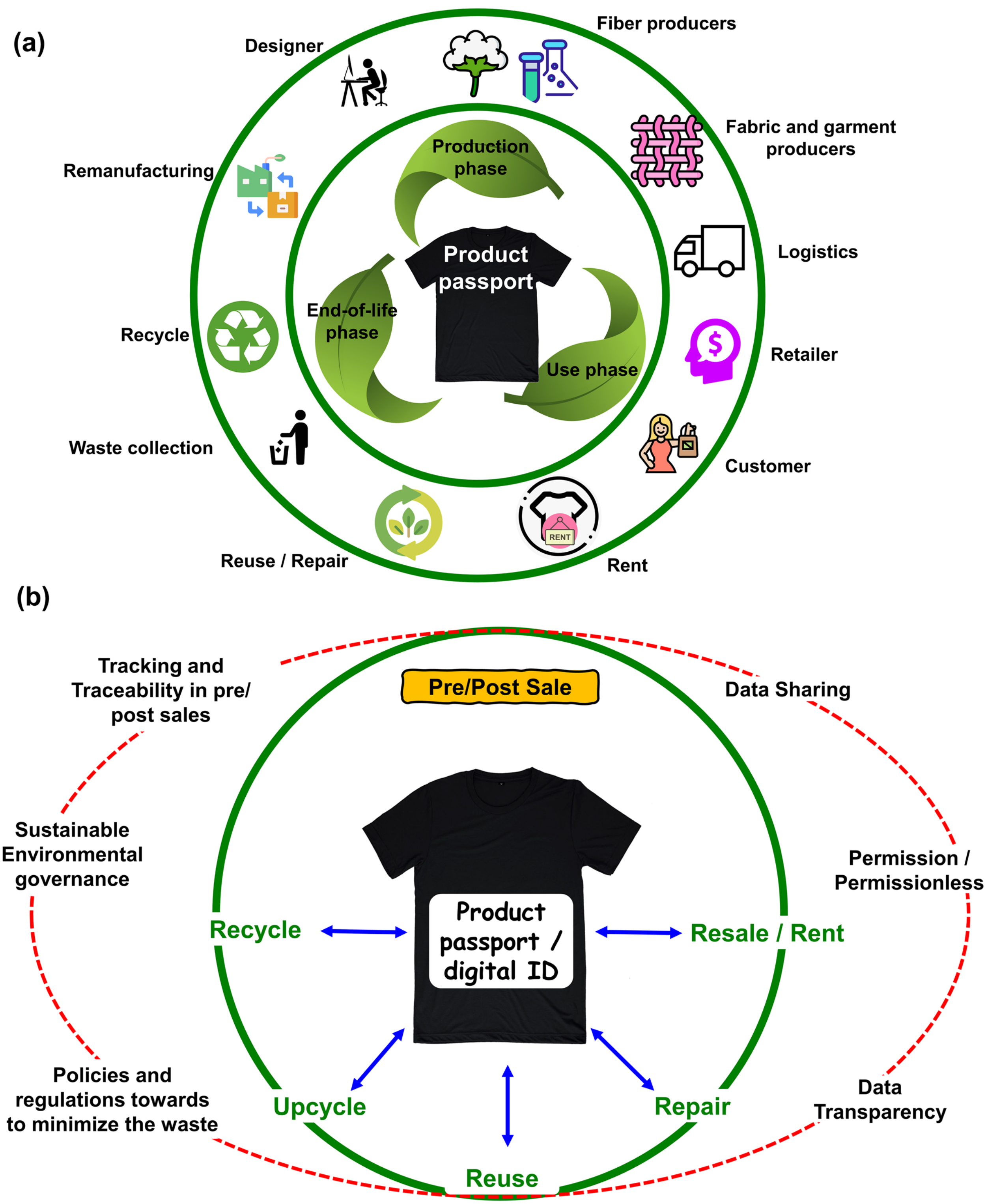

Fig. 1 The role of digital product passports in the fashion industry (**a**), and post-sales monitoring (**b**)

retail platform industry by introducing a new paradigm, wherein various technologies exhibit disparate annual growth rates. The integration of data and IoT represents a crucial component in connecting tangible and intangible goods (Synergy Consulting 2023). The sneakers and apparel are linked to Near-field communication (NFC) technology, which is a component of the IoT. Additionally, they utilize NFTs data, which pertains to the user, product, release, and the creator of the underlying raw materials. This serves as a form of digital product passport (Andon and Pham 2021).

2.6.1 Role of IoT in retail and manufacturing

The IoT has been increasingly employed in the manufacturing industry over the last decade, following its initial implementation in the retail domain. The utilization of quick response (QR) codes or bar codes has facilitated the retrieval of product specifications and other pertinent information, thereby contributing to the effective management of inventory and product availability (Vall 2023). This, in turn, has enabled the monitoring of systems through the use of IoT. Upon the arrival of products at the warehouse, they were scanned using Radiofrequency Identification (RFID) tags, and the resulting data was stored in computer systems. This is a commonly utilized practice in both commercial and consumer sectors (Unhelkar et al. 2022). Manufacturers employ them to accomplish operations, track products on the work floor, identify bottlenecks, and offer data visibility on every product and element present on the floor. RFID tags are utilized by retailers for the purpose of verifying sales points. NFC is widely employed across various sectors, with a notable emphasis on the banking industry (Liu and Ma 2018). It is possible to utilize debit or credit cards without physical contact with the proof-of-sale devices. However, within the field of fashion and retail, this identical technology has been employed for varying objectives.

- Traceability
- Phygital goods.
- Machine vision technology (camera as a sensor)

The majority of fiber traceability services utilize blockchain-based software as a service, with NFC serving as the underlying technology grid to ensure traceability and transparency. The emergence of phygital goods in the fashion industry is closely linked to the increasing presence of digitally native generations in the workforce and their growing purchasing power. The Nike RTFKT and Satoshi Studio black hoodies have recently become available for purchase through both physical and online means, including the use of NFTs (Mcdowell 2022). This development has garnered attention in the market. Satoshi Studio is a sneaker brand that operates on the blockchain platform and offers high-quality products at competitive prices. The brand is committed to promoting transparency and fostering a circular and inclusive economy for its clientele (Jain et al. 2021).

Machine vision technology is a crucial infrastructure that facilitates the potential of precision marketing and real-time fashion manufacturing with a high degree of accuracy. Machine vision involves several essential components, including a camera, lighting, lenses, image processing software, and a processing unit that utilizes ML to analyze the image and generate the desired output (Davies 2012; Goh et al. 2021; Javaid et al. 2022). The outputs are obtained through software derivatives that employ algorithms to compare against master data or metadata. The following examples illustrate the use of digital technology in manufacturing inspection. One approach involves utilizing Software as a Service (SaaS) to capture images and manually assess the quality of goods (Sun et al. 2007). This method represents a partially digital or data visualization-based approach to quality control systems. Another technique involves machine vision, which employs cameras as sensors to identify defects in garments, such as stitching errors. The identification and mitigation of fabric flaws, color inconsistency, sizing, and fit are crucial factors in achieving real-time manufacturing. Machine vision is also utilized by buyers and brands in the front end to offer personalized fitting through virtual try-ons and inventory management systems. Sophisticated algorithms for identifying digital-to-physical materials, digital creations generated by artificial intelligence, and 3D products produced through the utilization of CLO-Browzwear are all examples of advanced technological developments (Min and Carrico 2018; Browzwear 2023). The intricacies involved in the creation of these 3D products are noteworthy. It is imperative to choose appropriate materials that align with the physical products. Recent advancements in artificial intelligence have led to the development of algorithms that utilize computer vision to detect materials (Mennel et al. 2020; Ai et al. 2023). These algorithms are capable of identifying materials with a high degree of accuracy. To create metadata pertaining to viscose-based fibers and fabric characteristics, machine vision cameras are employed. Select appropriate materials for manufacturing purposes.

2.7 Human interfaces

The utilization of tools is necessary to facilitate our online access and connectivity with the metaverse. Contemporary cutting-edge technologies such as computers and smartphones may necessitate supplementary components to establish communication with the metaverse.

Thus, the utilization of gesture sensors such as haptic, voice, and visual, facilitated by VR devices and smart glasses, was deemed necessary (Lee and Hui 2018). The employment of VR technology to create immersive experiences has enabled the provision of a real-time store encounter that closely approximates the ideal physical experience. The primary obstacle to the implementation of a metaverse in retail or workplace settings is the current high cost and limited accessibility of its human interface, which poses a significant challenge for the general public. The transportation of numerous devices between locations poses a significant challenge for users of the metaverse, given that the forthcoming trends in shopping, work, and education are all converging towards this virtual world (Yoo et al. 2023).

Mobile device manufacturers are employing various strategies, such as incorporating gesture sensors and VR portals, to enhance the functionality of their products. In the foreseeable future, the utilization of LI-DAR sensors is expected to enable mobile access to the metaverse (Li et al. 2022). The recently introduced LI-DAR sensor functionality has the potential to assist individuals with visual impairments in detecting the presence of individuals in their vicinity. It can convert any physical object into 3D models, and it enhances AR (Maiese et al. 2022). Gesture sensors enabled mobiles may replace the haptics which needs to carry now. In order to achieve comprehensive technological advancement and attract a significant user base by 2030, the metaverse must incorporate additional techno-craft features (Maiese et al. 2022; Li et al. 2022).

3 Metaverse vs fashion sustainability

The imperative of ensuring the longevity of the fashion industry underscores the significance of digital transformation across the entire supply chain. The achievement of sustainability necessitates a digital transformation. In the contemporary era, the utilization of crucial digital infrastructure in manufacturing and design procedures has enabled brands and manufacturers to optimize their capacity for generating revenue and maximizing profits. Achieving high levels of efficiency in production processes and subsequently selling the resulting products at a premium price point is a viable strategy that can yield benefits for the entire value chain. Ultimately, the ramifications of such assertive approaches toward production and commercialization run counter to the principles of sustainability. It is imperative for the global community to mitigate the effects of global warming by limiting the increase in temperature to 2°C (Zhao and You 2023). Furthermore, the contemporary cohort of internet consumers and labour force exhibit distinctive attributes that differentiate them from preceding generations. The integration of vertical and horizontal digital platforms in manufacturing is being pursued to revolutionize the value chain and enable circular integration in response to change demand. Inside the apparel and fashion industry, a digital platform currently exists whereby the manufacturing stage utilizes the primary layer of digital infrastructure, while the pre-manufacturing process employs the secondary layer of digital infrastructure (Moshiri et al. 2020). The design is predicated on the utilization of the third layer of digital infrastructure, which is customized to individual use cases (Moshiri et al. 2020). The utilization of diverse digital infrastructure layers varies across the value chain of distinct components such as fiber, yarn, button, zipper, fabric, and brand (Bertola and Teunissen 2018). The digital data and infrastructure facilitate the ability of each value chain to independently track and analyse its own data, thereby enhancing productivity, planning capacity, cost-effectiveness, and product compatibility within their respective facilities (Grieco et al. 2017; Bertola and Teunissen 2018).

Excessive production resulting in surplus inventory and overconsumption has led to the depletion of natural resources across various manufacturing sectors, including energy and fiber production (Nazir 2021; Rauturier 2022), as it results in an unsustainable approach to material usage. The presence of homogeneous goods, wherein no distinguishing characteristic exists between the products of different brands, and the occurrence of common market failure, which pertains to the excessive depletion of natural resources, are noteworthy phenomena in the field of economics. The comprehension of the fundamental constituents of metaverse is imperative. Each stratum within metaverse has been employed for distinct objectives. For instance, the IoT is implemented in a tangible commodity to facilitate traceability, production, and logistics supervision, as well as inventory administration. The IoT components utilized for tracking eye and gesture-sensor motion in AR/VR glasses are collectively referred to as metaverse. The metaverse infrastructure facilitates human interaction with the metauniverse (Zao et al. 2016; Jo and Kim 2019; Syed et al. 2022).

The advanced development and pre-loaded material (PLM) offered by software programs such as CLO, Browzwear, Optitex, and Kinetix provide extended capabilities for second and third-layer development (Min and Carrico 2018; Browzwear 2023). The integration of digital elements and components with machine learning is facilitated by artificial generative intelligence (AGI) (Baidoo-Anu and Owusu Ansah 2023). Facilitate a platform for end-users to engage in co-creation utilizing text-to-image models, prompt models, image-to-image interruption models, and voice-to-image models. The utilization of artificial generative intelligence is expected to significantly expedite the process of metaverse digital asset

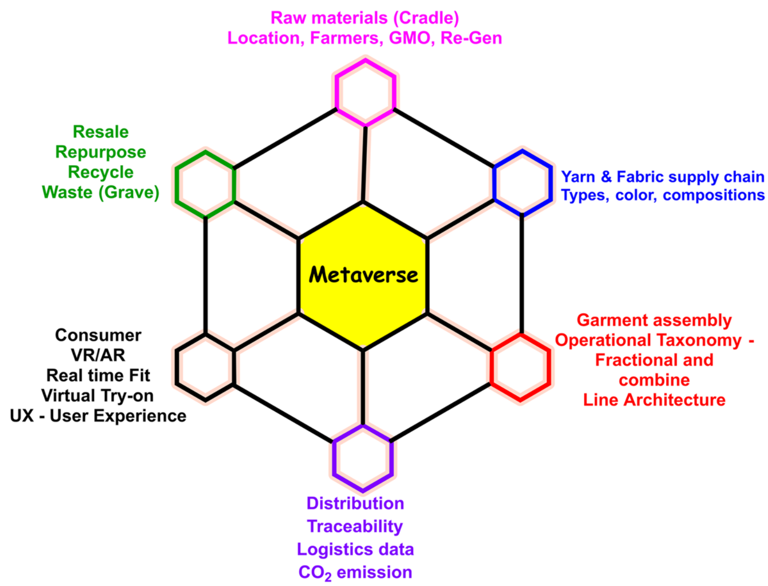

Fig. 2 Synchronization and transparency of metaverse in fashion supply chain

creation, thereby assuming a pivotal role in this domain. The advancement of artificial intelligence is experiencing a deceleration as a result of regulatory and policy hurdles.

These capabilities enable real-time manufacturing and simplify the sampling process, while also facilitating easy approval and promoting sustainability. Digital-only fashion studios, such as Fabricant and RTFKT, are incorporating digital fashion into their frontend and fortune designs, as well as engaging with the community (Mcdowell 2022). The initial layer of technologies, including but not limited to customer relationship management (CRM), manufacturing execution systems (MES), enterprise resource planning (ERP), supply chain management (SCM), product data management (PDM), and systems applications and products (SAP), are all actively pursuing integration with blockchain technology (2022b), as depicted in Fig. 2.

The concept of Fashion 4.0 entails the implementation of traceability and transparency in the supply chain, catering to demand-driven requirements, optimizing raw material usage, particularly those based on natural resources such as fibers and yarns, minimizing waste, and reducing the stock of raw materials in the showroom supply chain, as depicted in Fig. 3. In instances where the

Fig. 3 Characteristics of Fashion 4.0

ultimate purchaser of a retail brand cannot be located, is unidentifiable, or when there is a lack of transparency regarding the brand, the consumer's ability to make purchases is diminished from its optimal level (Grieco et al. 2017; Bertola and Teunissen 2018). The process of digital transformation necessitates the exposure of all digital infrastructure layers to all stakeholders in the value chain. This enables them to comprehend their individual responsibilities and ensures that the delivery of products to customers is conducted with transparency, which is a critical factor. The endeavor to integrate diverse digital infrastructures has been undertaken. An example of a system with the potential for data processing and supply chain integration is the SAP system, which stands for system, application, and product. A digital strategy consisting of a single bullet was deemed necessary for the purpose of facilitating digital transformation (Hofmann and Rüsch 2017; Francisco and Swanson 2018). The precision and coherence of digital data and information facilitate prompt decision-making, rapid response, and real-time work.

- All value chain from back and forth exposes their functionalities through the service interface.
- value must communicate with each other through this interface.
- There will be no form of inter-process communication allowed other than the digital interface.
- No direct linking. no direct reading of other team data stores and no shared memory models. no back doors, only service interface called over the network.
- Does not matter what technology uses HTTP, core, or custom protocols.
- All service interfaces must be designed ground up to be externalizable people outside the company can use them.
- Team must plan and design to be able to expose the interface to developers in the outside world with no exceptions.

Internally, data and information are shared in a similar manner as they are shared externally, via service buses. Blockchain and distributed ledger technology represent a prominent and optimal solution for integration purposes. The implementation of blockchain technology within business networks (value chains) has been shown to enhance the trust, security, transparency, and traceability of shared data. Additionally, this technology has been found to promote cost savings through increased efficiency (Bas et al. 2022; Yang et al. 2023). From 2010 to 2019, sustainability and digital transformation have become optional for brands, challenging the marketing status quo. The COVID-19 pandemic has prompted a shift in the attitudes and practices of fashion industry leaders, who have come to appreciate the values and conduct of Gen Z, the demographic group at the forefront of the digital transformation era (Mourtzis et al. 2022; Pop et al. 2023; Abidi et al. 2023).

In instances where customers discontinue in-store visits, online guest access websites, e-commerce, and multichannel internet platforms in marketplaces are utilized to effectively cater to the guest, customer, and end user. Consumer behavior has recently prompted inquiries regarding the origin of a product, including its manufacturing process, the sourcing of its components and raw materials, the compensation of workers involved, and the completion of social-life cycle assessment (S-LCA) and worldwide responsible accredited production (WRAP) certification (Guinée 2012; Periyasamy and Militky 2020b; Ashby 2024). The extant protocols pertaining to quick response (QR) codes or barcodes ought to elucidate the metadata of commodities, given that such particulars remain enigmatic to nascent consumers (such as gen Z) worldwide. Digital native software is present in every supply chain across the industry. Inventory-based enterprise resource planning (ERP) is utilized by suppliers of raw materials (Choi et al. 2013). Planning-based ERP systems are utilized by manufacturers. The implementation of an ERP system that is centred around the point of sale (POS) can be attributed to either the seller or the brand. Each of these software applications offers efficiency, performance, planning, and data for their respective purposes through their utilization. However, the proprietor of the purchased product fails to adequately provide information regarding its usage and features. The fashion industry's covert motives or protracted assessment resulted in numerous instances of the tragedy of the commons such as the EU-China in 2005 (Garrity 2012), as well as the overexploitation of natural resources, exemplified by the unpredictable fluctuations in cotton prices that necessitated high inventory levels on a weekly basis (Thomas 2021). Walmart employs a strategy of targeting prominent retailers by leveraging insights gleaned from the fashion industry's previous ten years of data. This approach is documented in reference (Project Pro 2022). Numerous failures are occurring in both the market and various products. The most pressing challenge facing the industry and its leadership team is devising effective strategies to address these tragedies. In the context of sustainability implementations, numerous practical issues and non-transparent mindsets exist within each layer of a fashion product.

An additional distinctive instance of pragmatic applications of non-fungible tokens pertains to the domain of digital fashion. In a recent development, RTFKT, a virtual fashion brand owned by Nike, has successfully

Fig. 4 AR in marketing: Wanna Kicks AR app (Reused from (Mike Bitanga 2019); https://wanna.fashion)

conducted an auction of a digital jacket, which fetched a price exceeding $125,000 (Dugal 2022). The Fabricant, a fashion brand, released the Iridescence Dress in 2019, which was the first dress to be exclusively digital and utilize blockchain technology. The Iridescence Dress was initially valued at $9,500 upon its issuance. The value of the subject in question is likely to have experienced a significant increase over a period of time, as indicated by reference (Mowatt 2019). Notably, prominent fashion labels including LVMH, Hermes, Gucci, Marc Jacobs, and Burberry are contemplating the possibility of venturing into the realm of NFTs (Geroni 2021). Upon purchase by a consumer, NFTs undergo a process of minting, which deploys ownership onto the blockchain. The customer also receives the tangible product, thereby augmenting the product's accountability and traceability in the inventory. The individual who possesses the item bears the responsibility of disposing it, or alternatively, they may opt to exchange, reuse, repurpose, or resell it, thereby extending the product's life cycle (Raman and Edwin Raj 2021; Rehman et al. 2021).

3.1 AR/VR influence on customers and ways to reduce waste

The term 'extended reality' or 'cross reality' (XR) encompasses a range of immersive technologies that generate electronic and digital environments for the representation and display of data. VR, AR, and mixed reality (MR) are all constituent elements of XR. The various XR modalities described above involve individuals perceiving and interacting with a digital environment that is either wholly or partially artificial in nature and has been generated using technology (Pellas et al. 2021).

3.1.1 Augmented reality

The expeditious expansion of AR technology, which enhances the in-person and virtual shopping experience, is transforming the operational procedures at the forefront of the retail industry. The use of AR retail apps (ARRAs) has emerged as a rapidly evolving, distinctive, and forward-thinking retail innovation that is employed in both brick-and-mortar stores and e-commerce platforms to augment the retail atmosphere and improve the customer experience (Chiu et al. 2021). In contrast to VR which generates a wholly synthetic environment, AR superimposes fresh information onto the pre-existing environment. The addition of a digital layer to the physical environment using AR does not provide a fully immersive experience, as opposed to VR which necessitates the use of specialized headsets or glasses to transport users into a wholly digital world (Carmigniani et al. 2011; Berryman 2012; Rauschnabel et al. 2022a). AR technology enabled users to sustain their interaction with the tangible environment.

Figure 4 depicts the 3D representation of shoes that can be virtually placed in a physical space within the user's room through a mobile device. This feature enables users to verify whether the size and appearance of the shoes match the background before making a purchase, thereby avoiding the inconvenience of having to replace and transport items due to incorrect size or color selection. Additional illustrations depict sneakers that can be worn on the foot without being physically present. Customers can also view and encounter 3D sneakers that can be positioned on their legs for visualization purposes. In a scenario where customers refrain from visiting physical stores in person. This results in significant reductions in transportation costs and eliminates the inconvenience associated with purchasing a product (Sadamali Jayawardena et al. 2023).

The utilization of visual aids, such as information and images, enhances the process of decision-making through the application of AR technology. Wayfair and IKEA have responded to customer feedback regarding the challenge of visualizing furniture within their decor by providing AR-based online catalogs (Brewton 2020; Hagberg and Jonsson 2022). Consumers are provided with the alternative of digitally installing, relocating and modifying the color of lifelike 3D furniture models, such as a coffee/computer table, intended for their living space. Moreover, AR is increasingly utilized to fulfill the needs of consumers who seek supplementary visual product details to enhance their decision-making abilities. The AR application known as KabaQ has been developed to augment restaurant menu cards by providing virtual information pertaining to ingredients, calories, and portion sizes (Manzoor and Hasan 2021; Styliaras 2021). Patrons can examine menu offerings through three-dimensional digital depictions from multiple perspectives and dimensions. One potential approach to facilitate product assessment and stimulate sales is to implement an AR retail interface. As a result, numerous retailers are expeditiously incorporating AR interfaces into their primary retail operations. The present uses of AR-based applications are delineated in Table S1.

3.1.2 Virtual reality

In the last decade, there has been a significant focus on the swiftly growing domain of virtual reality (VR). VR employs computer-based technology to generate and simulate applications that may or may not be realistic (Grieco et al. 2017). From a technical standpoint, VR denotes a computer-generated three-dimensional environment. One may engage in a VR encounter and interact with it within an immersive and captivating setting. Individuals are fully engaged within the VR setting and possess the ability to manipulate various objects or perform diverse tasks (Rauschnabel et al. 2022b). While the definition of VR may blur the distinction between the metaverse and VR to some degree, it is crucial to recognize that VR can provide access solely to a contained experience or a limited virtual environment. VR is a means of experiencing the metaverse, but it should not be confused with the metaverse itself. According to Fig. 5, an individual who dons a headset can access a predetermined and restricted digital or virtual setting to participate in a designated task or encounter. VR technology can be utilized to facilitate various activities such as tourism, healthcare, fashion, and important training sessions within virtual environments. The utilization of an AR headset enables individuals to retrieve data and engage with the VR environment. Customers can visually assess the product's fit, size, and color, and may select alternative color options, provided that the virtual environment in question offers such alternatives. The technology provides an immersive experience that is akin to being physically present in a retail store (Hamad and Jia 2022; Villagran-Vizcarra et al. 2023). In contrast to AR,

Fig. 5 VR in apparel sector, (Reused from, https://cinematicvr.pl/ (Konrad Ziaja 2019))

VR offers a more immersive and immediate experience as it enables users to interact within a digital environment.

- AR- access 3D products and fit them through your interactive tools (i.e., mobile/tablet /PC).
- VR—Access 3D products and interact with the environment using a VR headset. Customers can still feel your presence in the physical environment.

The metaverse is a form of volumetric video that demonstrates a significant level of resilience, enabling users to completely engage in an virtual environment and experience unrestricted entry to digital space (Mystakidis 2022). Roblox and Minecraft are often cited as exemplars of the metaverse, however, it is important to note that these platforms are centralized in nature.

Incorporating one-way customers into the design and fit of clothing and accessories has the potential to curtail the number of purchases made by said customers. Individuals have the autonomy to purchase precisely what they desire. The potential impact of sustainable fashion lies in its ability to address the issue of excess clothing production, which currently stands at 27% globally (Peleg Mizrachi and Tal 2022). This surplus results in a significant amount of clothing ending up in landfills, rendering it useless. The economic unsustainability of the excessive manufacturing process, coupled with the exploitation of 27% more natural resources, further underscores the need for sustainable fashion practices (Rauturier 2022). According to sources (Bick et al. 2018; Dardana 2021; Nazir 2021), in an alternate dimension, the total emissions resulting from both the manufacturing and disposal of a product are twice the amount of CO_2 released. Considering all the garments that remain unsold or unutilized are not reintegrated into the proper recycling system (Uprichard 2019).

The metaverse is poised to revolutionize the retail and fashion industries, as individuals often underestimate the transformative impact that emerging technologies can have on these sectors. During the nascent stage of the internet, individuals were not cognizant of the prospective advantages of e-commerce, including its capacity to provide customers with sustainable options. Furthermore, the epidemic expedited the transition towards online retail, and with the persistent growth of e-commerce transactions, a greater number of retail establishments are expected to cease operations in the forthcoming decades (Nathaniel Meyersohn 2021). As per UBS's estimation, it is anticipated that approximately 80,000 retail outlets will cease operations within the next five years (Meyersohn 2021). The growth of fashion e-commerce can be attributed to the emergence of novel consumer behavior patterns and the digital transformation of the fashion retail sector. In 2020, the United States witnessed a significant contribution of 29.5% from e-commerce towards the overall sales of apparel retail, as reported (Pereira et al. 2022). According to the researcher's projections, it is anticipated that the sectors encompassing apparel, consumer electronics, home decor, and sports equipment will experience the highest number of store closures within the specified period. Most retailers, including those selling clothing, electronics, furniture, and athletic goods, will be closed during that time, according to the study's authors (TechWire 2022).

3.2 Customized design for B2C/ B2B

In a digital creation scenario, the final consumers are granted access to the product. Due to the uniqueness of each user, visitor, and client, they may seek highly customized items tailored to their specific needs and preferences. Due to the presence of physical goods in front of the customer, they are compelled to purchase the most suitable option available. With the current availability of digital editing and customization options, manufacturers may encounter challenges in determining optimal production quantities (Choi 2022; Periyasami and Periyasamy 2022). The anticipated quantities are expected to be of a diminutive nature, while the standards for quality are projected to be elevated. This terms it as,

- On Demand manufacturing/precision marketing
- Accurate manufacturing.
- Data-driven manufacturing

Mass manufacturing during a typical fashion season often results in an excess of 30% in the number of produced items beyond what is required. This phenomenon leads to an increase in product prices and is deemed to be unsustainable (Hoppenbrouwer 2022). Both brands and retailers could explore novel direct-to-consumer supply tactics. These platforms function as sales channels that provide curated designs for buyers to select from, which can be further customized before placing the order for production.

This interaction can occur among customers of varying levels worldwide. What is the rationale behind the categorization of customers into distinct levels, and how will the implementation of these three technologies facilitate their support. AR technology can be accessed through user-friendly mobile devices, allowing individuals to select products that are tailored to their specific needs (Rumiński and Walczak 2013; Jain et al.

2017). Globally, the number of smartphone users who have the capability to access AR applications is estimated to be 6.65 billion. The utilization of the personalized design is not a feasible option for the consumer. However, they may opt to select the appropriate product, size, and hue that best suits their preferences. This practice mitigates the frequency of customers returning items to physical stores or online marketplaces. This solves below difficulties.

- Customer return rates reduces drastically
- Customers don't want to pay for the return of goods
- Reverse will affect sustainability policies

3.3 3D printing and 3D knitting

The integration of manufacturing and raw material innovations, as well as machinery innovations, holds significant potential for achieving genuine sustainability and the Inclusive Wealth Index (IWI)-ESG-LCA (Finkbeiner et al. 2010; Roman and Thiry 2016). The achievement of minimal waste and high accuracy in product manufacturing, as well as the implementation of wasteless or low waste manufacturing infrastructure, can only be realized through additive manufacturing (Lewis et al. 2017; Niinimäki et al. 2020). Over the past decade, the utilization of seamless knit technology in the sportswear and underwear market has experienced growth. As a result, the industry has achieved a 43% reduction in carbon footprint associated with production (Nayak et al. 2020; Gorea et al. 2021). Additive manufacturing technology has been utilized to produce 3D designs from modified raw materials with high efficiency, quality, and consistency (Loy et al. 2016; Javaid et al. 2021).

Currently, there is widespread discourse surrounding the topic of 3D printing, also known as additive manufacturing. It has been observed that three-dimensional printing technology has the capability to produce a diverse range of objects, such as edibles, dwellings, and even anatomical structures (Chakraborty and Biswas 2020; Lee et al. 2023; Shahbazi et al. 2023). The fashion industry is expected to be influenced by the forthcoming advancements in 3D printing technology. Despite the initial sluggish adoption of 3D printing in the fashion industry and the numerous technological hurdles it faced, recent advancements have significantly enhanced this technology (Palsenbarg 2014). Despite the advancements in 3D printing technology, the tactile qualities of garments produced through this method do not match the smoothness, flexibility, and comfort of conventional garments crafted from cotton or other textile fibers. Currently, the employment of 3D printing technology in the fashion industry has been limited to the production of footwear and accessories (Vanessa Palsenbarg 2014).

In contrast to the conventional process of producing sneakers that necessitates the use of a metallic mold for sole manufacturing and takes more than a month to complete, the utilization of 3D printing technology accelerates the production process to less than two hours (Bain 2017). Moreover, the technology of 3D printing offers the opportunity to tailor the dimensions and suitability of the footwear to the specific needs of the customer and their foot. Fleet Shoes, a nascent American enterprise, provides personalized 3D-printed footwear that can be tailored to individual preferences (Fleet and Feet 2022). The company's proprietary application enables users to gauge their foot dimensions and choose from a variety of shoe designs and hues. The personalized sneakers, produced through 3D-printing technology, are delivered to customers within a timeframe of 7 days (Maiti et al. 2022; Pei 2022a; Periyasami and Periyasamy 2022). In contrast to 3D printing, the utilization of 3D knitting has been more extensively adopted by business-to-business (B2B) and business-to-consumer (B2C) fashion brands. This is because 3D knitting technology closely resembles the conventional 2D knitting process, and it employs yarns to create 3D fabrics and garments (Liu et al. 2018; Periyasami and Periyasamy 2022). The implementation of this technology facilitates the production of small quantities or on a demand basis, leading to a significant reduction in inventory and logistics for businesses. The utilization of 3D knitting technology to produce garments based on customer demand is a popular choice for B2C industries. Furthermore, the implementation of AR/VR technology allows customers to make selections pertaining to design, yarn varieties (e.g., based on their properties, and recyclability), accessories, and zippers. The metaverse platform offers supply chain transparency, enabling customers to gain insight into waste reduction measures. For instance, the utilization of 3D knitting technology has been shown to decrease material waste from 35 to 21% (Chiles 2021; Pavko Čuden 2022; Krinner 2023).

3.4 Metaverse influence on manufacturing

The metaverse presents a tangible application for the industrial and manufacturing sectors through the utilization of 'Digital Twin' technology (Nielsen et al. 2020; Malik and Brem 2021). It is noteworthy that digital twins serve as fundamental components of the metaverse. A digital twin refers to a computer-generated replica of physical objects or systems that are utilized in the manufacturing process. Manufacturing teams utilize digital twins to strategize and evaluate novel production lines. The 3D design of denim products has been completed and is now available (Cotton Inc 2022). Simulation of

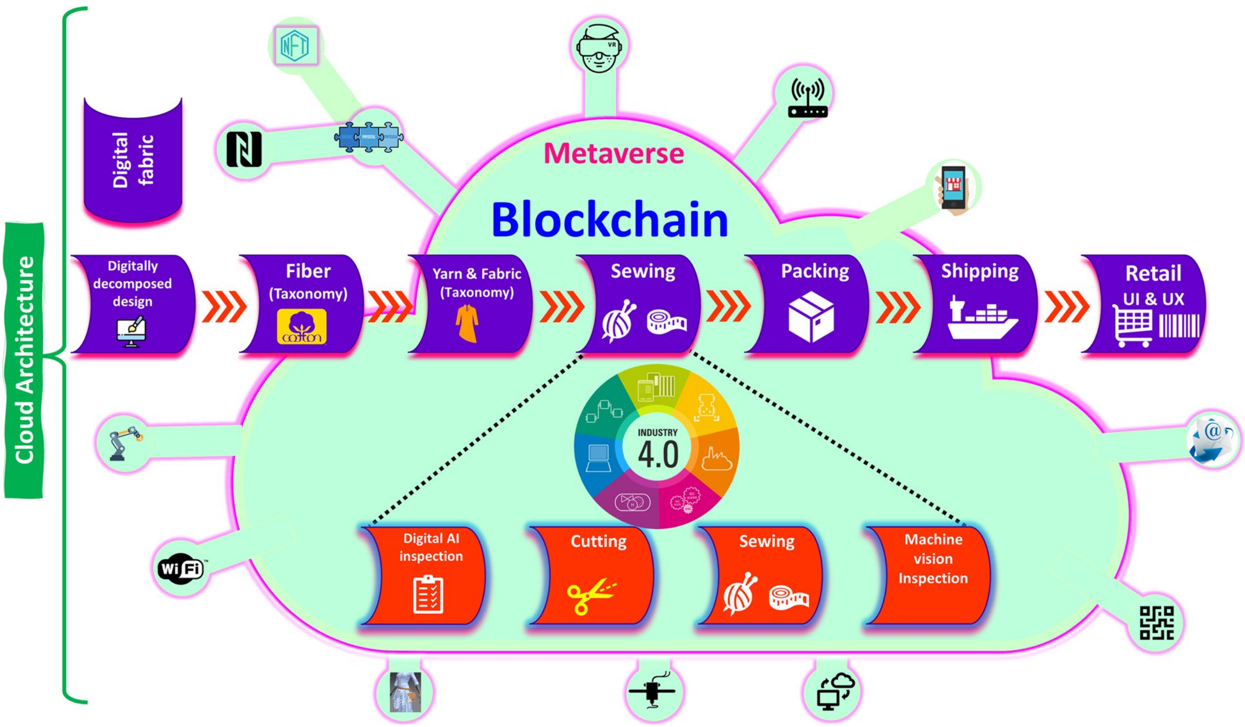

Fig. 6 Anticipated impact of the metaverse on the textile manufacturing industry

production operations and optimization of potential issues prior to the creation of the physical manufacturing platform can be employed to test the 3D design of a pair of jeans and develop predictable production plans (Cotton Inc 2022). The utilization of the digital twin visualization methodology has the potential to enhance problem visibility and facilitate communication across the entire production team (Malik and Brem 2021). The current utilization of underlying technologies varies in terms of their state and intended functions. Digital transformation is a multifaceted process that involves the integration of various digital technologies and tools, rather than a singular solution.

In the field of garment production, simulation technology commonly entails the generation of a prototype for a novel production element or a more intricate representation, such as a miniature replica of an entire manufacturing plant. Garment manufacturers and brands have endeavored to mitigate the detrimental impact of garment production on the environment. Simulation technology is being utilized to promote sustainable practices considering the growing implementation of advanced and efficient production methods (Kursun 2011; Jung et al. 2022). The implementation of technology in production processes allows companies to attain substantial efficiency advantages by facilitating the testing of minor alterations on the shop floor during the initial stages. The observed improvements can be ascribed to the capacity of technology to facilitate the experimentation of incremental modifications in business operations. Furthermore, the implementation of this technology can potentially mitigate waste through the utilization of lean manufacturing methodologies, thereby contributing to the reduction of carbon emissions (Hamja et al. 2019).

The term 'waste' can also encompass the quantity of time that is expended on endeavors that do not have a direct correlation to productivity. When a worker is required to visit an alternative production site, such as those involved in chemical processing, yarn manufacturing, or fabric manufacturing, to carry out their daily duties, the act of traveling can result in a loss of time and energy, as well as an increase in the carbon footprint (Wadud et al. 2016). The metaverse platform facilitates the interconnection of various processes and devices through the IoT, enabling digital access to information from any location. Consequently, this feature contributes to the mitigation of environmental pollution. The metaverse and its impact on the garment supply chain were expounded upon in Fig. 6. Furthermore, the simulation has the potential to identify strategies for reducing tangible waste. It is plausible that altering the approach could result in a reduction of the proportion of unsuccessful endeavors while simultaneously increasing the proportion of successful ones. This exemplifies another efficacious implementation of simulation within the world of sustainability.

Moreover, metaverse aids enterprises in enhancing their factory layouts to attain energy conservation advantages through the implementation of more effective methods and enhancing the ergonomics of production or process flows (Radoff 2021; Mystakidis 2022; Al-Emran and Griffy-Brown 2023). Its primary objective is to achieve productivity. Metaverse technology plays a crucial role in enhancing the resilience of the supply chain by facilitating the simulation of diverse components of the broader supply chain. This approach ensures that more transparent and open processes are implemented in the physical realm. Thus, manufacturers can ensure the longevity and adaptability of their operations on the factory floor, as well as in their supply chain and distribution procedures. The following components must be established prior to the implementation of a digital twin or metaverse in the manufacturing industry.

- Currently, 3D modeling has become a popular trend. Various 3D modeling simulators, such as Brozwear, CLO, and optitex, are readily accessible and possess the capability to comprehend the manufacturing aspect of the garment industry (Min and Carrico 2018). These simulators enable the creation of 3D models for the purpose of presenting them to buyers for review and approval prior to the commencement of actual garment production. Following the process of 3D modeling, the conventional approach to producing goods is resumed. Organizations may opt to utilize this software as a service for an additional fee or to accommodate customer demands. However, the primary objective is to transform 3D modeling into a product that can be integrated into machine-to-machine communication and integration architectures, which are crucial for the advancement of manufacturing processes (Min and Carrico 2018).
- These virtual 3D models have been produced in the physical world thanks to computer-aided design (Tuck Tech CAD), which can transform a 2D blueprint into a 3D model. Products with a limited variety or production volume may nonetheless be used for manufacturing a wide variety of designs due to the potential of fabric consumption and pattern grading (Kim et al. 2023b).
- Nexio IoT system which is used for manufacturing garments and this approach can be used for all kinds of sewing machines. These systems track the operations step by step and calculate stitches and quality control over the products and improve production efficiency (Brother 2021). In current manufacturing, IoT is involved to monitor production and productivity, which are the basis IoT of RFID chips, that reader connected in each machine and section before transfer from one department to another department, or one operation to another operation. But actual digital twin/ transformation requires inbuild or compatible IoT integrations in the machine to pull production data and stimulation in real time.
- Nexio IoT (from Brother) system can function with low initial investment and can be used in factories of any size or type. This technology automates time-consuming processes including data gathering, transcribing, and reporting to lighten the strain and speed up garment production (Brother 2021). Since it eliminates the need for manual production management on a whiteboard by showing the progress with a big display, this technology shortens the lead time and makes real-time data collecting possible. Data on production or lines can be accessed in real time from anywhere in the world, not just inside the factory. Further, it generates more precise data and reports, which lessens quality difficulties caused by human mistakes (i.e., size measurement spec sheet).
- Sewing machines can be considered IoT devices due to their ability to execute preloaded programs for various materials and products (Jung et al. 2020). IoT-connected systems will enable precise monitoring of real-time production, efficiency, and deficiency simulation in real-time. The current iteration of 3D models includes precise specifications regarding stitch per inch and the quantity of components and constituent parts incorporated within simulated products. The utilization of intelligent data readers can aid in determining the requisite quantity of curves and turns in practical manufacturing processes. The replacement of resource-intensive technologies with those that generate less waste and consume less energy has a significant impact on long-term environmental sustainability.

3.5 Metaverse in fashion logistics

The fashion supply chain is a complex network involving multiple stakeholders who are accountable for the acquisition of raw materials from diverse sources and operations (Henninger 2015; Kumar et al. 2017). The fashion value chain is characterized by a lack of uniformity in its route, because the raw materials for a garment may be produced in one country, spinning in another, dyed and processed in a third, and turned into a garment in a facility that is geographically distant from the store. The fashion industry is characterized by high volatility, a short lifespan, unpredictability, and dependence on impulsive purchases. To effectively monitor a complex value chain, it is necessary to maintain a distributed database on the internet that provides access to all pertinent data and supply chain operations. The dataset would comprise pertinent details pertaining to the product, such as supply and demand, among other significant information (Henninger 2015; Kumar et al. 2017). To establish a sustainable supply chain, it is imperative that complete transparency is maintained and that access to the entire supply chain is provided. The implementation and advancement of blockchain technology would be advantageous for the stakeholders engaged in logistics operations. The intricate and opaque nature of conventional supply chains underscores the necessity for enhancing these procedures (Yli-Huumo et al. 2016).

The integration of metaverse-enabled blockchain technology has the potential to offer novel logistical services and business models within the fashion value chain. The stated objective is to achieve extensive decentralization, instantaneous peer-to-peer functionality, anonymity, transparency, immutability, and integrity (Tijan et al. 2019). Blockchain technology effectively resolves the issue of double spending and simultaneously verifies each transaction, thereby ensuring that fraudulent transactions cannot pass collective verification (Zhao et al. 2016). Blockchain technology has the potential to facilitate the verification and digital tracking of fashion products, from their raw material stage to their ultimate placement on retail shelves. The incorporation of this process leads to a notable improvement in its adaptability, rapidity, efficiency, and caliber, thereby resulting in an augmented potential for sustained utilization. The utilization of blockchain technology has the potential to mitigate logistical challenges, including but not limited to delivery delays, document loss, unidentified item origins, and inaccuracies. These challenges can be completely eradicated (Tijan et al. 2019; Tan et al. 2020).

4 Challenges and opportunities

In the context of limited-duration experiences, AR technology typically utilizes lightweight devices, while VR technology often necessitates the use of costly and cumbersome hardware. Certain methodologies amalgamate the advantages of AR and VR to enable seamless transition between AR and VR within a singular hardware component (Park and Kim 2022). Given that metaverse collects more granular behavioral data than mere user interactions or internet history, ensuring privacy and security becomes a critical concern. Enhancing the security of metaverse data can be achieved through the implementation of two-factor authentication for avatars, which is deemed essential. Additionally, it is imperative to exercise vigilance in monitoring any illicit conduct within the metaverse (Leenes 2008).

Sustained advancements in visual technology are imperative for the optimization of the metaverse, which engenders a simulated milieu of heightened realism. Numerous metaverse commodities derive inspiration from actual individuals, and users possess the ability to customize and adjust the designs of said products (Kshetri 2022). The design of the metaverse ought to be conducive to user input, which can be generated through the utilization of graphical techniques. It is plausible that a variety of 3D objects, such as residences, automobiles, and other items, could potentially be reconstructed within the metaverse, in addition to the creation of avatars. The extent of user actions is determined by the development of sensors and devices. Numerous forms of realistic interactions can be achieved through the utilization of diverse types of action input captured by different devices. There exist diverse resources that enable users to navigate, engage, manipulate, and customize entities within the metaverse. Furthermore, individuals have the capacity to convey intention and meaning through nonverbal cues, including but not limited to eye contact, physical movements, and the orientation of their heads (Bujak et al. 2013; Kshetri 2022; Chang et al. 2022; Allam et al. 2022).

4.1 Comfort versus digital fashion

The fashion industry considers comfort to be a multifaceted concept that is influenced by various physical and physiological factors such as prickling, itching, stiffness, and smoothness (Kar et al. 2011). Furthermore, the utilitarian purpose of clothing encompasses the act of concealing the body and providing insulation, as well as facilitating energy return in footwear, regulating body temperature through radiative and evaporative mechanisms, promoting moisture wicking and breathability, augmenting physical performance, and enabling stretchability (Watkins 2011; Maria Kulińska 2018; Cho and Kim 2022).

The latest developments in 3D measuring technology have enabled a precision of 0.01 mm in the measurement of internal volumes of footwear and clothing, surpassing the required level of adequacy (Watkins 2011; Guo et al. 2011; Liu 2018; Maria Kulińska 2018; Thomassey and Zeng 2018; Tadesse et al. 2019; Chen et al. 2020). Furthermore, it is possible to conduct these measurements in a dynamic manner that takes into consideration the evolving characteristics of materials, thereby facilitating a non-contact fitting process that closely approximates the experience of an in-store fitting. The reason for the suitability of modern laser scanners in digitizing the feet and body lies in their high measuring precision, which can reach fractions of a millimeter (Watkins 2011; Guo et al. 2011; Liu 2018; Maria Kulińska 2018; Thomassey and Zeng 2018; Tadesse et al. 2019; Chen et al. 2020). Nevertheless, these devices are deemed too costly and are not intended for personal utilization. Contemporary mobile applications designed for smartphones offer a level of accuracy in both foot and body measurements that ranges between 1–2 mm (Watkins 2011; Guo et al. 2011; Liu 2018; Maria Kulińska 2018; Thomassey and Zeng 2018; Tadesse et al. 2019; Chen et al. 2020). This technological advancement presents promising opportunities for the extensive digitization of the fashion industry (Li and Cohen 2021; Afteni et al. 2022).

The online fitting service utilizes AI algorithms to match digital twins of goods and buyers, enabling the identification of the most suitable fit between the buyer's anthropometric measurements and the actual interior volumes of clothing and footwear (Hidayati et al. 2018; Chen et al. 2023). This process considers various factors such as foot and body movement as well as material properties. The study aims to determine the mean level of digital proficiency among different brands in their apparel and footwear product lines, with a particular focus on demographic segments. This will be achieved by analyzing digital compliance indicators across various manufacturers and consumer groups (Hidayati et al. 2018). It is possible to store all of these metrics as universal digital comfort data. It is widely acknowledged that obtaining feedback from customers after they have used the products is the most effective means of ensuring optimal comfort for each individual. The refinement of confirmation data has resulted in the establishment of more precise criteria for determining customer comfort levels across multiple purchases. To this end, the online fitting service has been designed to equip each customer with a digital tool that is ideally suited for navigating the fashion metaverse. The integration of blockchain technology has proven to be a suitable digital counterpart for both comfortable apparel and footwear (Hidayati et al. 2018; Chen et al. 2023). NFTs offer a means for brands and manufacturers to confer a unique digital identity upon their products, while also enabling the storage of supplementary information such as the design, material, color, and size of a given item of clothing or footwear. The integration of digital twins can facilitate the inclusion of significant measurements related to the size and comfort of clothing and footwear designs in the NFTs (Rehman et al. 2021; Vidal-Tomás 2022a, b).

4.1.1 Virtual tried-on

Advanced contemporary techniques enable the exhibition of virtual garment static and dynamic performance through the consideration of human morphological and fabric properties, as well as their interactions. These techniques facilitate the importation of 3D body scan data and the simulation of various postures of the human body model, in addition to the importation of movement information (Lage and Ancutiene 2017). The virtual try-on software's reliance on mathematical models within their software limits its ability to provide a comprehensive and accurate assessment of a garment's fit. As a result, a thorough evaluation of fit cannot be achieved through these programs. Some examples are Clo 3D (CLO Virtual Fashion), Vidya (Assyst), Modaris 3D FIT (Lectra), V-Stitcher 3D (Browzwear), Scanatic DC Suite (TG3D Studio), Mobile Virtual Fitting (TriMirror), Q-Fit (Quantum Matrix Ltd.) (Lage and Ancutiene 2017; Luu 2021; Rhee and Lee 2021; Mong Hien Thi Nguyen 2022). Another technological advancement that allows you to try on garments without removing them is the interactive mirror, sometimes known as a 'virtual mirror', like the ones made by 3D Magic Mirrors (3D-A-PORTER Ltd.) or FXMirror (FXGear) (Pei 2022b). Combining RFIDs technology with AR, the smart virtual mirror simulates a dressing room (Danielsson et al. 2020). This screen is often used in retail establishment's fitting rooms and is used as an interactive mirror. Although they accomplish their goals in somewhat different ways, they both allow for the draping of an avatar in virtual clothing (Boonbrahm et al. 2015).

4.2 Virtual dressing rooms

Virtual dressing rooms (VDRs) serve as a means of bridging the divide between brick-and-mortar and e-commerce shopping by emulating the sensation of trying on garments (Masri and Al-Jabi 2019; Li and Cohen 2021). Virtual try-on services enable customers to evaluate the clothing items prior to completing a transaction. Through the utilization of AR and AI, customers could engage in a virtual try-on experience to assess the visual, tactile, and fitting aspects of a product prior to committing to a purchase (Caroline 2022). It is projected that the global virtual fitting room industry will experience a compound annual growth rate of 13.44%, resulting in a market value increase from $3 million in 2019 to $6.5 million in 2025 (Oliveira 2023). The COVID-19 pandemic has expedited this progress by modifying consumer conduct and promoting increased dependence on e-commerce to an unprecedented extent. A virtual dressing room application has the potential to enhance profits by reducing returns and augmenting sales, thereby signifying its significance (Gu et al. 2021).

4.3 Digital fitting

The digital fittings system encompasses various components, including virtual fabric and its associated properties, virtual garment design and its associated properties, virtual sewing line, virtual garment, and virtual garment simulation on a virtual human body model for the purpose of fit evaluation (Gill et al. 2022). The phrase 'virtual fabric' pertains to a fabric that possesses virtual attributes, specifically physical properties such as tensile strength, thickness, bending rigidity, drapeability, and areal density. A virtual garment can be defined as a 3D article of clothing that solely exists in digital form within a virtual environment (Gill et al. 2022; Mesjar et al. 2023). The following is a list of the virtual information used in the formation of the virtual garment:

- Meta information (i.e., garment type, garment design, garment color, and garment accessories).
- 2D pattern (i.e., fabric structures, other physical and mechanical properties) and 3D pattern (i.e., shape, drape).
- Sewing information (seam, stitching, puckering information).
- Information pertaining to fitting includes the distribution of surface strain, and balancing.

The potential for a metaverse to offer virtual renditions of tangible apparel worn in physical reality is a possibility. The entire lifecycle of clothing is monitored and updated using various technologies, such as IoT devices and AI-generated analytics, which facilitate the observation and management of virtual representations (Nouinou et al. 2023). Real-time modifications of these representations are possible. The accurate anticipation that the emergence of digital fashion would lead to a reduction in the duration of physical store visits for clothing shopping, thereby signifying a noteworthy progression in the industry, has been validated. The reduction in carbon emissions resulting from consumer and designer travel has led to a deceleration in the movement of the value chain towards the utilization of personalized materials, thereby minimizing the implementation of a 'locals-on-locals' approach (Adalbert Jahnz 2022). According to DressX, the production of digital apparel results in a 97% reduction in carbon emissions compared to the production of physical clothing (DressX 2022). The veracity of this statement remains uncertain, as the significant computational resources required for digital apparel and the metaverse may result in unforeseen repercussions (Durocher 2022).

5 Conclusion and future scope

In recent years, the concept of digital fashion has emerged as a prominent trend in the fashion industry. The utilization of metaverse technology is of notable importance within the fashion industry as it serves to bolster sustainability efforts throughout the entire lifecycle of a product. The integration of the metaverse and sustainability within the fashion industry is currently in its nascent stages. This study highlights novel business strategies that effectively manage and mitigate issues of surplus inventory and uneven market demand through tailored design while simultaneously promoting sustainable production practices. The conventional fashion business model is plagued by issues of imbalanced demand and excessive supply. This phenomenon arises due to the production of a greater quantity of goods without a comprehensive comprehension of customer expectations. The metaverse platform enables customers to engage in the creation of their own apparel, resulting in reduced inventory through customized production and service. Consequently, the fashion industry will witness a shift towards greater sustainability.

The advancement of digital infrastructure has facilitated the sewing and manufacturing processes, rendering the traditional linear arrangement of various machines unnecessary. It is imperative to modify the manufacturing architecture to a tree structure that can accommodate the production of multiple products and designs within a single line of sewing operations. In order to attain the objectives of flexibility, adoptability, and sustainability, it is imperative to devise an engineering system that operates diligently.

Furthermore, the utilization of metaverse and blockchain technology has resulted in enhanced transparency within the supply chain. As a result, consumers are now able to access comprehensive information regarding the product, ranging from the fibers used to the finished garments, recycling potential, and rental particulars. This enables consumers to make informed decisions regarding the appropriate design, color, price, and fit. As a result, the brand possesses a reduced inventory of unsold merchandise, all of which align with principles of ecological sustainability. Efficiency in sustainability can be achieved through the implementation of cleaner manufacturing techniques, as per the principles of the metaverse. The aim of this review article was to discuss the potential for sustainable clothing production, which presents a novel framework for incorporating ethical sustainability into intelligent manufacturing. For a successful business model, it is imperative that the metaverse aligns environmental sustainability with productivity. The contemporary Fashion 4.0 clientele seeks not only the traditional attributes of convenience, quality, and affordability, but also values expediency, diversity, adaptability, and openness in their shopping experience. The utilization of Industry 4.0 in the metaverse has resulted in the fashion industry's shift toward offshore manufacturing. This is due to the implementation of circular fashion practices within a specific region, which has led to a decrease in global fashion as a service and an increase in on-demand manufacturing. From a technical perspective, there exists a scope for further enhancement in the domain of infant digital fashion. To address these technical challenges, it is imperative to allocate additional funding toward research and development.

The potential of the Metaverse lies in its capacity to foster environmental sustainability through the deliberate design of virtual environments that effectively highlight the aesthetic allure and intrinsic significance of the natural world. The future state of the metaverse in the 2030s, specifically in terms of its contribution to environmental sustainability, remains uncertain. To date, there has been a notable dearth of scholarly inquiry into the sustainability aspects of the metaverse, despite the widely anticipated significant ramifications it may have on environmental, social, and economic sustainability. The adoption of the UN SDGs can serve as a valuable framework for the analysis and development of the metaverse, both presently and in the coming years. The issue of digital divides holds significant importance in ensuring the broader and indispensable social sustainability of the metaverse. It is imperative that individuals, irrespective of their geographical location or social and economic standing, are afforded equal opportunities to access the metaverse.

6 Supporting information

The supporting information contains the AR applications in fashion retailing.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1007/s44265-023-00016-z.

Additional file 1: Table S1. AR applications in fashion retailing.

Authors' contributions

Conceptualization, methodology, validation, verification, formal analysis, investigation, writing-original draft, writing-review & editing: APP; writing-review & editing: SP.

Availability of data and materials

Not applicable.

Declarations

Competing interests

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