

# Advancing the future of fashion: a bibliometric analysis of 3D technology in the apparel industry (2011–2024)

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## ABSTRACT – REZUMAT

### Advancing the future of fashion: a bibliometric analysis of 3D technology in the apparel industry (2011–2024)

The application of 3D technology in the apparel industry has accelerated significantly over the past decade, catalysing innovations in digital design, virtual simulation, and sustainable manufacturing. This study conducts a comprehensive bibliometric analysis of 1,079 publications (2011–2024) from the Web of Science using CiteSpace, mapping the field's temporal, spatial, and thematic evolution. To move beyond descriptive mapping and provide a critical interpretive lens, we introduce a three-tier conceptual framework that structures the analysis around the Technical core layer (e.g., 3D body scanning, virtual simulation, additive manufacturing), the Application and Integration layer (e.g., virtual try-on, digital showrooms, Metaverse fashion), and the Macro-impact layer (e.g., sustainability, consumer behaviour, ethical implications). Findings reveal China's dominant role in both research output and influence, driven by its robust apparel industry and national digitalisation policies. While significant progress has been made, persistent challenges remain, including the fidelity-realizability gap in fabric simulation, algorithmic biases in AI-driven sizing, and interoperability across digital platforms. Future research should prioritise enhancing simulation realism, developing standardised digital formats, integrating multi-sensory feedback, and establishing ethical frameworks to support a more inclusive and sustainable digital fashion ecosystem. This study offers a structured roadmap for scholars and practitioners aiming to leverage 3D technologies for transformative impact in the global apparel industry.

**Keywords:** 3D technology, virtual simulation, body scanning, digital fashion, sustainability, bibliometric analysis, conceptual framework

### Construind viitorul modei: o analiză bibliometrică a tehnologiei 3D în industria de îmbrăcăminte (2011–2024)

Aplicarea tehnologiei 3D în industria de îmbrăcăminte a cunoscut o accelerare semnificativă în ultimul deceniu, catalizând inovații în domeniul proiectării digitale, al simulării virtuale și al producției durabile. Prezentul studiu realizează o analiză bibliometrică cuprinzătoare a 1.079 de publicații (2011–2024) din Web of Science, utilizând CiteSpace, și cartografiază evoluția temporală, spațială și tematică a domeniului. Pentru a depăși cartografierea descriptivă și a oferi o perspectivă interpretativă critică, introducem un cadru conceptual pe trei niveluri care structurează analiza în jurul nivelului Tehnic de bază (de exemplu, scanarea 3D a corpului, simularea virtuală, fabricația aditivă), nivelului de Aplicare și integrare (de exemplu, probarea virtuală, showroom-urile digitale, moda Metaverse) și nivelului de Impact macro (de exemplu, sustenabilitatea, comportamentul consumatorilor, implicațiile etice). Rezultatele relevă rolul dominant al Chinei atât în ceea ce privește cercetarea, cât și în ceea ce privește influența, datorită industriei sale solide de articole de îmbrăcăminte și politicilor naționale de digitalizare. Deși s-au înregistrat progrese semnificative, persistă încă o serie de provocări, printre care decalajul dintre fidelitate și fezabilitate în simularea materialelor textile, prejudecățile algoritmice în stabilirea mărimilor bazată pe IA și interoperabilitatea între platformele digitale. Cercetările viitoare ar trebui să acorde prioritate îmbunătățirii realismului simulării, dezvoltării de formate digitale standardizate, integrării feedback-ului multisenzorial și stabilirii unor cadre etice pentru a sprijini un ecosistem digital al modei mai incluziv și mai durabil. Acest studiu oferă un parcurs structurat pentru cercetători și practicieni care doresc să utilizeze tehnologiile 3D pentru a genera un impact transformator în industria globală a articolelor de îmbrăcăminte.

**Cuvinte-cheie:** tehnologie 3D, simulare virtuală, scanare corporală, modă digitală, sustenabilitate, analiză bibliometrică, cadru conceptual

## INTRODUCTION

In recent years, the apparel industry has been progressively transforming through digitalisation and intelligentization. Traditional fashion design faces challenges such as low efficiency, limited variety, long sample-making cycles, and high development costs, prompting the market to demand higher standards for design. As a three-dimensional digital tech-

nology supported by computers and the Internet, 3D technology has evolved to construct virtual environments and simulate the real world with high realism and interactivity. Its application in fashion design significantly expands designers' creative possibilities and serves as a key to overcoming the limitations of traditional design. With 3D technology, designers and users can achieve highly realistic silk garment effects and transcend the constraints of traditional flat

designs through 360-degree simulation displays. Integrating 3D digital technology into the fashion industry is gradually transforming traditional design and manufacturing processes. It plays a crucial role in achieving zero-waste designs, reducing inventory, streamlining production, and promoting environmental sustainability. This not only enhances the efficiency and quality of the fashion manufacturing sector but also captures shifts in consumer demand, fostering healthy development on both the supply and demand sides. Despite the growing body of research and technological advancements in the field of 3D apparel, existing studies lack systematic reviews of research hotspots and development trends.

Therefore, this study selects relevant literature from the Web of Science database as the research object and employs CiteSpace for visualisation analysis to map the knowledge landscape. The aim is to review the global research progress in the 3D apparel domain over the past two decades and identify research hotspots, evolution trends, and future directions.

While bibliometric analysis is powerful for mapping the intellectual structure of a field, identifying key contributors, popular topics, and temporal trends, a purely descriptive approach offers limited insight into the *interconnections* between technological developments, their practical applications, and their broader implications. To address this gap and provide a more critical and interpretative lens, this study introduces a three-tier conceptual framework (figure 1) to analyse the findings. This framework posits that research in 3D apparel technology evolves through the dynamic interplay of three layers:

1. The Technical core layer, which encompasses foundational technologies such as 3D body scanning, virtual garment simulation, and additive manufacturing.
2. The Application and Integration layer, where core technologies are synthesised into practical solutions like virtual try-on systems and digital showrooms.
3. The Macro-impact layer, which addresses the broader consequences of these technologies on sustainability, consumer behaviour, and ethical norms.

This framework will not only serve to organise the bibliometric results but also to critically interpret them. It guides our analysis beyond describing *what* the research hotspots are, to exploring *why* they have emerged and *how* they influence and are influenced by broader industry and societal trends. Consequently, this paper seeks to not only map the landscape of 3D apparel technology research but also to provide a structured understanding of its drivers, dynamics, and future trajectory.

## DATA SOURCES AND RESEARCH METHODS

### Data sources

This study focuses on Web of Science (WOS), one of the most comprehensive and authoritative academic databases, covering high-impact journals across disciplines, including natural sciences, engineering, and biomedical sciences. Its robust indexing capabilities and multidisciplinary scope make it particularly suitable for bibliometric analysis [1]. The keywords “cloth”, “clothes”, “garment”, or “clothing” were used for retrieval, with an additional requirement that the

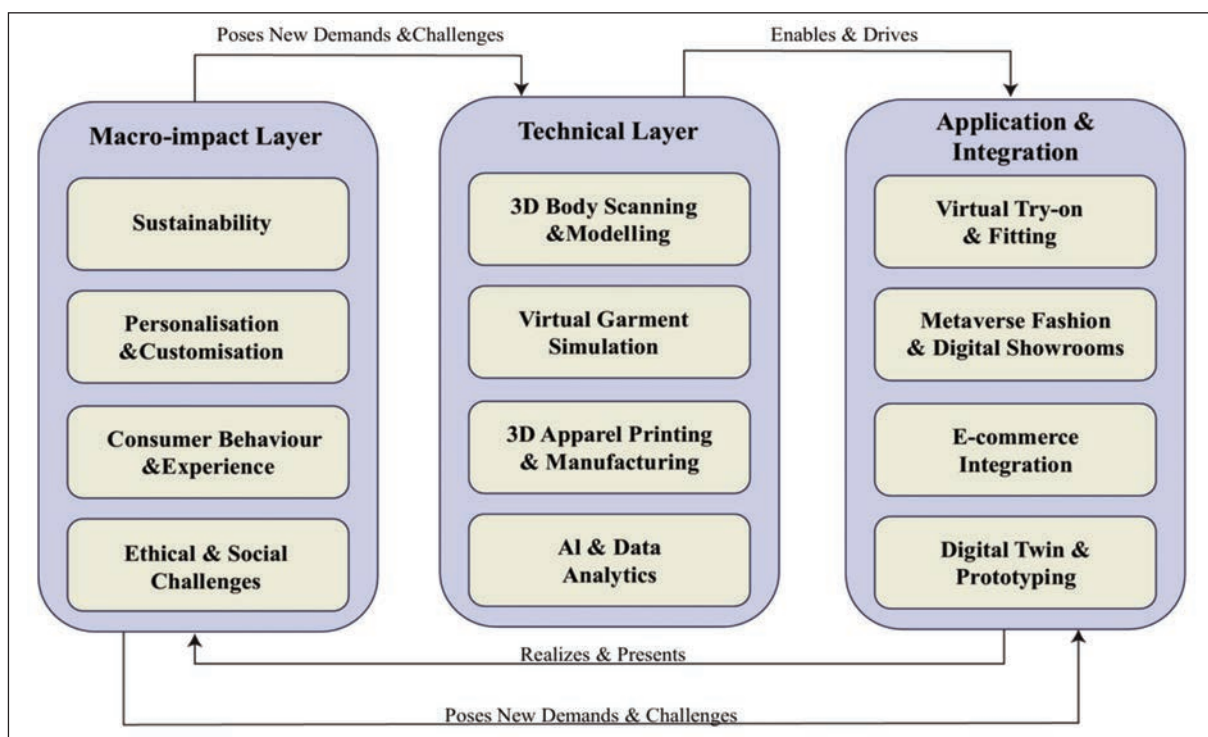


Fig. 1. A conceptual framework for analysing 3D apparel technology research, showing the interplay between the Technical core, Application & Integration, and Macro-impact layers

search results must include “3D” (include 3D). The time range for retrieval was not restricted. After deduplication using CiteSpace, all records were manually reviewed and validated. A total of 1,079 valid documents were identified, covering 387 journals, 4,095 authors, 2,525 institutions, and 221 countries and regions. The data retrieval was completed on December 28, 2024.

### Research methods

The concept of information visualisation refers to the process of converting large-scale, complex, and often unstructured information into visual formats to enhance cognitive understanding and analytical decision-making. It plays a vital role in domains such as literature analysis, where traditional manual methods often fall short in capturing research hotspots and intellectual structures over time [2]. Given the extensive volume of literature involved in this study, traditional literature analysis methods may result in omissions and fail to comprehensively and objectively reflect the research hotspots and frontiers in this field over the past two decades. Moreover, traditional manual literature review methods are prone to subjective biases. In contrast, bibliometric-based visual analysis and knowledge mapping, particularly through tools such as CiteSpace, enable a structured and objective synthesis of key literature, uncovering emerging research trends, intellectual structures, and thematic clusters within a field [3]. Specifically, techniques such as burst detection and timeline mapping, central to the CiteSpace toolkit, are powerful for identifying the evolution of research foci over time [3–15, 16].

This study primarily employs CiteSpace 6.4.R1 (64-bit), a software developed by Professor Chaomei Chen and his team at Drexel University in the United States, to conduct a multidimensional, temporal, and dynamic visualisation analysis of research literature in the 3D apparel field [3]. The analysis explores the academic pathways and development trends of 3D digital technology in the apparel sector through various dimensions, including the spatial and temporal distribution of literature, high-frequency keywords, highly cited papers, keyword clustering, and temporal evolution.

During the process of conducting a visual analysis of literature using CiteSpace, the following parameters were configured: first, the time slicing parameter was set from 2011 to 2024 to analyse the characteristics of literature on the application of 3D digital technology in the apparel field over the past decade. The granularity of time slicing (Years Per Slice) was set to one year, resulting in a total of 14 time slices. Second, the node types included various dimensions

such as authors, countries, institutions, and citations to enable multi-dimensional comparative analysis. Additionally, the g-index algorithm was employed to determine thresholds, with the k value set to 5 and the Top N threshold set to 50, aiming to identify key nodes within the network. The association strength between network nodes (Links) was calculated using the Cosine Similarity algorithm. Based on these parameter settings, this study visualised 1,079 selected articles to reveal the knowledge nodes, development trends, and collaboration networks in the 3D apparel field over the past decade. This analysis aims to delineate the research pathways and knowledge production patterns in this academic domain.

## BASIC RESEARCH AND PROGRESS IN THE 3D APPAREL FIELD

### Temporal distribution of literature

The volume and timeline of published literature reveal the evolutionary characteristics of a specific academic field. As shown in figure 2, the research in the 3D apparel field can be divided into three development stages. The first stage (2011–2015) represents a period of slow growth, with an average annual publication of approximately 38 articles. The second stage (2016–2020) marks a phase of steady growth, with the average annual publication rising to 80 articles. Entering the third stage (2021–2024), the field experienced rapid development, with the average annual publication significantly increasing to 146 articles. Overall, the publication volume in the 3D apparel field exhibits a steady and sustained growth trend. Notably, since 2020, there has been a significant surge in research output, likely driven by two main factors: first, the growing emphasis on 3D technology in the apparel industry as a mainstream trend in fashion; second, the impact of the COVID-19 pandemic, which disrupted offline international apparel trade. Consequently, 3D technologies enabled virtual garment displays for online selection, presentation, and transactions, playing a crucial role in international apparel trade. This period saw a positive correlation between market feedback and academic

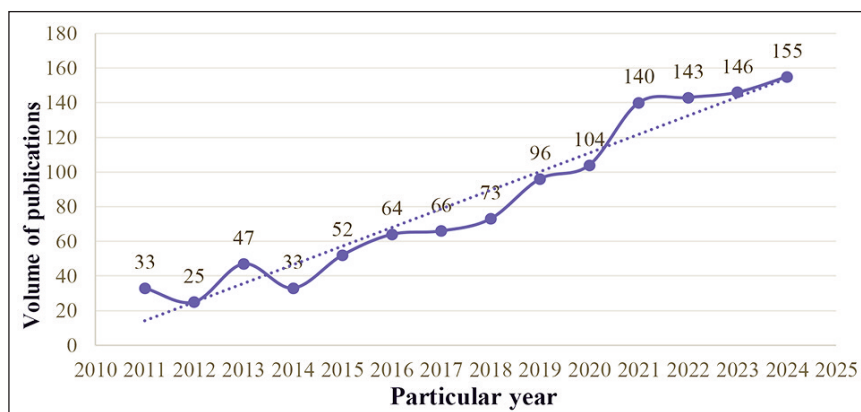


Fig. 2. Annual number of publications

research, leading to a significant increase in studies in the field.

### Spatial distribution of literature

#### National and institutional distribution characteristics

An analysis of the global distribution of research on 3D apparel reveals contributions from 74 countries, with the top 10 countries by publication volume listed in table 1. Countries with high betweenness centrality often serve as key nodes in specific research fields, marked in CiteSpace with purple rings (betweenness centrality > 0.1) to highlight their importance in the domain (figure 3). Based on publication volume and centrality rankings (table 1), China ranks as the leading country in terms of research output and influence in this field, with 490 publications and a betweenness centrality of 0.37, far surpassing other nations. Following China are the United States, South Korea, the United Kingdom, France, and others. The results indicate a positive correlation between publication volume and the development level of the apparel industry.

According to the latest statistics, China maintained its global leadership in apparel production and export in 2024. The China National Textile and Apparel Council reported that from January to December 2024, China's textile and apparel exports totalled USD 301.1 billion, a 2.8% increase year-on-year. Of this, textile exports amounted to USD 141.96 billion (a 5.7% increase), and apparel exports reached USD 159.14 billion (a 0.3% increase).

Additionally, from January to November 2024, China's apparel industry enterprises above a designated size produced 18.569 billion garments, a 3.94% increase year-on-year.

As the world's largest apparel producer and exporter, China's vast industry scale provides ample market demand and practical platforms for the research and application of 3D technology in the apparel field.

Table 1

RANKING OF NATIONAL IMPACT OF RELEVANT RESEARCH			
Mark	Country	Volume of publications	Centrality
1	China	490	0.37
2	USA	201	0.27
3	England	74	0.22
4	Romania	35	0.18
5	France	76	0.15
6	Germany	54	0.07
7	Turkey	17	0.07
8	Australia	25	0.06
9	South Korea	104	0.05
10	Switzerland	22	0.05

Simultaneously, China's apparel industry is accelerating its transformation toward higher quality and increased digitalisation, with a growing demand for digital technologies. The government has introduced a series of policies supporting smart manufacturing and the digital economy, such as the "14th Five-Year Plan for Digital Economy Development". These factors collectively position China as a global leader in 3D apparel research.

#### National and institutional distribution and collaboration characteristics

However, publication volume alone is not sufficient to measure a country's influence in the field of 3D apparel research. For instance, although South Korea's publication volume exceeds that of the United Kingdom, Romania, and France, its betweenness centrality does not show a positive correlation with publication volume. This indicates that while South Korea has an advantage in terms of publication output, its academic influence in the field may not be as significant as that of the United Kingdom, Romania, and France.

Further analysis using CiteSpace software on the effective samples produced the institutional distribution map of 3D apparel research, shown in figure 4.

A total of 1079 papers involved 336 research institutions, encompassing universities and research organisations. Based on centrality rankings (table 2), the top five influential institutions are Donghua University (79 papers), Hong Kong Polytechnic University (38 papers), Tsinghua University (21 papers), the Chinese Academy of Sciences (29 papers), and Zhejiang University. All of these institutions are based in China, underscoring China's leading position in the field of 3D apparel research.

In terms of specific research areas, Chinese universities such as Donghua University, Hong Kong Polytechnic

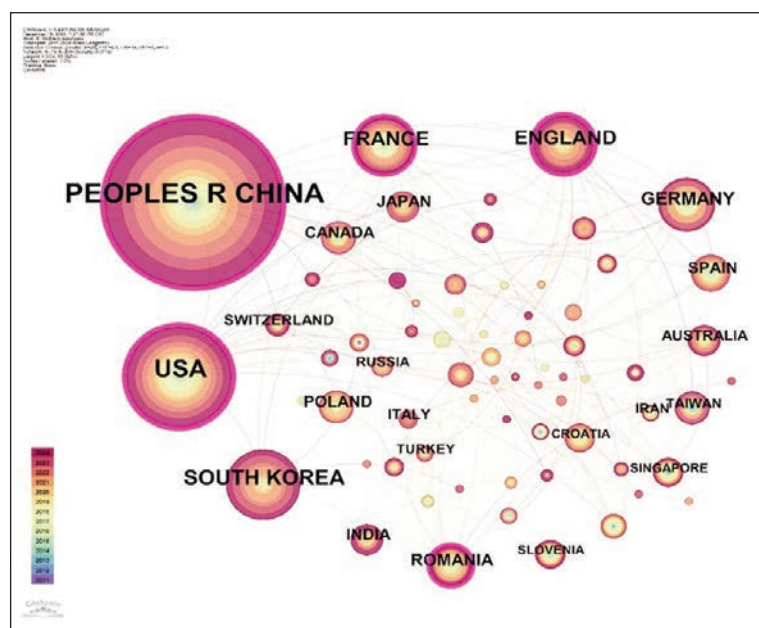


Fig. 3. Country distribution of relevant studies



Fig. 4. Institutional distribution of relevant research

University, Jiangnan University, Soochow University, and Xi'an Polytechnic University primarily focus on 3D body modelling, 3D apparel design, and modelling. Meanwhile, Zhejiang University and the Chinese Academy of Sciences concentrate on virtual simulation technologies and computer hardware and software development. Among the 336 nodes, there are 420 connections, resulting in a node density of 0.0075, indicating relatively robust collaboration and tight inter-institutional networks.

collaborations. For example, as shown in the author collaboration network, the top ten authors include Wang Jianping from Donghua University and Liu Kaixuan from Xi'an Polytechnic University. Both have collaborated with Bruniaux Pascal from ENSAIT (École Nationale Supérieure des Arts et Industries Textiles) in France, reflecting significant international partnerships.

#### Author distribution characteristics

Analysing authors provides insights into the representative scholars and core research forces in the field. According to the renowned scholar Price (1963), in a given research domain, half of the papers are written by a small group of high-productivity authors. This group's size is approximately equal to the square root of the total number of authors, a principle known as "Price's law":

$$\sum_{m+1}^l n(x) = \sqrt{N} \quad (1)$$

where  $n(x)$  represents the number of authors who have written xxx papers, and  $l = n_{\max}$  denotes the maximum number of papers authored by a single researcher in the field [4]. Based on the CiteSpace analysis,  $n_{\max} = 2$ , and  $N$  is the total number of authors. According to Price's law, the minimum number of papers authored by core authors in this field is calculated as:  $m = 0.749 \times \sqrt{n_{\max}} \approx 3.82$ . Thus, authors with four or more publications are identified as core authors in this field. CiteSpace analysis revealed that there are 46 core authors, contributing a total of 302 papers, accounting for 33.9% of the total publications. Among these, only 24 authors have published more than four papers, and just nine authors have published more than eight papers, indicating that there are relatively few high-productivity authors, leaving significant room for further research. Figure 5 lists the top ten high-productivity authors in this field.

Table 2

RANKING OF INSTITUTIONAL IMPACT (TOP 10)			
Count	Centrality	Year	Intuition
79	0.18	2011	Donghua University
38	0.15	2011	Hong Kong Polytechnic University
21	0.08	2013	Tsinghua University
29	0.07	2011	Chinese Academy of Sciences
32	0.07	2011	Zhejiang University
13	0.06	2013	Centre National de la Recherche Scientifique (CNRS)
16	0.05	2012	Swiss Federal Institutes of Technology Domain
38	0.05	2013	Université de Lille
3	0.04	2022	University of Alberta
17	0.04	2011	Cornell University

Comparing author and institutional collaboration networks reveals that the top five institutions maintain close cooperative relationships, largely due to their geographic concentration in China. However, certain institutions and authors also engage in international

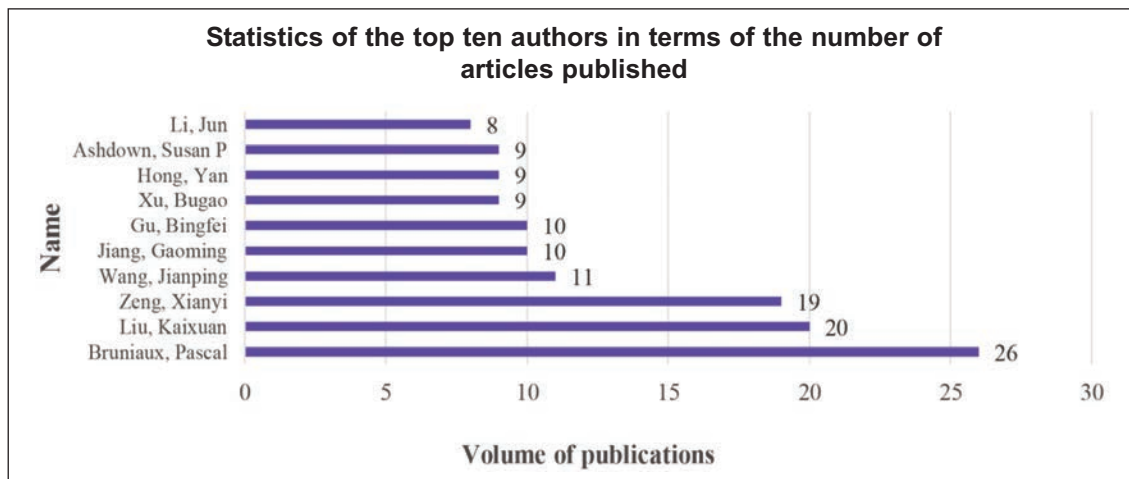


Fig. 5. Top 10 highly productive authors

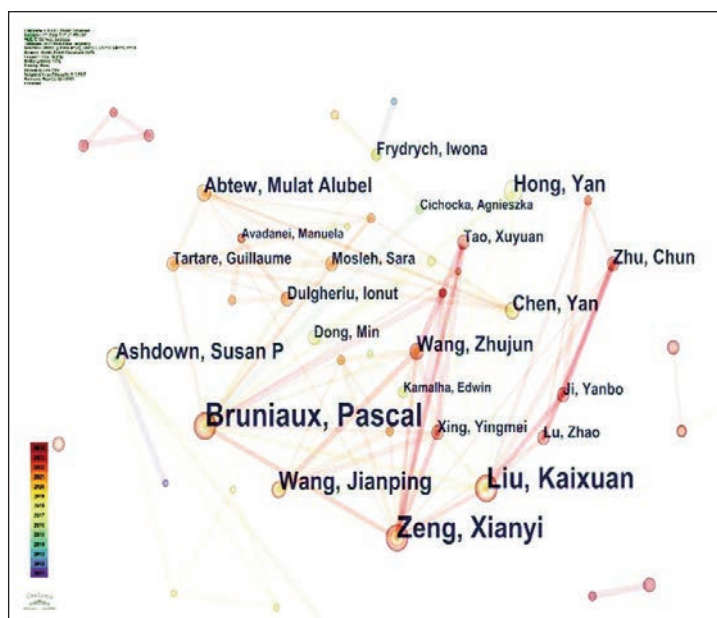


Fig. 6. Core author collaboration network

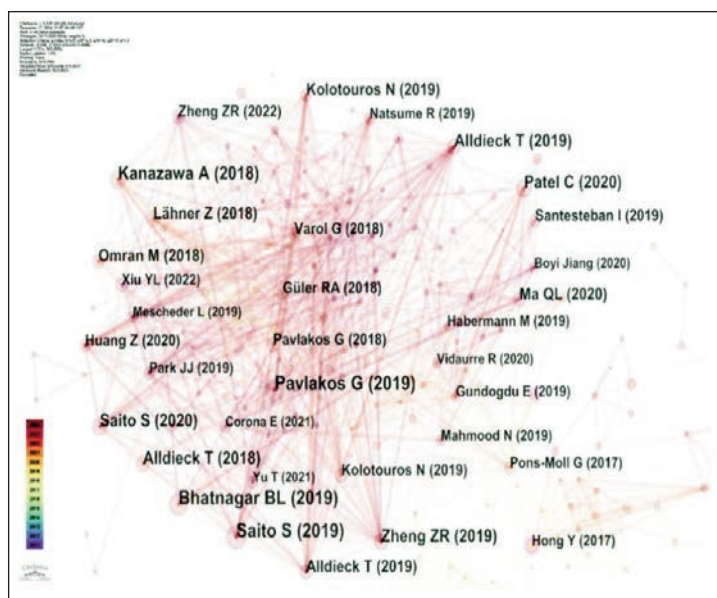


Fig. 7. Co-citation visualisation map of literature in the 3D clothing field

Using CiteSpace to analyse authors as nodes generated a collaborative network of core authors in the 3D apparel field (figure 6). The analysis identified 448 author nodes, 446 connections, a network density of 0.0045, and a modularity Q value of 0.9277. A modularity Q value greater than 0.3 indicates significant clustering, while values approaching 1 reflect strong and well-defined community structures [5]. Figure 6 shows that core authors have numerous and concentrated connections, with high node density, indicating a well-established collaborative network in the 3D apparel research field.

Further analysis of the author and institutional co-occurrence networks reveals that the top five influential institutions have strong collaborative relationships due to their shared location in China. Additionally, some authors from these institutions have established international collaborations. For example, as shown in table 4, Wang Jianping from Donghua University and Liu Kaixuan from Xi'an Polytechnic University have co-authored papers with Bruniaux Pascal from ENSAIT (École Nationale Supérieure des Arts et Industries Textiles) in France, highlighting their significant academic influence in international collaborations.

#### Highly cited literature analysis

According to Thomas Kuhn's theory of scientific development, scientific progress is often accompanied by significant discoveries, with classic literature serving as pivotal turning points in scientific fields. Betweenness centrality is a crucial structural indicator for evaluating the impact of literature. In CiteSpace, literature with high centrality often acts as a bridge connecting different research areas. These works, referred to as "Turning Points", are marked with purple rings (betweenness centrality > 0.1). By setting the node type to "reference", a co-citation visualisation map of literature in the 3D clothing field was generated (figure 7). Based on the CiteSpace analysis

report, the top 10 documents in terms of betweenness centrality, along with their authors, are listed in table 3.

Citation frequency is another key metric for assessing the impact of academic achievements. To further explore the citation patterns in the 3D clothing research field, we analysed the citation frequencies of high-impact papers (table 1). The findings are that the two most cited papers are *PIFu: Pixel-Aligned Implicit Function for High-Resolution Clothed Human Digitisation* and *Expressive Body Capture: 3D Hands, Face, and Body From a Single Image*, with citation frequencies of 1168 and 1068, respectively. These papers, authored by Shunsuke Saito and G. Pavlakos, were both published within the last five years. Saito's research systematically introduced the Pixel-Aligned Implicit Function (PIFu), a technique that aligns the pixels of 2D images with the global context of 3D objects locally, enabling high-resolution clothed human digitisation from a single image [6].

Among the top 10 most cited papers listed in table 1, five were published after 2015, accounting for 50%. This indicates that the quality of publications in the 3D clothing research field has significantly improved in recent years, making it a growing focus of academic attention.

The authors and institutions contributing to these highly cited papers show a concentration of academic influence within a few core research areas. These areas mainly involve 3D image processing, virtual clothing visualisation, and human digitisation modelling.

Through the combined analysis of betweenness centrality and citation frequency, it is evident that highly influential literature not only bridges different research areas but also provides a solid foundation for technological breakthroughs and academic development in the 3D clothing field. These studies have further advanced the adoption and dissemination of

3D clothing technologies in both academia and industry.

## VISUAL ANALYSIS OF RESEARCH HOTSPOTS IN THE FIELD OF 3D CLOTHING

### Keyword co-occurrence map analysis

Keywords serve as concise representations of a document's core themes. Analysing high-frequency keywords through bibliometric techniques can effectively reveal research hotspots, emerging trends, and the structural relationships between topics in a scientific domain [7].

Using CiteSpace software, high-frequency keyword analysis was conducted on the valid literature, generating a network with 498 nodes and 2181 connections, achieving a density of 0.016 and a modularity Q-value of 0.511, indicating good clustering. The keyword co-occurrence map for the 3D clothing research field from 2011 to 2024 is shown in figure 8. In figure 8, nodes are presented in the form of Tree Ring Histories. The size of the rings represents the frequency of keyword occurrences: the larger the ring, the higher the frequency. The colour of the rings reflects the active time period of the keywords, with the gradient from the inner to outer rings indicating the timeline of publications. The thickness of the rings is proportional to the frequency of keywords appearing in a specific time interval [3].

It can be observed that "human body", "virtual try-on" and "3D body" are the three core nodes. These keywords occupy a central position in the literature collection and radiate extensively to form a complex network structure. They are primarily connected to keywords such as "3D model", "3D printing", "3D body scanning", "3D reconstruction" and "protective clothes", indicating that the 3D clothing research field has developed a relatively mature thematic framework.

Table 3

MOST INFLUENTIAL LITERATURE STATISTICS (TOP 10)					
Mark	Centrality	Frequency	Author	Year	Title of document
1	0.2	8	He KaiMing	2016	Deep Residual Learning for Image Recognition
2	0.12	6	Chen Xiaowu	2015	Garment Modeling with a Depth Camera
3	0.11	15	Hong Yan	2017	Interactive virtual try-on based three-dimensional garment block design for disabled people of scoliosis type
4	0.08	11	Floraine Berthouzoz	2013	Parsing Sewing Patterns into 3D Garments
5	0.07	9	Meng Yuwei	2012	Computer aided clothing pattern design with 3D editing and pattern alteration
6	0.06	48	Shunsuke Saito	2019	PIFu: Pixel-Aligned Implicit Function for High-Resolution Clothed Human Digitization
7	0.06	45	G. Pavlakos	2019	Expressive Body Capture: 3D Hands, Face, and Body From a Single Image
8	0.06	6	Brouet Remi	2012	Design Preserving Garment Transfer
9	0.05	7	Guan Peng	2012	DRAPE: Dressing Any PErson
10	0.04	26	Theimo Alldieck	2019	Learning to Reconstruct People in Clothing From a Single RGB Camera

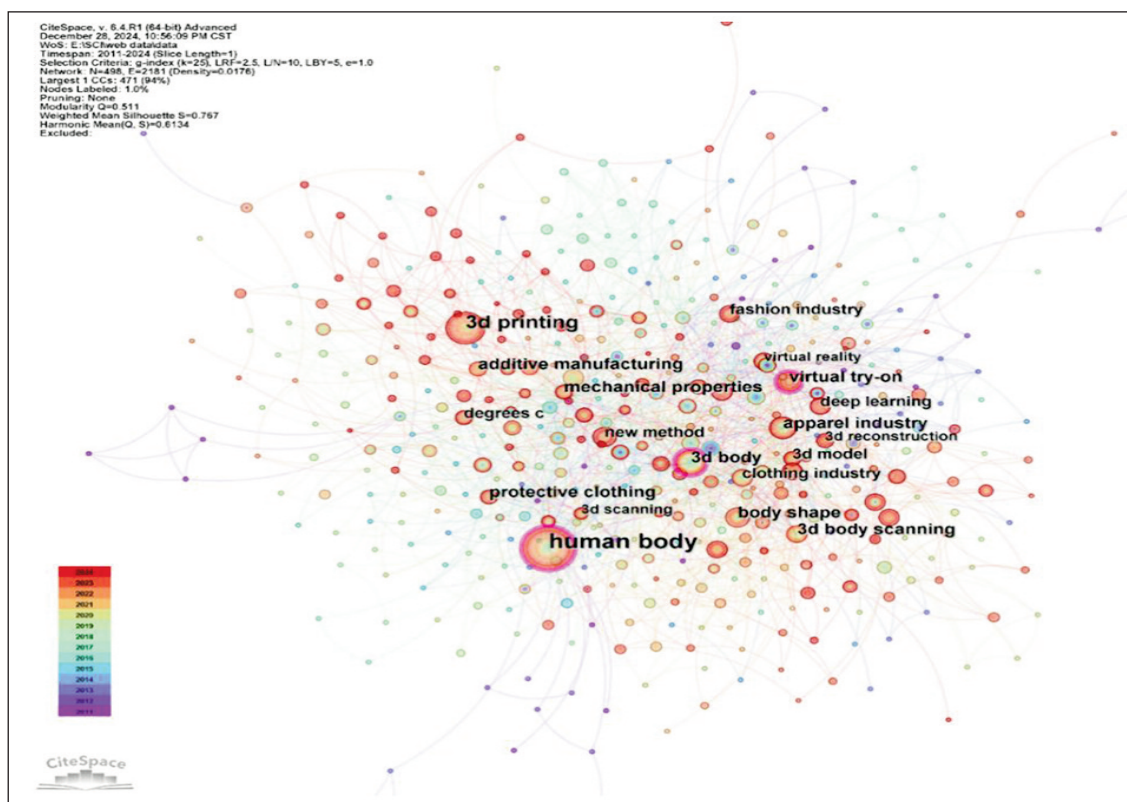


Fig. 8. Keyword co-occurrence map for the 3D clothing research field

Table 4

HIGH FREQUENCY KEYWORD STATISTICS			
Count	Centrality	Year	Phrases
150	0.15	2011	human body
84	0.02	2016	3d printing
46	0.11	2011	3d body
45	0.1	2013	virtual try-on
40	0.06	2013	protective clothing
40	0.08	2013	mechanical properties
37	0.08	2015	additive manufacturing
36	0.06	2013	body shape
36	0.09	2011	apparel industry
34	0.07	2011	3d body scanning

As shown in table 4, the most frequently occurring keywords are: “human body”, “3D printing”, “3D body”, “virtual try-on”, “protective clothing”, “mechanical properties”, “additive manufacturing”, “body shape”, “apparel industry” and “3D body scanning”. This demonstrates that substantial research efforts have been devoted to these key topics.

### Keyword cluster analysis

Keywords are a highly condensed summary of research in the field and can accurately reflect the primary focus of the literature. By performing co-occurrence clustering analysis of high-frequency keywords in the 3D clothing domain, research hotspots can be clearly visualised. Using CiteSpace software, a common clustering analysis of the keywords in

1,079 articles within the search scope was conducted. Based on the keyword network, the LLR clustering algorithm was applied, and the resulting keyword clustering model is shown in figure 9. In this model, the Q value and S value indicate clustering performance. The Q value reflects modularity, and the S value represents the average silhouette score. When  $Q > 0.3$ , the clustering structure is significant, and when  $S > 0.5$ , the clustering is highly reliable. In this study, the Q value is 0.511 ( $> 0.3$ ), and the S value is 0.767 ( $> 0.5$ ), indicating that the clustering structure is reasonable and credible [5].

The keyword clustering analysis yielded nine clusters: #0 3D printing technology, #1 3D body, #2 virtual reality, #3 virtual try-on, #4 design thinking, #5 garment design, #6 3D garments, #7 virtual fitting, and #8 3D body scan (table 5). To further summarise the research hotspots in this field, similar clustering labels were merged. Combined with high-frequency and high-centrality keywords, the primary knowledge groups in the 3D clothing research field were categorised into three main research directions: 3D Body Scanning (Type A), Virtual Clothing Simulation Technology (Type B), and 3D Clothing Printing (Type C).

Cluster A focuses on the 3D human body and includes the primary clustering terms #1 3D body and #8 3D body scan. The research on 3D body scanning extends from capturing body shape data to creating 3D body models, and from controlling overall body morphology to analysing specific body part features. This provides critical technical support and scientific

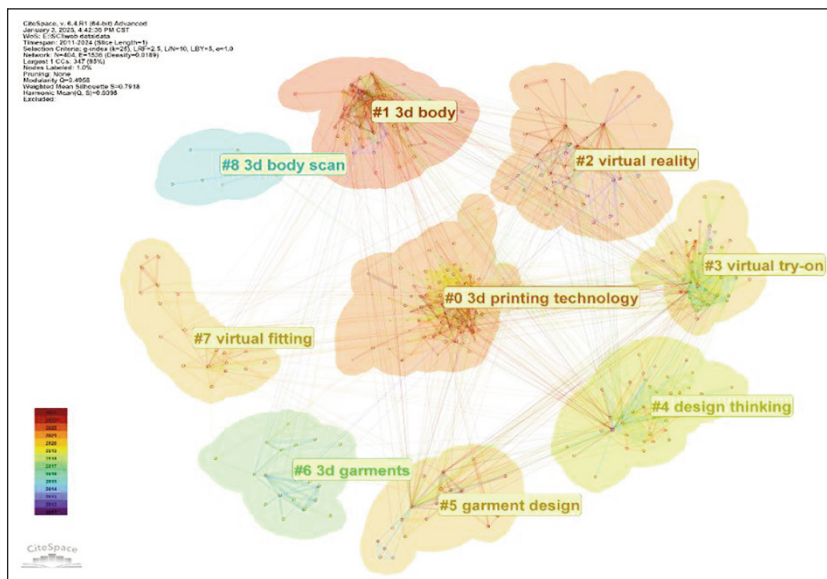


Fig. 9. Keyword clustering model map

foundations for the development of 3D clothing technology [8].

For instance, Wang Jun utilised 3D scanning technology to construct a parametric 3D lower-body model for women with different body types. The study included classifying young female samples by body type, reconstructing characteristic curves, and establishing 3D lower-body models for three distinct body types. This approach offers an effective method for building parametric 3D lower-body models, serving as a reference for parametric virtual human modelling and virtual fitting for pants [9–12]. Moreover, Liu Kaixuan proposed a new research direction that applies artificial intelligence to predict human body dimensions in the apparel industry. The study introduced a new model based on backpropagation artificial neural networks (BP-ANN) to improve the efficiency and accuracy of garment pattern-making [9].

Cluster B focuses on 3D virtual simulation technology for apparel, encompassing the main clustering terms #2 virtual reality, #3 virtual try-on, #7 virtual fitting, and #6 3D garments. The technology for precise simulation of clothing was first developed in 1990 by the MIRALAB Laboratory at the University of Geneva in Switzerland. This innovation combined virtual fabric, human body modelling, and dynamic presentation technologies to enable virtual dressing functionality [10]. Subsequently, the lab developed several iconic virtual fitting systems, such as VirtualTryOn, Fit-me.com [11], and the MIRA Cloth system, which allows dynamic dressing effects to be demonstrated via interactive devices.

Building upon this foundation, recent innovations have introduced deep learning-based 3D modelling, real-time physics-based simulations, and interactive Metaverse environments to deliver highly immersive digital fashion experiences, transforming both consumer engagement and apparel production workflows [13].

Over the past five years, 3D virtual simulation technology for apparel design has gained widespread acceptance and application in the market. Systems such as CLO3D and Style3D dominate the field, enabling comprehensive workflows for clothing design, including fabric selection, colour and pattern design, human modelling, pattern drafting, stitching, fitting, showcasing, and runway presentation. Many designers approach the process by analysing external elements such as colour, fabric, and patterns. They focus on virtual fabric textures and material properties to study the static effects of different

Table 5

CLUSTERING HIGH-FREQUENCY KEYWORD		
Mark	Cluster	High-frequency keywords
0	3D printing technology	3D printing; mechanical properties; mechanical properties; protective clothing; additive manufacturing; degrees C
1	3D body	3D body; apparel industry; body shape; clothing industry
2	virtual reality	human body; new method; virtual reality; garment fit; fashion design
3	virtual try-on	virtual try-on; 3D model; deep learning; 3D reconstruction; the-art methods
4	design thinking	laser cladding; clothing design; 3D modelling; process parameters
5	garment design	garment design; 3D body scanner; human bodies; apparel design; clothing pressure
6	3D garments	2D patterns; novel approach; 3D simulation; 3D garments
7	fast garment fitting	cloth simulation; first time; effective approach; existing approaches; pose recovery
8	3D body scan	gait recognition; 3D body model; feature extraction; point cloud; clothing variations



with keywords such as “3D scanning”, “body”, “3D model” and “shape” emerging as central themes. This focus reflects the field’s primary challenge of accurately capturing and digitally reconstructing the human form, which serves as the essential substrate for all subsequent applications. The subsequent period (2015–2019) witnessed a diversification towards materialisation and preliminary interaction, marked by the rising prominence of keywords like “fabrics”, “3D printing”, “additive manufacturing” and “virtual reality”. This shift signifies a maturation of basic scanning technologies and a growing research impetus to translate digital designs into physical products and rudimentary immersive experiences.

The most recent phase (post-2019) has seen the emergence of keywords such as “three-dimensional displays”, “image reconstruction”, “virtual simulation” and “digital reconstruction”, pointing towards advancements in fidelity and integration. The particularly long duration of activity associated with “virtual simulation”, coupled with its relatively weak co-occurrence links with other terms, suggests that this sub-domain is not only a persistent research hotspot but also one experiencing rapid, and often parallel, technological iterations, potentially leading to a fragmented intellectual landscape.

However, despite these significant strides, the Technical core layer confronts persistent and formidable challenges that curtail its broader efficacy and adoption. A primary impediment is the fidelity-realizability gap. Although parametric body modelling has achieved considerable sophistication [8], accurately simulating the nonlinear, dynamic behaviour of complex textiles, such as the drape of silk or the structural integrity of knitted fabrics under mechanical stress, remains a largely unsolved problem. The technical hurdles involve replicating physical properties like buckling, stretching, and collision response in real-time, which are computationally intensive and often simplified to the detriment of realism. Furthermore, while AI-driven solutions for body dimension prediction [9] and garment digitisation [6] offer transformative potential for automation, their performance is frequently constrained by limitations in training data. The reliance on anthropometric datasets that lack diversity in ethnicity, age, and body type can perpetuate biases and hinder the global applicability of these tools. This gap between idealised digital representation and physical reality constitutes a fundamental constraint within the current technical paradigm.

A comparative analysis of the field’s development reveals an intriguing geopolitical dimension. The concentration of high-volume research output and institutionally central contributors in China (as detailed in Section 2.2) appears closely aligned with

national industrial policies and the demands of a massive manufacturing sector, emphasising applied technological development and rapid integration. In contrast, several foundational algorithmic breakthroughs, such as the development of the PIFu model for high-resolution clothed human digitisation [6], originated from a more globally diverse research base. This suggests a potential strategic dichotomy wherein research in East Asia may excel in applied engineering, scalability, and integration, while contributions from North America and Europe are more pronounced in pioneering the underlying core algorithms and computer graphics theories. This dynamic not only shapes the global knowledge production network but also influences the types of technical challenges that are prioritised for investigation.

**The Application and Integration layer: from technology to solution**

The maturation of the Technical Core Layer has directly catalysed the proliferation of solutions within the Application and Integration layer, where foundational technologies are synthesised into practical tools and experiences for both industry and consumers. This layer encompasses the implementation of 3D assets in virtual try-on systems, e-commerce platforms, and most notably, within immersive Metaverse environments. Bibliometric trends from the past three years confirm a decisive shift from purely technological development towards practical application and commercialisation.

*Core technological applications: virtual try-on and fitting*

A primary manifestation of this layer is in virtual try-on (VTO) and fitting systems. These applications leverage the Technical core, 3D body scanning, modelling, and simulation algorithms, to create realistic garment behaviours on digital avatars. They reconstruct human body models from anthropometric data and apply intelligent algorithms to establish garment-body spatial relationships, enabling accurate virtual try-on

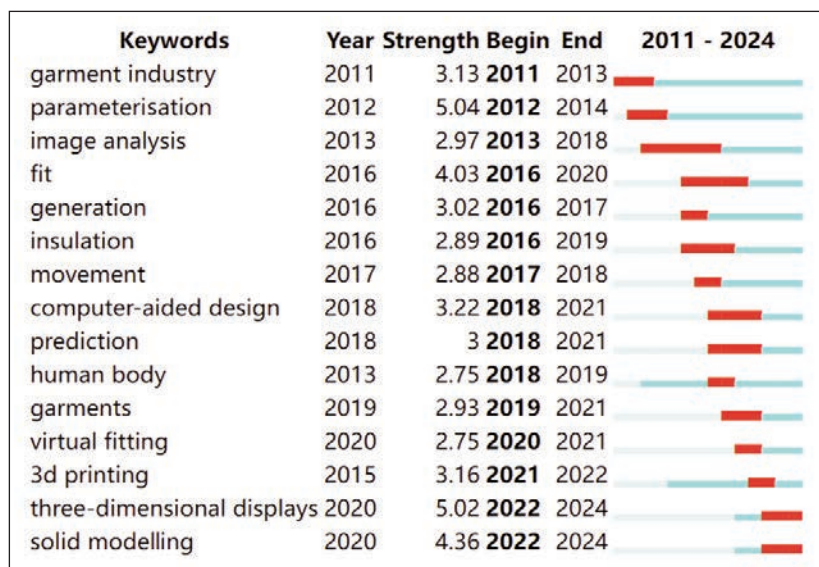


Fig. 11. Top 15 keywords with the strongest citation burst

experiences [17]. Early systems, such as the My Virtual Model (MVM) developed by a Canadian research team, laid the groundwork by generating dynamic 3D avatars from user data. This innovation has been adopted and advanced by retailers; for instance, brands like H&M have explored online fitting room solutions to enhance user interaction and digital visualisation [11].

The evolution within this sub-domain is increasingly driven by Artificial Intelligence. Recent years have seen the emergence of AI-powered personalised size recommendation systems (e.g., “The Right Size”, “Fit Me”) that utilise deep learning and pose estimation techniques to improve sizing accuracy in online fashion retail [18]. These systems calculate patterns and infer dimensions based on consumer measurements to recommend suitable garments. Research institutions have also contributed significantly to this field. The University of London’s Bidynetics system digitises body dimensions to assess garment-body match [19], while Germany’s Fraunhofer Society employs 3D scanning to directly capture body shape features, generating 1:1 scale models for garment recommendation [20, 21].

However, the seamless integration and effectiveness of these applications remain constrained by the limitations of the underlying Technical Core. Although these technologies integrate numerous advanced processes, the challenge of simulating the nonlinear, dynamic behaviour of fabrics, such as precise drape, wrinkles, and collision response in real-time, persists. The computational intensity required often leads to simplifications that detrimentally impact realism. Thus, while the applications are innovative, their fidelity and user trust are ultimately bound by the unresolved challenges of physical simulation.

#### *Emerging commercial paradigms: digital fashion and the Metaverse*

The most avant-garde expression of the Application layer is the integration of virtual clothing into the Metaverse and digital ecosystems. This represents a significant evolution in the digitalisation of fashion, moving beyond tools to digital-only end-products themselves. The expansion of the Metaverse and the growing importance of digital identities have spurred a “digital avatar economy”, with the fashion industry demonstrating particularly high engagement [21].

Early milestones, such as The Fabricant’s sale of the Iridescence digital dress for \$9,500 in 2019 [19], marked the emergence of fashion NFTs and validated digital fashion as a valuable asset [20]. This commercial movement has been rapidly adopted by luxury brands. Academic research confirms that for luxury brands, the Metaverse represents a new frontier for experiential marketing and brand storytelling [22–24]. This strategic imperative has led to rapid commercial adoption. Gucci, for example, has launched virtual garment collections on platforms like Zepeto, treating digital fashion as a consumable commodity in its own right [21]. Similarly, Balenciaga partnered with Fortnite to open a virtual retail space [22], and Decentraland hosted the inaugural Metaverse

Fashion Week in 2022, featuring collections from major luxury houses.

Academic inquiry is beginning to investigate this phenomenon. Research suggests that immersive fashion experiences, particularly in VR, can foster emotional engagement and enhance brand storytelling, which plays a critical role in shaping consumer loyalty [25–27]. Furthermore, empirical studies confirm that 3D virtual try-on technology in Metaverse environments significantly influences consumers’ purchase intentions and acceptance of digital garments [28]. Beyond these specific empirical findings, the broader academic trajectory is becoming clear. The trajectory revealed by this bibliometric analysis, highlighting the Metaverse as a key research frontier, is further explained by comprehensive academic inquiry. Dwivedi et al. posit that the Metaverse will act as a transformative force for marketing, enabling new levels of customer interaction through immersive XR journeys and the rise of a ‘digital avatar economy’ [26]. This aligns with the observed research focus on virtual try-on and digital fashion, suggesting the industry is not merely responding to hype but is engaging with a complex new paradigm for consumer engagement, identity expression, and value creation. A critical analysis, however, reveals a significant tension between the pace of commercial adoption and scholarly understanding. As Chan et al. systematically reveal, extant literature predominantly still defines digital fashion as a tool for design or marketing [21], largely neglecting its conceptualisation as a digital-only end-product [23]. This gap is exemplified by industry pioneers like The Fabricant and Gucci operating on a fundamentally different paradigm than what is reflected in much of the academic literature. Therefore, a pressing need exists for academic research to reconceptualise digital fashion within a framework that aligns with its current industrial trajectory, exploring its implications for consumption, ownership, and value creation in digital economies.

#### **The Macro-impact layer: broader implications and future frontiers**

The advancements and applications within the Technical Core and Application Layers inevitably precipitate profound consequences at the Macro-impact layer, affecting broader industrial practices, consumer societies, and ethical norms. This layer transcends technological specifics to address the sustainability, inclusivity, economic, and experiential paradigms shifted by 3D apparel technologies. The bibliometric analysis underscores that future research must extend beyond technical optimisation to grapple with these larger implications.

#### *Addressing the sustainability paradox and technical bottlenecks*

A primary macro-impact is the potential of 3D technologies to advance fashion sustainability, for instance, through virtual sampling that reduces material waste. However, this promise is contingent upon overcoming persistent technical bottlenecks. A major issue remains the difficulty in reproducing highly

realistic fabric drape and dynamic behaviours, particularly for complex textiles like silk or multi-layered garments. While researchers like Wang have demonstrated improvements through parametric human body modelling, significant limitations persist in simulating garments under varied environmental conditions [8]. Similarly, Yu and Kim have emphasised unresolved integration problems between 3D body models and garment geometries, despite advances in scanning and printing technologies [14]. This creates a sustainability paradox: the digital process itself consumes significant energy for computation and data storage. Therefore, a critical future research direction involves conducting comprehensive life-cycle assessments (LCA) to quantify the net environmental benefit of adopting these digital technologies, ensuring that the solution does not inadvertently exacerbate the problem.

#### *Ensuring algorithmic fairness and global inclusivity*

The push towards personalisation and AI-driven solutions introduces another macro-level challenge: algorithmic bias and exclusion. Another significant challenge lies in the effectiveness and fairness of AI-powered size recommendation systems. Although applications like “The Right Size” and “Fit Me” have mitigated size uncertainties in online retail, their universal applicability is hindered by data sparsity, cultural diversity in body shapes, and inherent biases in anthropometric datasets [18]. This reliance on non-representative data risks perpetuating discrimination and excluding global populations from the benefits of digital fashion. Future research must, therefore, prioritise the development of inclusive and representative datasets, as well as adaptive algorithms that are culturally and anthropometrically diverse, to ensure that the digital fashion revolution does not leave a significant portion of the world’s population behind.

#### *Governing digital ecosystems and defining value*

Furthermore, the integration of 3D fashion technologies into Metaverse platforms introduces complex interdisciplinary questions concerning the governance of new digital ecosystems. Issues of interoperability between closed platforms, intellectual property protection for digital garments, and establishing consumer trust and acceptance of virtual fashion remain largely unaddressed [27]. Moreover, the absence of haptic feedback and multi-sensory experiences in current virtual try-on systems limits their ability to deliver fully immersive and persuasive environments [28]. Addressing these challenges will require unprecedented interdisciplinary collaboration across computer graphics, textile engineering, human-computer interaction, law, and business ethics to establish the norms, standards, and economic models that will define value and ownership in the digital fashion economy.

#### *Future research agenda: a call for interdisciplinary convergence*

The future trajectory of 3D apparel technology is poised at the convergence of AI, the Metaverse, and advanced simulation, a shift confirmed by recent studies showing how this fusion transforms consumer

engagement and retail models by enhancing customer loyalty through virtual try-on and AI-driven personalisation in immersive environments [29]. Consequently, the findings of this bibliometric review culminate in a clear and interdisciplinary future research agenda. Going forward, scholarly efforts must prioritise developing standardised digital garment formats and materials to ensure interoperability across platforms, whilst also exploring multi-sensory feedback systems, encompassing haptic and auditory elements, to bridge the experiential gap between physical and digital fashion. Furthermore, establishing robust ethical frameworks for AI usage, data privacy, and the environmental claims of digital fashion is paramount. In parallel, there is a pressing need to investigate new consumer behaviours, psychological ownership, and value perception concerning digital-only products. This comprehensive agenda moves beyond solving isolated technical problems towards shaping a responsible, inclusive, and sustainable digital future for the entire fashion industry through concerted interdisciplinary efforts.

## **CONCLUSION**

In conclusion, this study has moved beyond a descriptive bibliometric summary by proposing and applying a three-tier conceptual framework (Technical core, Application & Integration, Macro-impact) to analyse the evolution of 3D apparel technology research. This approach has provided a structured and critical lens through which to interpret a decade of scholarly activity, revealing not only the field’s thematic hotspots but also the dynamic interplays and tensions between technological advancement, practical application, and broader societal implications.

The findings confirm China’s preeminent role, particularly in the applied research and development that characterises the Application and Integration Layer. The analysis further identifies enduring challenges that span across these layers: the fidelity-realizability gap in physical simulation within the Technical Core, the commercial-academic conceptual gap regarding digital fashion as an end-product in the Application layer, and the sustainability paradox and issues of algorithmic bias at the Macro-impact level. Addressing these complex challenges necessitates deeper interdisciplinary collaboration that extends beyond computer graphics and textile engineering to include ethics, social science, and business strategy. Looking forward, the convergence of 3D technologies with the Metaverse, AR, and AI is poised to redefine fashion fundamentally. To navigate this transition responsibly, future research must be guided by the imperatives of this framework: developing standardised formats to ensure interoperability, pioneering multi-sensory experiences to bridge the physical-digital divide, and establishing robust ethical frameworks to ensure inclusivity and sustainability. The adoption of 3D technology is not merely a technical upgrade but a pivotal step toward a more innovative, efficient, and consciously designed future for the global apparel industry.

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