Highlights in Art and Design
ISSN: 2957-8787 | Vol. 12, No. 1, 2025

Knowledge Graph-Based Visual Analysis of Intelligent Apparel Research

Ziyi Le

Department of Art, Wuhan Textile University, Wuhan, Hubei, China

Abstract: To explore the development trends of smart clothing by analyzing its research status and hotspots over the past decade. Using CiteSpace 6.4.R software, we conducted a visualization analysis of annual publication volume, author and institutional collaboration, keywords, and other aspects of domestic and international smart clothing-related literature. The sample comprised relevant literature indexed in the CNKI and Web of Science databases. The overall publication volume in smart clothing research shows an upward trend. Collaboration between core authors and institutions remains limited and warrants strengthening. Countries such as China, South Korea, and the United States have conducted substantial research with significant influence. Research in the field is advancing toward multifunctional integration, new material applications, data processing and analysis, and health monitoring. With continuous technological progress, smart clothing is expected to provide more personalized and precise health monitoring solutions in the future. This study reviews the development status of smart clothing over the past decade, providing additional references for exploring future research trends in this field.

Keywords: Citespace; Review; Smart Clothing; Visual Analysis.

1. Introduction

Smart clothing originated in the 1960s, stemming from the concept of detaching computer equipment and attaching it to the body. From the early 1980s to the early 1990s, this technology underwent intensive research. By the late 1990s, wearable computer research began developing smarter garments that were more comfortable and user-friendly. Depending on the user and purpose, smart clothing is currently being developed and applied across diverse industrial sectors including sports, healthcare, military, entertainment, daily life, and commerce [1]. Smart clothing represents a novel garment integrating textile technology with modern information technology. Its core lies in embedding electronic components, sensors, and smart materials to achieve sensing, processing, and feedback functions for user physiological and environmental information [2]. Beyond fulfilling the basic functions of traditional clothing, these garments enhance user experience through human-computer interaction technologies, addressing diverse needs such as health monitoring, athletic performance tracking, and environmental adaptation [3]. As a significant intersection of technology and fashion in recent years, the development of smart clothing is influenced by multiple factors including technological advancements, market demands, design paradigms, material innovations, and commercialization processes. As a product of the digital era, smart clothing is progressively transforming people's lifestyles and wearing habits. With continuous technological breakthroughs and growing market demand, smart clothing is poised for broader application and industrial development in the future. This study employs CiteSpace 6.4.R1 software to conduct an in-depth analysis of relevant literature from the China National Knowledge Infrastructure (CNKI) database and Web of Science (WOS) database. By examining the content of these publications, it explores the current state, application domains, and future trends in the smart clothing field over the past decade.

2. Research Methods and Data Sources

2.1. Data Sources and Processing

This study utilizes literature data from the CNKI Knowledge Network database and the Web of Science (WOS) core database to review the current state of smart clothing research both domestically and internationally. For CNKI literature data, a search was conducted in the CNKI database using the keyword “intelligent clothing” within the Chinese full-text database. The search period was set from 2011 to December 9, 2024, yielding 223 literature records. Irrelevant materials such as news articles, reports, conference proceedings, and interviews were excluded, resulting in 164 final records exported in RefWorks format. WOS Literature Data A search query was executed in the Web of Science (WOS) database using the following search formula: TS= (smart clothing) Search period: January 1, 2011 to December 9, 2024 Language: English The search yielded 385 documents. After screening and consolidation, invalid documents were excluded, resulting in 222 documents. These were exported in plain text format (full records and cited references).

2.2. Research Methods

CiteSpace is a literature visualization analysis tool developed by Professor Chao Mei Chen and his team at Drexel University in the United States [4]. The CiteSpace software features functions such as author, institution, country, keyword co-occurrence, and emergent keyword detection [5]. With its powerful and convenient capabilities, the software is widely applied across various academic disciplines [6]. By conducting bibliometric analysis on relevant literature, it visually presents research progress and development trends within a specific discipline or field over a defined time period through knowledge maps [7]. This paper follows the primary research pathway of “Selecting Databases → Data Preprocessing → Visual Analysis → Map Adjustment and Beautification → Result Interpretation and Analysis,” as illustrated in Figure 1. Using CiteSpace software (version

6.4.R1), we conducted a metaanalysis of relevant domestic and international literature samples from 2011 to 2024. Based on metrics such as publication volume, author collaboration, research institutions, keyword co-occurrence, keyword salience, and keyword clustering, we constructed a literature knowledge map to identify research hotspots and trends in the field of smart clothing research [8].

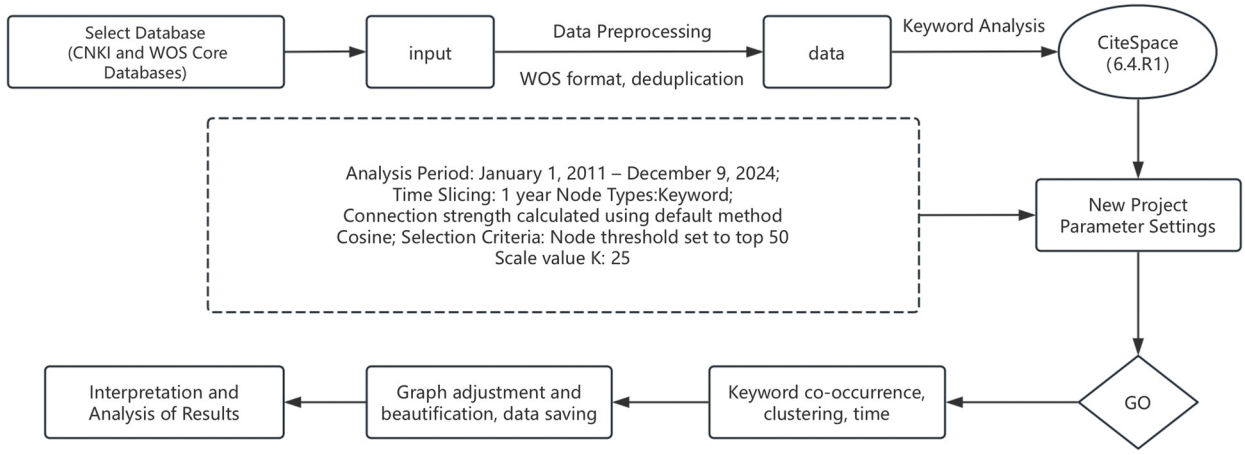


Figure 1. Schematic of Research Pathway

3. Overview of Domestic and International Research

3.1. Annual Publication Volume Analysis

The annual publication volume provides an intuitive assessment of the development status in this research field [9]. Based on the annual trend in smart clothing research literature volume (Figure 2), the research intensity and dynamics of smart clothing studies domestically and internationally across different time periods can be observed. As shown in Figure 2, the annual publication volume in CNKI literature remained relatively stable overall. From 2011 to 2017, the number of research papers fluctuated slightly, while from 2019 to 2024, it began to show an upward trend. WOS publication volume exhibits an overall stable upward trend. From 2011 to 2017, annual WOS publications fluctuated within a stable range. From 2018 to 2024, they experienced rapid growth, with a minor decline in 2019 followed by a sustained upward trajectory thereafter. As shown in Figure 2, both CNKI and WOS publication volumes surged rapidly from 2019 to 2022, primarily driven by heightened demand for medical protective clothing during the COVID-19 pandemic. In recent years, the continuous emergence of new materials and technologies internationally has attracted increased attention from global scholars in this field, leading to a significant increase in English-language publications compared to Chinese publications from 2021 to 2024. From 2011 to 2024, the annual publication volume both domestically and internationally showed a significant overall upward trend, indicating that the research focus on the field of smart clothing has been continuously increasing in recent years. It is expected that there will be a rapid upward trend in the future (statistics only up to December 2024, not representing an overall downward trend).

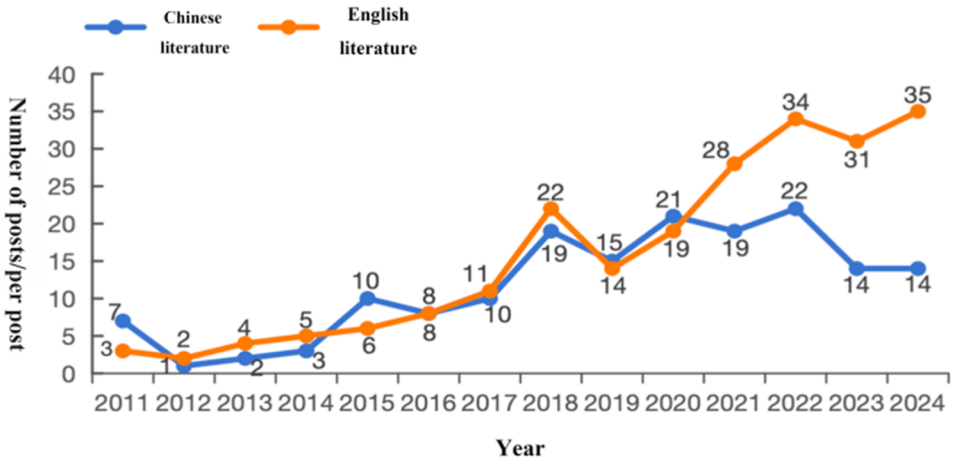


Figure 2. Trends in the number of CNKI and WOS publication from 2011 to 2024

3.2. Core Authors and Institutions

3.2.1. Key Domestic Authors and Research Institutions

Using CiteSpace 6.4.R1 software, a collaborative network map of domestic and international smart clothing research literature was generated. The connections between nodes reflect the closeness of author collaboration: thicker lines indicate stronger cooperative relationships, while thinner lines suggest no collaboration between authors [10].

The CNKI literature network diagram comprises 238 nodes and 258 connections, with a network density of 0.0091 (see Figure 3). Applying Price's Law formula—where M

represents total publications and Nmax denotes the output of the most prolific author—enables identification of core authors in the field of generative font design research globally [9]. For intelligent apparel research in the CNKI database, the author count is 14. Calculating M yields ≈2.803, rounded to 3. Thus, the list of authors with ≥3 publications comprises 12 individuals. Due to space constraints, only the top 10 authors by publication frequency are presented in Table 1. Based on the betweenness centrality analysis of core authors in Figure 3, Shen Lei exhibits the highest betweenness centrality, indicating his pivotal bridging role within the collaboration network. Other authors demonstrate lower betweenness centrality, suggesting a fragmented collaboration network where research primarily occurs through small-scale collaborations within this field.

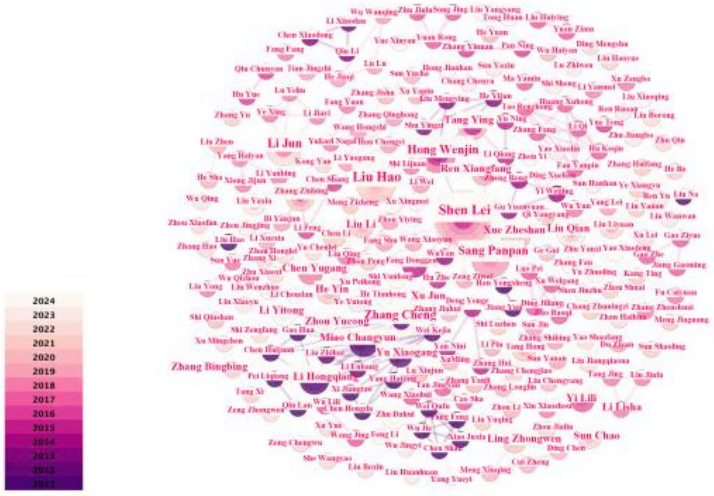


Figure 3. Collaborative Research Network of Institutions in CNKI Literature

Table 1. Core Authors List of CNKI Literature

Serial Number	Author	frequency
1	Shen Lei	14
2	Liu Hao	6
3	Sang Panpan	5
4	Hong Wenjin	5
5	Li Jun	4
6	Zhang Cheng	4
7	Liu Qian	3
8	Zhang Zhibin	3
9	Li Hongqiang	3
10	Tang Ying	3

Using CiteSpace 6.4.R1 software, select “Institution” as the node type to generate a network map of research institutions studying smart clothing domestically and internationally. In the map, larger node sizes indicate higher publication volumes from each institution, while thicker lines and higher density reflect stronger collaborative relationships between institutions [11]. The CNKI literature research institution collaboration network diagram shows 160 nodes, 124 connections, and a network density of 0.0097, as depicted in Figure 4. Domestic research institutions are predominantly universities, encompassing various colleges across many institutions. The Donghua University School of Fashion and Art Design serves as a hub for active collaboration, establishing field-specific partnerships with entities such as the Shanghai International Design Innovation Institute, the Donghua University Key Laboratory of Modern Fashion Design and Technology (Ministry of Education), and the Suzhou University School of Textile and Apparel Engineering. This indicates the interdisciplinary and cross-disciplinary nature of research in this field, yielding more related smart apparel research outcomes. The network reveals that all intermediary centrality values for research institutions in this field are zero. This indicates that domestic smart apparel research institutions primarily operate independently or in collaborations involving only one or two partners, with limited inter-institutional cooperation that requires strengthening. As shown in Table 2, analysis of the top ten research institutions reveals that their geographical distribution is concentrated in eastern and central China, with limited presence in western regions, indicating significant room for development.

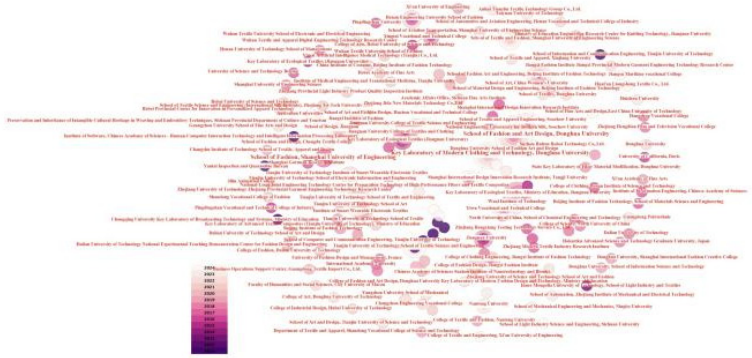


Figure 4. Cooperation map of research institutions in CNKI documents

Table 2. List of Top Ten Research Institutions by Publication Frequency in CNKI Literature

Serial Number	Institution	frequency
1	School of Fashion and Art Design, Donghua University	11
2	School of Textile Science and Engineering, Tianjin University of Technology	10
3	Key Laboratory of Modern Fashion Design and Technology, Ministry of Education, Donghua University	7
4	Key Laboratory of Ecological Textiles, Ministry of Education, Jiangnan University	7
5	School of Design, Jiangnan University	6
6	School of Textile and Apparel Engineering, Soochow University	5
7	Beijing Institute of Fashion Technology, School of Fashion Art and Engineering	5
8	School of Textiles and Clothing, Jiangnan University	5
9	Wuxi Vocational College of Arts and Crafts	4
10	Yiwu Vocational College of Industry and Commerce	4

3.2.2. Key Foreign Authors and Research Institutions

The network diagram of WOS literature comprises 296 nodes and 345 connections, with a network density of 0.0079, as shown in Figure 5. Applying Price's Law formula, when the maximum publication count nmax is set to 3, M≈1.3 is obtained. Rounding this to the nearest integer yields 1. Consequently, 40 core authors with at least 2 publications are identified. Authors with publication counts ≥2 are listed in Table 3. As shown in Figure 5, interactions among core authors are not particularly dense, indicating that research in this field primarily takes the form of small-scale collaborations.

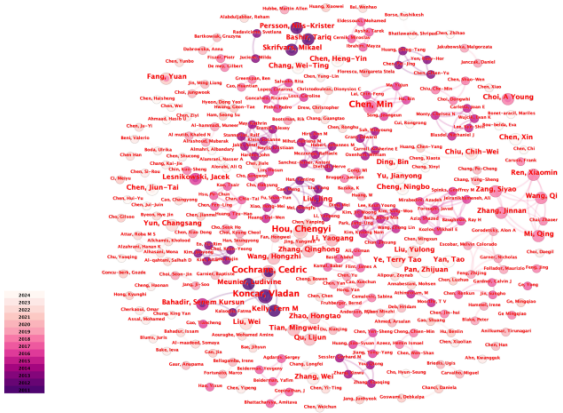


Figure 5. Author collaboration map of WOS literature

The WOS research institution collaboration network map shows a total of 196 nodes and 220 connections, with a network density of 0.0115, as depicted in Figure 6. Overseas research institutions are also predominantly universities. The institution with the highest publication frequency is Donghua University (16 publications), followed by those with publication frequencies of 6 or more: Chinese Academy of Sciences (11 publications), Jiangnan University (7), Qingdao University (7), Ecole Nationale Supérieure des Arts et Industries Textiles (ENSAIT) (6), Huazhong University of Science and Technology (6), Soochow University-China (6 times), Donghua University (16 times), and the Chinese Academy of Sciences (11 times) demonstrate a clear advantage in publication frequency, indicating China's relatively high level of expertise in smart clothing research. Other universities also rank prominently in this field, including Jiangnan University and Qingdao University, which are notably active contributors. Overall, collaboration among international institutions remains insufficient, necessitating further strengthening of institutional partnerships.

3.3. Distribution by Country (Region)

Using CiteSpace 6.4.R1 software, the national (regional) distribution map yielded 42 nodes, 62 connections, and a network density of 0.072, as shown in Figure 7. Countries (regions) were ranked by publication frequency, and their betweenness centrality was calculated. Due to space constraints, only the top fifteen countries (regions) by publication frequency are listed in Table 5.

Statistics indicate that 42 countries (regions) worldwide have conducted research in the field of smart clothing. Among them, China published 116 papers with an intermediary centrality of 0.80, ranking first in this field. This clearly demonstrates China's high priority and significant influence in smart clothing research, achieving outstanding results across multiple aspects of the field. South Korea published 33 papers, ranking second only to China, underscoring its significant research contributions in this domain. The United States, Poland, and Belgium all exhibit centrality values exceeding 0.1, indicating substantial influence in smart clothing research. Figure 7 reveals relatively strong collaborative ties among most nations.

4. Research Hotspots and Trend Analysis

Keywords represent the distilled essence of an article's content. When a keyword appears two or more times, it is termed keyword co-occurrence. A larger node area indicates higher keyword frequency [12]. In CiteSpace 6.4.R1 software, setting the node type to Keyword generates keyword co-occurrence maps and high-frequency keyword frequency lists for CNKI and WOS literature.

Table 3. List of core authors of WOS literature (top ten)

Serial Number	Author	frequency
1	Chen,Min	3
2	Cochrane,Cedric	3
3	Hou,Chengyi	3
4	Koncar,Vladan	3
5	Bahadir,Senem Kurun	2
6	Bashir,Tarig	2
7	Chang,Wei-Ting	2
8	Chen,Heng-Yin	5
9	Chen,Jiun-Tai	4
10	Chen,Xin	4

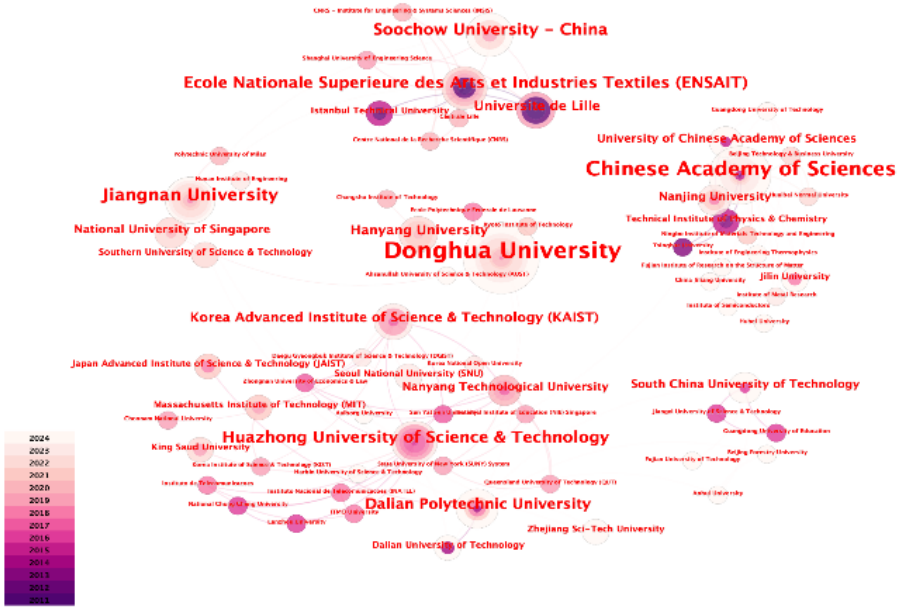


Figure 6. Research Institution Collaboration Map of WOS Literature

Table 4. List of Top Ten Research Institutions by Publication Frequency in WOS Literature

Serial Number	Institution	frequency
1	Donghua University	16
2	Chinese Academy of Sciences	11
3	Jiangnan University	7
4	Qingdao University	7
5	Ecole Nationale Superieure des Arts et Industries Textiles (ENSAIT)	6
6	Huazhong University of Science & Technology	6
7	Soochow University - China	6
8	Chang Gung University	5
9	Dalian Polytechnic University	5
10	Lodz University of Technology	5

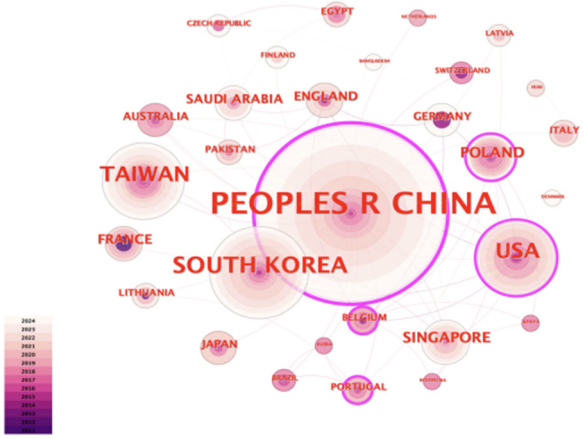


Figure 7. National Research Collaboration Map

4.1. Analysis of Research Hotspots

4.1.1. Analysis of Domestic Research Hotspots

The co-occurrence word map of CNKI literature reveals a network comprising 246 nodes and 431 connections, with a network density of 0.0143 (see Figure 8). As shown in Figure 8, “smart clothing” serves as the central node, forming close connections with keywords such as “sensors,” “breathing monitoring,” and “clothing design.” This indicates that smart clothing research focuses not only on the design of the garments themselves but also encompasses the application of intelligent technologies, such as sensor integration and health data monitoring [13].

Table 5. List of Publication Frequencies by Country (Region) (Top 15)

Serial Number	frequency	Centrality	Year	Country
1	116	0.80	2013	China
2	33	0.00	2013	South Korea
3	24	0.10	2014	United States
4	23	0.00	2013	Taiwan
5	8	0.00	2017	Singapore
6	8	0.12	2015	Poland
7	7	0.00	2015	India
8	6	0.02	2011	France
9	5	0.05	2014	England
10	5	0.03	2017	Saudi Arabia
11	4	0.02	2014	Germany
12	4	0.00	2016	Japan
13	4	0.00	2016	Australia
14	3	0.00	2012	Turkey
15	3	0.11	2014	Belgium

The frequency of keyword occurrences is summarized in Table 6. Among the top 10 high-frequency keywords in CNKI literature, five keywords exhibit intermediary centrality exceeding 0.1. These are: smart clothing, sensors, intelligentization, apparel, and apparel design, with respective intermediary centralities of 1.02, 0.11, 0.18, 0.27, and 0.45. This indicates that these keywords represent significant research focal points within China's smart clothing field.

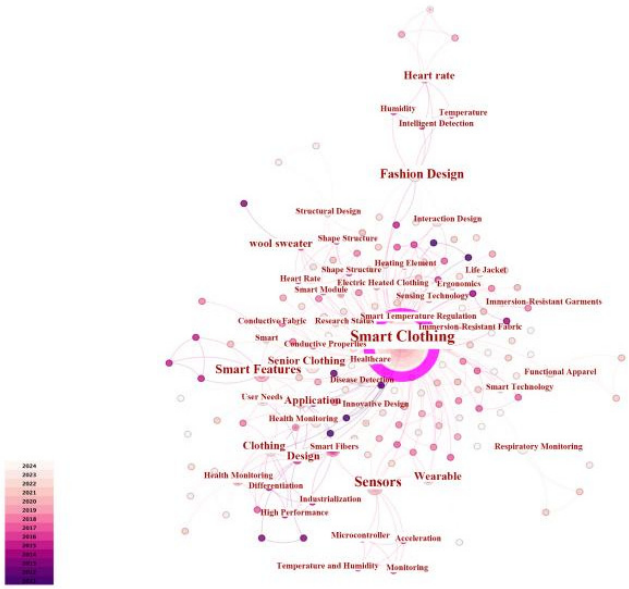


Figure 8. Keyword co-occurrence Map of CNKI Literature

Table 6. High-Frequency Keywords in CNKI Literature

Serial Number	Keyword	frequency	Intermediary Centrality	Year
1	Smart Clothing	84	1.02	2011
2	Sensor	7	0.11	2017
3	Intelligent	7	0.18	2015
4	Application	6	0.06	2011
5	Clothing	6	0.27	2011
6	Breathing Monitoring	5	0.04	2021
7	Health Monitoring	5	0.06	2018
8	Fashion Design	5	0.14	2015
9	Design	5	0.45	2013
10	Senior Apparel	4	0.08	2020

4.1.2. Analysis of Research Hotspots Abroad

The co-occurrence network map of keywords in WOS literature reveals 314 nodes and 862 connections, with a network density of 0.0175 (see Figure 9). This indicates relatively weak connections among keyword studies. Calculating the keyword frequency in WOS literature yields the intermediary centrality, as shown in Table 7. Among the top 10 high-frequency keywords in WOS literature, 7 keywords have an intermediary centrality greater than 0.1. These are: smart clothing, textiles, performance, composites, films, smart textiles, and energy. Based on the network and list, smart clothing, composites, and energy are the three most frequently occurring keywords. Among these, smart clothing has an intermediary centrality of 0.68, while composites and energy have intermediary centralities of 0.28 and 0.17, respectively. This indicates that composites and energy are the primary influencing factors in the smart clothing field.

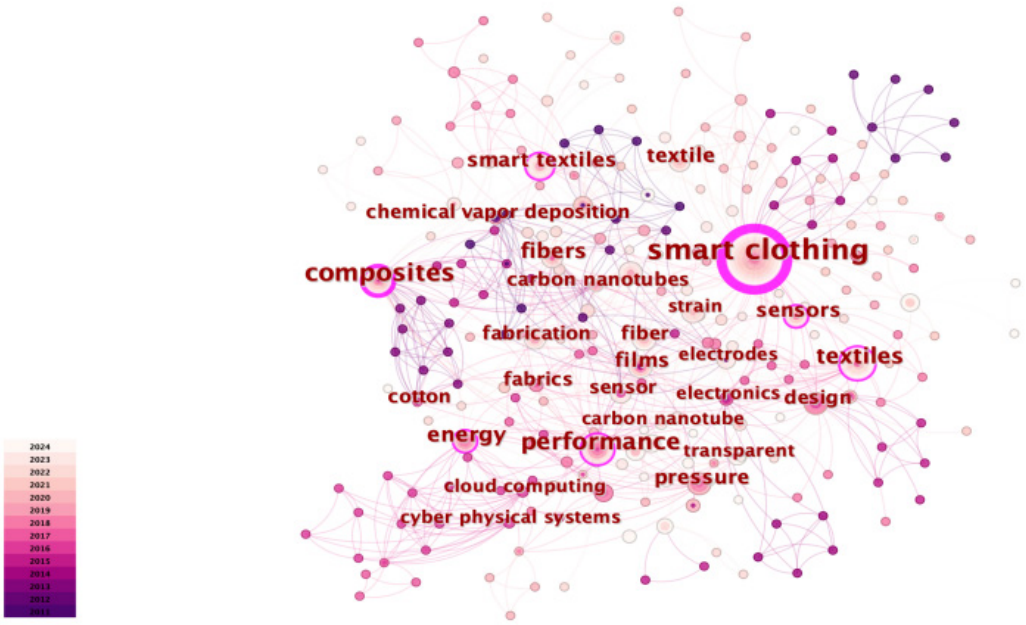


Figure 9. Keyword Co-occurrence Map of WOS Literature

Table 7. Frequency Table of High-Frequency Keywords in WOS Literature

Serial Number	Keyword	frequency	Intermediary Centrality	Year
1	Smart Clothing	53	0.68	2012
2	Textiles	14	0.13	2017
3	Performance	13	0.14	2015
4	Composites	11	0.28	2013
5	Design	10	0.07	2015
6	Films	10	0.10	2011
7	Smart textiles	10	0.10	2016
8	Sensor	8	0.05	2012
9	Energy	8	0.17	2016

4.2. Research Trend Analysis

A keyword timeline reflects the evolving research trends of a specific subject over time [14]. Emergent keywords refer to terms whose citation frequency rapidly increases during a particular period, illustrating the overall developmental trajectory of a research field across different timeframes [15].

4.2.1. Analysis of Domestic Research Trends

The domestic literature map reveals a total of 246 nodes and 386 connections, with a network density of 0.0128, as shown in Figure 10-11. Research in the field of smart clothing began emerging in 2011 and has continued as a sustained research theme to the present day. From 2011 to 2015, clustered themes such as smart clothing, apparel, and intelligentization appeared.

These clusters encompassed topics like optical measurement, applications, design, woolen garments, and smart fibers. This indicates that optical measurement and smart fiber applications were integrated into smart clothing early in the field's development, alongside research into smart clothing design and woolen garment design. From 2015 to 2020, clusters emerged around heart rate, sensors, and two-dimensional transition metal carbides. These clusters encompassed sensors, wearables, smart technologies, the Internet of Things, and conductive fabrics [16], indicating deeper scholarly exploration into health monitoring and technological aspects of smart clothing. As shown in Figure 10, four significant emergent keywords appeared in 2021: respiratory monitoring, elderly wear [17], health monitoring, and apparel design. These remain key research hotspots and focal points in the smart apparel field to this day, reflecting the multidisciplinary convergence within this domain.

Keyword clustering involves deriving a keyword cluster map from a co-occurrence network graph for cluster analysis. Modularity clustering module value (Q-value): Generally, a Q-value > 0.3 indicates a significant clustering structure. Silhouette clustering average silhouette value (S-value): Typically, an S-value > 0.5 suggests reasonable clustering, while S-value > 0.7 indicates convincing clustering [18].

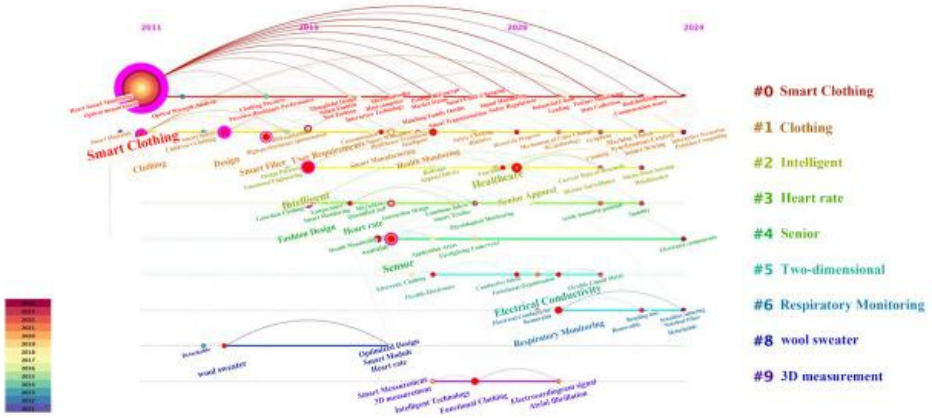


Figure 10. Keyword Timeline Map of CNKI Literature

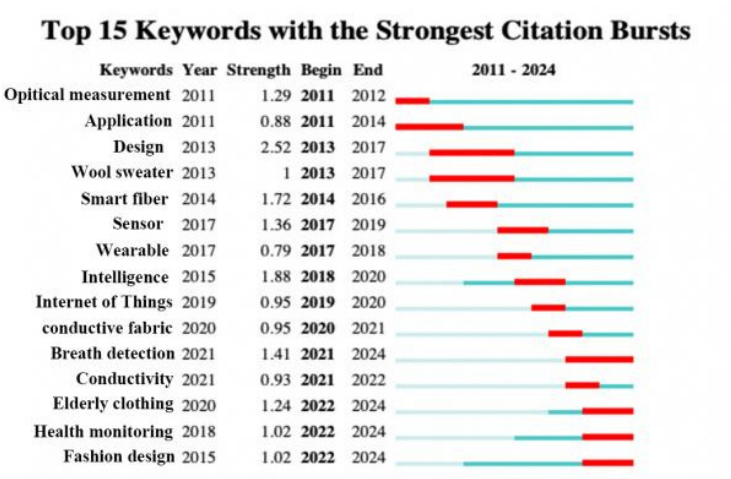


Figure 11. Keyword Salience Map of CNKI Literature

The clustering results show Q=0.7728 and S=0.9876, both indicating excellent clustering reliability for the keyword clustering network, as shown in Figure 12. The keyword clustering map of CNKI literature formed 10 major clusters: #0 Smart Clothing, #1 Clothing, #2 Intelligence, #3 Heart Rate, #4 Sensors, #5 Two-Dimensional Transition Metal Carbides, #6 Breathing Monitoring, #8 Wool Sweaters, #9 3D Measurement. #7 is not a valid cluster and is therefore not displayed in the cluster map. The keyword cluster table is shown in Table 8. Based on the keyword cluster labels in Table 8, the core research hotspots in China's smart clothing field can be summarized as follows: #1 Apparel encompasses clothing design, applications, and smart fiber utilization, emphasizing the integration of fashion design with intelligent technologies. #2 Intelligence relates to elderly wear and smart design strategies, highlighting applications for specific demographics and intelligent design methodologies. #3 Heart rate and humidity correlate with apparel design, indicating smart clothing's role in health monitoring. #4 Sensors signify technology as the functional backbone of smart clothing, with research focusing on acceleration, temperature, and humidity monitoring. #5 Two-dimensional transition metal carbides relate to conductivity and UV resistance in fabrics, connecting to material science and functionality in smart apparel. #6 Breathing monitoring reflects technological advancements tied to health tracking and wearability in smart clothing. #8 Wool sweaters demonstrate smart apparel applications on specific materials. #9 3D measurement relates to personalized customization and precise sizing in smart clothing.



Figure 12. Keyword Clustering Map of CNKI Literature

Table 8. Keyword Clustering Table for Smart Clothing Research

Cluster ID	Cluster Size	Clustered Label Name	Clustering Keywords
#0	71	Smart Clothing	Smart clothing; apparel; smart textiles; comfort; optical measurement
#1	31	Clothing	Apparel; Applications; Smart Fibers; Smart Clothing; Design
#2	16	Intelligent	Smart Technology; Senior Apparel; Research Status; Smart Design Strategies; Functionality
#3	14	Heart rate	Heart rate; humidity; apparel design; smart monitoring; microdata
#4	10	Sensor	Sensors; Acceleration; Temperature and Humidity; Wearable; Monitoring
#5	7	Two-dimensional transition metal carbides	Two-dimensional transition metal carbides; conductive fabrics; cotton knits; UV protection functionality; functional finishing
#6	7	Respiratory Monitoring	Breathing monitoring; detachable; real-time monitoring; flexible sensor; seamless integration
#7	6	Wool sweater	Wool sweater; optimized design; structural shaping; heart rate monitoring; smart module
#8	6	3D measurement	Smart Technology; Smart Customization; Acupoint Targeting; Eco-Health Socks

4.2.2. Analysis of International Research Trends

The international literature map reveals a total of 314 nodes and 641 connections, with a network density of 0.8347, as shown in Figures 13-14. As shown in Figure 13, smart clothing remains a core research theme with sustained interest to date. Research on carbon nanotube applications in smart clothing is gradually increasing. Studies on humidity management technology in smart clothing saw a significant rise after 2015. Research on washable light-emitting fabrics is gradually gaining attention.

The spectral analysis results in Figure 10 show Q=0.8347 and S=0.9433, indicating a high degree of reliability for the keyword clustering spectral network. The keyword spectrum of WOS literature formed 10 major clusters, as shown in Figure 14: #0 smart clothing, #1 carbon nanotube, #2 moisture management, #3 washable luminous fabric, #4 composite sensing fabric, #5 data classification, #6 films, #7 cloud computing, #8 antioxidant activity, and #9 monitoring. #0 smart clothing has exhibited strong research momentum since 2011 and continues to this day, indicating its growing importance and attention as a core research theme. In 2015, #1 carbon nanotube showed a significant surge in citations,

likely related to its application studies in smart clothing—such as in sensors and conductive materials. #2 Moisture management gained research momentum after 2015, likely tied to smart clothing applications in sports and health monitoring.

Top 15 Keywords with the Strongest Citation Bursts

Keywords	Year	Strength	Begin	End	2011 - 2024
polymerization	2011	1.27	2011	2012	
polymers	2011	1.27	2011	2012	
chemical vapor deposition	2011	1.21	2011	2012	
electronics	2014	1.47	2014	2017	
design	2015	3.53	2015	2018	
generator	2015	1.67	2015	2018	
energy	2016	1.67	2016	2019	
pressure	2017	2.36	2017	2018	
fabrics	2017	1.6	2017	2018	
carbon nanotubes	2015	1.27	2019	2020	
textile	2020	1.81	2020	2021	
textiles	2017	2.88	2022	2024	
strain	2020	1.8	2022	2024	
wearable electronics	2019	1.8	2022	2024	
smart textiles	2016	1.78	2022	2024	

Figure 13. Keyword Salience Map of WOS Literature

Moisture sensors track perspiration to assess exercise intensity or health status. #3 Washable luminous fabric research gained traction after 2017, likely due to smart clothing applications in fashion and safety, such as enhancing visibility in nighttime or low-light environments [19-20]. #4 Research interest in composite sensing fabric increased after 2017, likely due to smart clothing applications in health monitoring and environmental adaptability [21-22], such as monitoring diverse physiological parameters or environmental conditions through integrated multi-sensor systems. #5 Research interest in data classification increased after 2017, likely due to the vast amounts of data generated by smart clothing, necessitating effective classification and analysis methods to extract useful information. #6 Research interest in films increased after 2017, likely related to smart clothing applications in flexible electronics and sensors, such as using film technology to manufacture thinner, more flexible electronic components [23]. #7 Cloud research intensity increased after 2017, likely due to smart clothing applications in data processing and storage, such as utilizing cloud computing platforms to process and analyze data collected by smart garments [24]. #8 Antioxidant activity research intensity increased after 2020, likely due to smart clothing applications in health and wellness, such as enhancing garments' health benefits through antioxidant materials. #9 Monitoring research intensity increased after 2020, potentially linked to smart clothing applications in remote health monitoring and emergency response, such as using smart garments to monitor health conditions of chronic disease patients or the elderly [25].



Figure 14. Keyword Clustering Map of WOS Literature

As shown in Figure 14, early research hotspots centered on keywords such as polymerization, polymers, and chemical vapor deposition, indicating that smart clothing research is linked to developments in materials science and nanotechnology. Over time, the emergence of keywords like electronics, design, generators, and energy reflects the influence of technological advancements on the research field. Design, in particular, showed its highest spike intensity (3.53) in 2015, indicating that smart clothing research that year was associated with innovations in design methodologies or concepts. In 2016, spikes in keywords like pressure, fabrics, and carbon nanotubes were linked to research on nanomaterials for pressure applications and fabric reinforcement. Peaks in textiles during 2017 and 2020 corresponded with developments in smart textiles and wearable technology. The emergence of strain and smart textiles, alongside their shared period of focus with electronic wearables, indicates increasing interdisciplinary research between materials science, electronics, and textile engineering [26].

Keyword clusters are shown in Table 9. The "smart clothing" category includes terms such as "empirical mode decomposition," "information technology," "fabric antenna," and "skin-electrode interface capacitance." These keywords point to research directions in signal processing, information technology integration, and human physiological signal monitoring related to smart clothing.

Table 9. Keyword Clustering Table for Smart Clothing Research

Cluster ID	Cluster Size	Cluster Label Name	Cluster Profile	Clustering Keywords
#0	31	Smart clothing	0.979	Smart clothing; empirical mode decomposition; information technology; Fabric antenna; skin-electrode interface capacitance
#1	24	Carbon nanotube	0.969	Carbon nanotube; actuators; sports insoles; textile-based electroosmotic pumps; tag
#2	22	Moisture management	0.979	Moisture management; chemiresistor; pore response; gold; cab embroidery
#3	22	Washable luminous fabric	0.936	Washable luminous fabric; viscose; acel; military
#4	21	Composite sensing fabric	0.952	Composite sensing fabric; temperature sensors; strain-sensing yarn; nanocomposites; tourmaline
#5	20	Data classification	0.971	Data classification; colorimetric chemosensor; multipe sensors; piezoresistive sensors; muscle tremor
#6	20	films	0.868	Films; 3D printing; transparent conductor; capactive electrodes; conductive pla
#7	17	Cloud computing	0.988	Cloud computing; smartphone; robot; industrial wireless networks; big data
#8	15	Antioxidant activity	0.869	Antioxidant activity; uv protection; conductive films; biosynthesis; ag nanoparticles
#9	15	monitoring	0.955	Monitoring; biomedical monitoring; clothing; real-time monitoring; digital twins

Carbon nanotubes are associated with keywords like "actuators," "sports insoles," and "textile-based electroosmotic pumps." These terms indicate applications of carbon nanotubes in sensors, actuators, and smart textiles within smart clothing. Moisture management keywords include "chemiresistor," "pore response," and "gold," pointing to research in humidity sensing and regulation within smart clothing. Washable luminous fabric keywords like "viscose" and "military" may indicate research into smart clothing for military applications and specialized materials. Composite sensing fabric keywords include "temperature sensors," "strain-sensing yarn," and "nanocomposites," pointing to smart clothing applications in multi-parameter sensing and health monitoring. Data classification keywords include "colorimetric chemosensor" and "multiple sensors," pointing to research on data processing and analysis in smart clothing. Films keywords include "3D printing" and "transparent conductor," indicating research in manufacturing techniques and materials science for smart clothing. Cloud computing keywords include "smartphone," "robot," "industrial wireless networks," and "big data," indicating research on data storage, processing, and analysis in smart clothing. Antioxidant activity keywords include "UV protection," "conductive films," and "biosynthesis," pointing to research in health protection and materials science for smart clothing. Monitoring keywords include "biomedical monitoring," "clothing," "real-time monitoring," and "digital twins," pointing to applications in health monitoring and personalized medicine.

In summary, research hotspots in the smart clothing field center on material innovation, sensor technology, data processing, and health monitoring, while also incorporating emerging technologies like cloud computing and antioxidant properties. These studies not only advance smart clothing technology but also provide new perspectives and methodologies for related research domains.

5. Research Findings

From the perspective of annual publication volume, research on smart clothing both domestically and internationally has shown a significant upward trend from 2011 to 2024. Data from the CNKI and WOS databases indicate that research activity in the smart clothing field surged significantly between 2019 and 2024, closely tied to the increased demand for medical protective clothing during the COVID-19 pandemic. Furthermore, the continuous emergence of new materials and technologies in recent years has attracted greater scholarly attention, driving rapid advancement in smart clothing research. Research hotspots in this field center on material innovation, sensor technology, data processing, and health monitoring, while also encompassing emerging technologies such as cloud

computing and antioxidant applications. These studies not only propel the development of smart clothing technology but also provide novel approaches and methodologies for related research domains.

Regarding collaboration among core authors and institutions, a tightly knit cooperative network has yet to form within the global smart clothing research community. Domestically, research institutions centered around universities like Donghua University hold considerable influence in this field, though inter-institutional collaboration requires further strengthening. Among international research institutions, Donghua University and the Chinese Academy of Sciences demonstrate a clear advantage in publication frequency, highlighting China's active presence and influence in smart clothing research.

In terms of national distribution, China leads both in the volume of research publications and intermediary centrality within the smart clothing field, reflecting the nation's high priority and significant contributions to this domain. Countries like South Korea and the United States also exhibit high activity and influence in smart clothing research, with their findings providing crucial technical support and theoretical foundations for the field's advancement.

Research hotspots in smart clothing concentrate on material innovation, sensor technology, data processing, and health monitoring. By integrating advanced sensors and electronic components, smart clothing enables real-time monitoring of human physiological parameters such as heart rate, body temperature, and respiratory rate. Additionally, significant progress has been made in developing temperature-adaptive smart fabrics through materials science. These studies not only advance smart clothing technology but also offer new approaches and methodologies for related fields.

Overall research trends indicate that smart clothing development is progressing toward multifunctional integration, novel material applications, data processing and analysis, and health monitoring. Future research may further explore the integration of smart clothing with health, environmental monitoring, and fashion design, as well as how technological innovations can enhance comfort, durability, and user experience [27-28]. Moreover, with the continuous advancement of IoT and AI technologies, smart clothing is expected to deliver more personalized and precise health monitoring solutions in the future [29-30].

6. Conclusion

Research on smart clothing is an ongoing process of development and innovation, having already yielded significant achievements. Smart clothing has not only achieved technological breakthroughs but also continuously expanded its application domains, bringing convenience and new experiences to people's lives. This study conducted a visualization analysis of smart clothing-related literature indexed in the CNKI and Web of Science databases from 2011 to 2024. Utilizing CiteSpace 6.4.R1 software, it performed an in-depth analysis of publication volume, authors and institutions, countries, keywords, and other aspects, identifying development trends and research hotspots in the field of smart clothing both domestically and internationally. The findings indicate that smart clothing research is advancing in directions such as multifunctional integration, new material applications, data processing and analysis, and health monitoring, demonstrating broad application prospects and significant market potential. This study provides important references and assistance for subsequent research on smart clothing, contributing to further development and innovation in the field. However, the study has some limitations. On one hand, the research data samples were primarily selected from the CNKI and Web of Science databases, which may suffer from incomplete coverage, potentially excluding some research findings from the analysis scope, thus imposing certain limitations. On the other hand, due to differences in researchers' knowledge backgrounds and perspectives, the analysis and interpretation of research hotspots and trends may involve subjectivity, leading to varying understandings and viewpoints among scholars. It is hoped that this study will assist relevant scholars in gaining a better understanding of the research hotspots and trends in the field of smart clothing both domestically and internationally, providing valuable references and inspiration for future research. We look forward to the emergence of more research findings on smart clothing in the future, driving the continuous development and innovation of this field.

References

[1] LIM H S, LEE D W, SHIM W S. Artificial Intelligent Clothing Embedded Digital Technologies[J]. Journal of Fashion Business, 2010, 14(6): 70-83.

[2] LIU W H. Research on the Current Status and Development Trend of Smart Clothing[J]. Southern Agricultural Machinery, 2019, 50(14): 233-234.

[3] GU W, HOU C Y, ZHANG Q H, et al. Current Status and Development Trend of Smart Clothing[J]. Journal of Donghua University (Science and Technology Edition), 2019, 45(6): 837-843.

[4] CHEN Y, CHEN C M, LIU Z Y, et al. Methodological Function of CiteSpace Knowledge Graph[J]. Scientific Research on Science, 2015, 33(2): 242-253.

[5] ZHOU Q, YAO Z. Comparative Analysis of Domestic and International Participatory Design Research Based on CiteSpace [J]. Packaging Engineering, 2023, 44(10): 241-250+ 268.

[6] KUANG Y X, LI Z M, HUANG Q W. Research Hotspots and Trend Analysis of Cultural and Creative Products Based on Knowledge Graphs[J]. Packaging Engineering, 2020, 41(18): 154-164.

[7] ZHANG H, SUN Y Q, SI J H. Analysis of International Ecotourism Research Based on Knowledge Graph Method[J]. Journal of Natural Resources, 2017, 32(2): 342-352.

[8] LUO S, ZHU D H, YAN S. Visual Analysis of Research Progress and Development Trends of Temperature-regulating Clothing[J]. Silk, 2024, 61(12): 104-116.

[9] DOU J H, ZHANG B R, QIAN X S. A Review of Artificial Intelligence Empowering Cultural Heritage Research - A Visual Analysis Based on CiteSpace[J]. Packaging Engineering, 2023, 44(14): 1-20.

[10] GAO Y, SU Y, HE J Q. CiteSpace Visualization Analysis of Research Hotspots and Trends in Green Building Design[J]. Industrial Construction, 2023, 53(S2): 131-134.

[11] WU L F, LU D B, WU Y, et al. Visual Analysis of Multisensory Design: Research Progress, Hotspots and Trends[J]. Packaging Engineering, 2022, 43(22): 205-220.

[12] WANG Y C, LUO S W, YANG Y B, et al. Review of Knowledge Graph Visualization[J]. Journal of Computer-Aided Design & Computer Graphics, 2019, 31(10): 1666-1676.

[13] HAO J Y, LI Y M. Present Development Status and Trends of Smart Clothing[J]. Textile Leader, 2020(4): 62-65.

[14] CAO S J, WU Y B, WEI J Z, et al. Threads, Schools and Trends of Knowledge Graph Research - A Bibliometric and Visual Analysis Based on SSCI and CSSCI Journal Papers[J]. Journal of Chinese Library Science, 2015, 41(05): 16-34.

[15] LIU W S, GUO Q H, LI Z X, et al. Analysis of Research Status and Trends in Service Design in China Based on Bibliometrics[J]. Packaging Engineering, 2023, 44(10): 231-240.

[16] FANG D G, SHEN L. Overview of Smart Clothing Materials Research[J]. Knitting Industry, 2016(1): 34-38.

[17] JI Y L, WANG J. Research Status and Development Trends of Smart Clothing for the Elderly[J]. Shandong Textile Science and Technology, 2024, 65(4): 52-56.

[18] DOSHI P, et al. Smart Clothing in Military Applications[J]. Journal of Textile and Apparel, Technology and Management, 2015, 10(3): 1-10.

[19] KNIGHT A. Smart Clothing for Health Monitoring[J]. Sensors, 2017, 17(3): 567-578.

[20] SHI X, ZUO Y, ZHAI P, et al. Smart Clothing for Health Monitoring[J]. Nature, 2021, 591: 240-245.

[21] DOSHI P, et al. Smart Clothing in Military Applications[J]. Journal of Textile and Apparel, Technology and Management, 2015, 10(3): 1-10.

[22] CHEN L, LU M, YANG H, et al. Smart Clothing for Health Monitoring[J]. ACS Nano, 2020, 14: 8191-8201.

[23] LIMAN M L R, ISLAM M T, HOSSAIN M M, et al. Smart Clothing for Health Monitoring[J]. Adv. Electron. Mater., 2022, 8.

[24] ZHOU R. Design Patterns and Development Trends of Smart Clothing[J]. Guangdong Sericulture, 2020, 54(01): 82-83.

[25] SUN R C, XU D F, LI Z X. Application Paths, Development Issues and Future Trends of Smart Clothing[J]. Textile Finishing Technology, 2020, 42(3): 13-17.

[26] GU W, HOU C Y, ZHANG Q H, et al. Present Status and Development Trend of Smart Clothing[J]. Journal of Donghua University (Natural Science Edition), 2019, 45(6): 837-843.

[27] ZHANG G W. Smart Clothing Design Based on High-tech Fibers and Bionic Materials[J]. Synthetic Fibers, 2023, 52(10): 20-23.

[28] SHEN L, SANG P P. Development Status and Trends of Smart Clothing under Different Field Technologies[J]. Silk, 2019, 56(03): 45-53.

[29] ZHAO L D, ZHANG J, GUO Z. Research Progress and Development Trends of Smart Health Monitoring Clothing[J]. Tianjin Textile Science and Technology, 2024(1): 20-24.

[30] LI S, CHEN D S. Current Development Status and Future Trends of Smart Clothing[J]. International Textile Leader, 2023, 51(2): 30-36.