NOVA IMS Information Management School

MDSAA

Master Degree Program in

Data Science and Advanced Analytics

ANALYZING SMART TEXTILES

A Bibliometric Analysis and Systematic Review

Ana Sofia Vieira Mendonça

Master Thesis

presented as partial requirement for obtaining a Master's Degree in Data Science and Advanced Analytics

NOVA Information Management School
Instituto Superior de Estatística e Gestão de Informação
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by

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Master Thesis presented as partial requirement for obtaining the Master's degree in Data Science and Advanced Analytics, with a specialization in Business Analytics.

Supervised by

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July, 2024

STATEMENT OF INTEGRITY

I hereby declare having conducted this academic work with integrity. I confirm that I have not used plagiarism or any form of undue use of information or falsification of results along the process leading to its elaboration. I further declare that I have fully acknowledged the Rules of Conduct and Code of Honor from the NOVA Information Management School.

Funchal, 15 of July 2024

To my friends: those I have known for over a decade, thank you for always believing in me, being like a second family and supporting me through all my achievements. To the friends I met at university, I could not have completed my degrees without your support. Thank you for being my second teachers and believing in me when I didn't. To those I met on the other side of the world, thank you for making me a better person and transforming my perspective on friendship and life.

To my family, especially my mother, father, and sister, thank you for your unwavering support, invaluable advice, and for being examples of strength and determination. To my grandmother, I aspire to one day embody half the strength and character you have. All the women in my family are the best figures I looked up to growing up, I am fortunate to have my grandmothers, mother and many aunts who are independent and strong as people to look up to.

I am completely aware of how I have been blessed by having a home I can run to in the hard times and to be surrounded by family and friends who are always there to welcome me.

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Abstract

Smart textiles, which integrate advanced materials and electronic components into fabrics, represent a rapidly evolving field with a wide range of applications, including healthcare, sports, and wearable technology. To objectively uncover the current state of research in the field of smart textiles, this paper employs the Bibliometrix and Biblioshiny software packages, as well as VOSviewer, to analyze a dataset of 9,313 documents indexed in the Scopus database, spanning from 1980 to the present. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were utilized to ensure a systematic and transparent approach in the selection and evaluation of the literature.

The study identifies China and the United States as the most prolific countries, with China leading at 2,197 publications and the United States following with 1,614 publications. The top publication sources are 'ACS Applied Materials & Interfaces' and 'Textile Research Journal', indicating a broad interdisciplinary engagement in the field. The research field of Smart Textiles has demonstrated substantial growth, particularly since 2018, with an average annual growth rate of 18.61% in publications. Leading institutions driving research include the Ministry of Education of the People's Republic of China, Donghua University, and The Hong Kong Polytechnic University. Future research in smart textiles should focus on integrating deep learning, improving mechanical properties, utilizing 3D printing, enhancing performance capabilities, developing self-powered textiles with nanogenerators, and advancing personalized healthcare solutions.

This thesis provides a detailed overview of the evolving landscape of Smart Textiles research, highlighting the main countries, sources, and institutions contributing to the field. The findings underscore the global collaboration and sustained interest that are propelling advancements in Smart Textiles, offering valuable insights for researchers, policymakers, and industry stakeholders engaged in this dynamic and rapidly expanding domain.

Keywords: Smart Textiles, Bibliometric analysis, Bibliometrix, VOSviewer

Sustainable Development Goals (SDG):

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Introduction

The Smart Textiles industry has experienced rapid growth and innovation in recent years, spurred by advancements in technology and the development of novel materials and processes (Júnior et al., 2022). This expansion has coincided with the emergence of a multitude of new tools and technologies within the smart textiles domain.

Researchers have extensively documented the various applications and benefits of smart textiles across different sectors. These studies highlight the versatility of smart textiles in areas such as healthcare, sports performance, fashion, and military applications. Smart textiles offer opportunities for personalized health monitoring, enhanced athletic performance through real-time feedback, adaptive clothing for individuals with disabilities, and protective gear with integrated sensors for military personnel.

Despite the wealth of research on specific applications of smart textiles, there remains a gap in understanding the collective impact and potential affordances of smart textiles across industries. There is a need for a comprehensive review of existing literature to elucidate the full spectrum of opportunities offered by smart textiles in various sectors.

Therefore, the aim of this study is to conduct a systematic review of smart textiles research from 1980 to 2023. By synthesizing and analyzing the existing literature, this review seeks to provide insights into the diverse applications and potential benefits of smart textiles across different industries. By doing so, this study aims to inform researchers, practitioners, and policymakers about the evolving landscape of the smart textiles industry and its implications for future developments and innovations.

1.1 Smart Textiles

Smart textiles represent a fascinating convergence of technology and traditional fabrics, revolutionizing the way we perceive and interact with clothing. Embedded with electronic components or advanced materials, these textiles have the ability to sense and respond to changes in the environment or the wearer's body, opening up a realm of possibilities for innovation across various industries. They can be defined as 'textiles that are able to sense and respond to changes in their environment' (Koncar, 2016).

1.1.1 Types of smart textiles

These can be divided into two categories based on their sensitivity and intelligence level to react to stimuli (Md Raihan Hossain & Alam, 2023):

Passive Smart Textiles The initial generation of smart textiles, which only have sensing capabilities—their materials can detect environmental stimuli.

Active Smart Textiles The second generation which has both actuators and sensors, this allows it to detect and react to environmental stimuli.

1.1.2 History

Although textiles have been used for years as protection or for warmth, the term 'smart textiles' can be traced back to the 20th century, when researchers began exploring the integration of electronic components into fabrics. There exists varying opinions regarding the first textile material that was labelled as 'smart'. An illustration of this is the Ventile fabric from the 1940s, serving as a waterproof protective layer. This material functioned through the swelling property of cotton yarn, impeding water from permeating beyond the necessary amount for the swelling process (Persson et al., 2018a).

In the year 1968, the Museum of Contemporary Art in New York City organized a pioneering exhibition titled 'Body Covering' delving into the convergence of technology and clothing (Ganesan & Sornapudi, 2017). This exhibition featured a remarkable display of astronaut spacesuits and garments with advanced functionalities, including the ability to inflate, deflate, illuminate, provide heating, and offer comfort (Md Raihan Hossain & Alam, 2023).

Yet, it wasn't until the 1980s that textiles, particularly garments, were recognized as a promising domain for enhancing through various technologies like sensorics, enabling the measurement of the wearer and monitoring the surroundings. In 1985, the inventor Harry Wainwright crafted the first fully animated sweatshirt. This garment incorporated fiber optics, LEDs, and a microprocessor to control individual animation frames. The outcome was a vibrant, full-color cartoon showcased on the shirt's surface (Md Raihan Hossain & Alam, 2023). Around the same time, in 1995, the first textile material to be labeled as a smart textile was silk thread with a memory effect, created in Japan. The discovery of shape-memory materials in the 1960s and intelligent polymeric gels in the 1970s, on the other hand, was widely regarded as the birth of actual smart materials (Koncar, 2016). Simultaneously, in the United States, Wainwright continued to innovate by creating a machine to transform fiberglass into fabric. Collaborating with German designer Herbert Selbach, he introduced the first CNC (computer numerical control) machine for this purpose by 1998. Wainwright's patents for embedding fiberglass and LED/optical displays, along with Disney's acquisition of his animation technology in 1998, paved the way for innovative developments, including a Bluetooth-enabled jacket with a GSR (galvanic skin response) sensor demonstrated in 2007.

1.1.3 Current situation

In recent times, there has been successful development and application of various smart textile devices in many different fields such as Healthcare (Ye et al., 2020), Military (Rube & Varnaitė, 2008), Aerospace (Cherston & Paradiso, 2019) and the Textile industry in general (Kan & Lam, 2021).

According to Ruckdashel et al., 2021 the implementation of standardized electronic textiles faces three main obstacles: flexible conductive wiring, continuous power generation, and garment production. Electronic textiles have struggled commercially, with few products sustaining long-term success. In contrast, smartphones and wearables have dominated the market, challenging smart textiles to demonstrate their unique advantages.

Additionally, most bibliometric research in this field focuses on specific applications or materials, leaving a broader understanding of smart textiles underexplored. A market forecast estimates that the wearable devices industry will surpass $155 billion by 2027 (Cesarelli et al., n.d.). Consequently, continuous bibliometric reviews and systematic studies are crucial to keep pace with the rapid advancements in this evolving field, underscoring the significance of this thesis.

1.2 Objectives

The primary aim of this study is to analyze literature concerning Smart Textiles research, utilizing a dataset of 9313 documents indexed in the Scopus database spanning from 1980 to 2023. Thus this paper aims to answer the following questions:

1. What are the most prolific authors, institutions, journals and papers in the field of Smart Textiles based on their publication output?

2. What is the contribution by country in terms of research on Smart Textiles?

3. What are the most often explored topics in the field of Smart Textiles?

4. Are there any emerging topics or areas of interest within the field of Smart Textiles, as evidenced by recent publications?

2

Literature Review

2.1 Areas of Study

Despite the growing importance and rapid advancements in this field (Cesarelli et al., n.d.), only a limited number of studies have conducted in-depth bibliometric reviews to systematically map the research landscape, identify trends, and highlight emerging areas of interest. The existing papers focus more on specific topics such as the components used in the production of these textiles and on various applications (Grancaric et al., 2018; Honarvar & Latifi, 2017; Koncar, 2016; Park & Jayaraman, 2003; Ruckdashel et al., 2022; Xing et al., 2023; Zhou et al., 2010) across industries such as healthcare (X. Chen et al., 2023; Degli Esposti et al., 2022; Khan et al., 2023; Libanori et al., 2022; X. Liu et al., 2021; Mecnika et al., 2014; Mertz, 2020; Rai et al., 2012; Tat et al., 2022; Zada et al., 2023), defense (Degenstein et al., 2021; Q. Li & Tao, 2014; Mertz, 2020; Rube & Varnaitė, 2008; Sahin et al., 2005), and fashion (Cabigiosu & Cabigiosu, 2020; Holland, 2016; McKeegan, 2019). Recognizing this critical gap, this thesis provides an overview of the smart textile landscape. Through an exhaustive review of existing literature, the study aims to elucidate market trends, identify emerging technologies, and forecast future developments within the smart textile industry.

2.2 Related Works

This section will examine the bibliometric reviews in the field of smart textiles that are most analogous to this study. The papers by S. Li et al., 2022, Wang et al., 2023, and Sajovic et al., 2023 provide valuable insights into the smart textile and functional clothing industries through comprehensive bibliometric analyses. S. Li et al., 2022 analyze 4,153 pieces of literature from Web of Science, highlighting the interdisciplinary nature of functional clothing research and emphasizing material science. Wang et al., 2023 examine 2,398 publications to identify research trends and hotspots in intelligent textile clothing from 2012 to 2022, using CiteSpace and VOSviewer software. Sajovic et al., 2023 investigate the field of smart textiles by analyzing 5,810 documents, focusing on global research outputs, publication trends, influential documents, and potential future directions. However, these studies are limited by the shorter time spans and smaller datasets they encompass, which can be restrictive given the rapid evolution of the field. In contrast, this thesis extends the scope of these works by incorporating a broader range of literature over a more extended period. As the field of smart textiles is rapidly evolving, continuous and comprehensive studies are essential to maintain an accurate understanding of current trends and advancements.

On the other hand, some bibliometric analysis in the field focus on specific applications or themes within smart textiles rather than the entire domain. For instance, Lee et al., 2023 evaluate the effectiveness of electronic textiles (e-textiles) in enhancing thermal comfort in cold environments, conducting a systematic review and meta-analysis of just 8 papers from 1948 to 2022. Z. Liu et al., 2023 analyze 2,839 articles on medical textiles, using bibliometric tools like CiteSpace and VOSviewer to map collaborations and identify research hotspots across various disciplines. Azizan et al., 2024 focus on wearable health sensors, examining 147 papers to identify research gaps, prominent topics, and developmental trends. Similarly, Tian and Li, 2019 analyze 1,735 publications on protective clothing over a 20-year period, using Web of Science and CiteSpace combined with Google Earth to map key trends and influential scholars in the field. Finally, Cesarelli et al., n.d. provide a comprehensive overview of advancements in smart e-textiles designed for healthcare monitoring, focusing on biomedical sensors and devices developed for medical applications covering 71 papers from a decade-long search on Scopus and PubMed.

Overall, this thesis significantly extends these studies by offering a more up-to-date analysis that encompasses a broader range of literature. By doing so, it not only builds upon the foundational work of prior studies but also addresses the rapidly evolving nature of the smart textile industry. This contributes a crucial, extensive exploration of current trends and advancements, ensuring a more accurate and holistic understanding of the field.

3 Methodology

3.1 Search Strategy

In order to comprehensively explore the literature relevant to the topic, searches were conducted using both Scopus and Web of Science databases. The search queries included a wide range of combinations related to smart textiles, encompassing various terms such as 'e-textile', 'smart fabric', 'intelligent garment' and others. These terms were obtained by combining the suggested keywords from Scopus and and commonly encountered synonyms of 'e-textiles' found across a spectrum of literature in the field. The keywords were combined using Boolean operators, and the *TITLE-ABS-KEY* search field in Scopus was employed to construct a comprehensive search query. This method allows for searching within the title, abstract, and keywords of documents to ensure the capture of relevant literature effectively. A portion of the search query is presented below, with the complete query provided in the appendix.

```
( TITLE-ABS-KEY ('e textile') OR TITLE-ABS-KEY ('e textiles')
OR TITLE-ABS-KEY ('e cloth') OR TITLE-ABS-KEY ('e clothes')
OR TITLE-ABS-KEY ('e clothing') OR TITLE-ABS-KEY ('e fabric')
OR TITLE-ABS-KEY ('e fabrics') OR TITLE-ABS-KEY ('e garment')
OR TITLE-ABS-KEY ('e garments') OR TITLE-ABS-KEY ('e apparel')
OR TITLE-ABS-KEY ('e thread') OR TITLE-ABS-KEY ('e threads') )
OR ( TITLE-ABS-KEY ('smart textile') OR TITLE-ABS-KEY ('smart textiles')
OR TITLE-ABS-KEY ('smart cloth') OR TITLE-ABS-KEY ( 'smart clothes' )
OR TITLE-ABS-KEY ('smart clothing') OR TITLE-ABS-KEY ('smart fabric')
OR TITLE-ABS-KEY ('smart fabrics') OR TITLE-ABS-KEY ('smart garment')
OR TITLE-ABS-KEY ('smart garments') OR TITLE-ABS-KEY ('smart apparel')
OR TITLE-ABS-KEY ('smart thread') OR TITLE-ABS-KEY ('smart threads') )
```

While both databases yielded relevant documents, Scopus returned a significantly larger number of results (11492) compared to Web of Science (7147). Consequently, due to the broader coverage and depth of literature available, Scopus was used as the main literature source and insights extraction.

3.2 Screening Strategy

The data screening process involved several steps to ensure the relevance and quality of the collected literature. Initially, the search was restricted to documents published between 1980 and 2023. Only documents written in English were considered to maintain consistency and comprehensibility. Furthermore, the document types were limited to articles, conference papers, and reviews, as these forms typically provide comprehensive and peer-reviewed insights relevant to the research objectives. This process resulted in the identification of 9418 documents, which were then manually reviewed to remove duplicates, ultimately leading to 9313 documents being analyzed in the bibliometric analysis. For the visualization of the collected data, thesaurus files were utilized in VOSviewer to ensure consistency and accuracy. A thesaurus file is a text file utilized for data cleaning when generating a map based on bibliographic or text data (van Eck & Waltman, 2018). The files were created by manually looking at all different keywords and standardizing them by addressing variations such as synonyms, different spellings, and abbreviations (for example *'3-d printing'*, *'3d printers'*, *'3d printing'*, *'3d-printing'* all were different keywords before the thesaurus file).

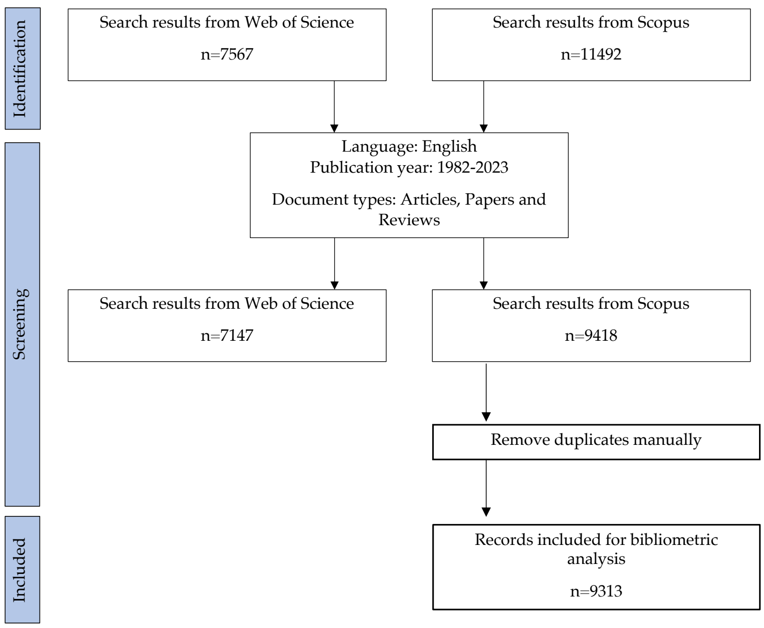

Figure 3.1: Screening process.

3.3 Bibliometric Analysis

The selected papers were evaluated using the Bibliometrix package from R software (Aria & Cuccurullo, 2017). Conducting a bibliometric analysis provides insights into research activities from scientific communities, enabling the exploration and visualization of their evolution over time. This approach yields both a global and specialized perspective on the literature.

3.4 Systematic Review

After conducting an extensive review of various review articles and bibliometric analyses (Crompton & Burke, 2023; Deepthi & Bansal, 2024; Guimeráns-Sánchez et al., 2024; Sarker & Bartok, 2024; Tsunoda et al., 2020), the decision was made to adhere to the PRISMA checklist to ensure a more systematic approach to the review process. The Preferred Reporting Items for Systematic Review and Meta-Analysis Protocols (PRISMA-P) is a guideline developed to improve the quality of systematic review protocols. It provides a checklist to aid authors in preparing clear and complete documents outlining the methods for their systematic reviews.This methodology presents a four-step flowchart (identification, selection, eligibility, and inclusion) that has been adapted to the needs of the present research ("Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015 statement", 2016).

3.5 Growth Rate of Publications

The compound annual growth rate (CAGR) formula is given by:

$$\text{CAGR} = \left(\frac{\text{Ending Value}}{\text{Beginning Value}}\right)^{\frac{1}{\text{Number of Years}}} - 1$$

Figure 3.2: Compound Annual Growth Rate.

4

Results and Analysis

4.1 Main Information

Some of the main characteristics of the collected data are shown in Table 4.1, there are 9313 documents in the time span of 41 years. These documents were written by a total of 18.571 authors from 2.448 different sources. The average age of the documents being 7.48 years shows that most of the research has been done in the last decade.

Table 4.1: Overview of the collected data.

Description	Results
Total Documents	9313
Time Span	1982-2023
Authors	18571
Author's keywords	16188
Average citations per document	24.19
Sources	2448
Annual Growth Rate	18.61%
Document average age	7.48

4.2 Analysis of Publications

4.2.1 Distribution of Annual Publications

The quantity of the publications is an important indicator that reveals the development trends of scientific research. Initially, from 1982 to 1998, the number of publications remained low and stable, indicating limited interest or recognition of the field. However, from 1998 to 2014, a gradual increase in publications is observed, reflecting growing interest and advancements in smart textiles. The period from 2014 to 2018 marks a

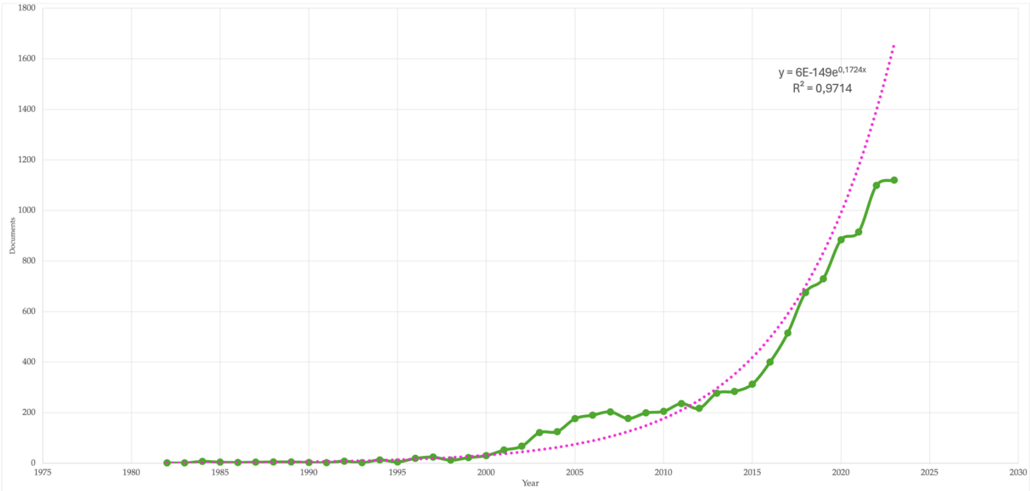

Figure 4.1: The distribution of bibliographic records per year along with the fitted exponential curve and its R^2 squared value.

phase of significant growth. Most notably, from 2018 onwards, there is an exponential rise in the number of publications, suggesting a major surge in research activity. By 2023, the graph reaches its peak, indicating the highest level of research activity in the field to date. Figure 4.1 plots the annual trends of publications about Smart Textiles. Over the span of 1995 to 2023, the average growth rate of scientific research papers within this domain stood at 18.61% (3.5). The number of publications increased steeply between 2012 and 2023, accounting for 79.4% of all included papers. When analyzing the exponential fit, the equation $y = 6 \times 10^{-149} e^{0.1724x}$ with an R^2 value of 0.9714 indicates that the number of bibliographic records per year follows an exponential growth pattern. The high R^2 value suggests that the model explains approximately 97.14% of the variance in the data, demonstrating a very good fit.

4.2.2 Analysis of Cited Publications

As stated before 4.1, we observed that the average number of citations per document in the field of Smart Textiles is 24.19. This section focuses on the most highly cited papers, which are pivotal in shaping the research landscape of Smart Textiles. Table 4.2 provides a detailed list of these influential articles, including their titles, DOI numbers, total citation counts, and citations per year. The most cited document in this field is by Gladman et al., 2016, which discusses the innovative concept of Biomimetic 4D printing, inspired by nastic plant motions, to create shape-morphing systems using composite hydrogel architectures. By controlling the alignment of cellulose fibrils, researchers achieve programmable fabrication of structures that change shape in response to stimuli.

Table 4.2: Most Global Cited Documents in the field of Smart Textiles.

Paper	Title	DOI	Total Citations	TC per Year
SYDNEY GLADMAN A, 2016, NAT MATER	Biomimetic 4D printing	10.1038/nmat4544	2242	249.11
PANTELOPOULOS A, 2010, IEEE TRANS SYST MAN CYBERN PT C APPL REV	A Survey on Wearable Sensor-Based Systems for Health Monitoring and Prognosis	10.1109/TSMCC.2009.2032660	1802	120.13
STOPPA M, 2014, SENSORS	Wearable Electronics and Smart Textiles: A Critical Review	10.3390/s140711957	1550	140.91
LENG J, 2011, PROG MATER SCI	Shape-memory polymers and their composites: Stimulus methods and applications	10.1016/j.pmatsci.2011.03.001	1303	93.07
AHAMED M, 2010, CLIN CHIM ACTA	Silver nanoparticle applications and human health	10.1016/j.cca.2010.08.016	1101	73.40
MENG Y, 2013, ADV MATER	All-Graphene Core-Sheath Microfibers for All-Solid-State, Stretchable Fibriform Supercapacitors and Wearable Electronic Textiles	10.1002/adma.201300132	1010	84.17
MONDAL S, 2008, APPL THERM ENG	Phase change materials for smart textiles – An overview	10.1016/j.applthermaleng.2007.08.009	1006	59.18
LEE J, 2015, ADV MATER	Conductive Fiber-Based Ultrasensitive Textile Pressure Sensor for Wearable Electronics	10.1002/adma.201500009	938	93.80
CHEN J, 2016, NAT ENERGY	Micro-cable structured textile for simultaneously harvesting solar and mechanical energy	10.1038/nenergy.2016.138	859	95.44
XUE J, 2017, ACC CHEM RES	Electrospun Nanofibers: New Concepts, Materials, and Applications	10.1021/acs.accounts.7b00218	819	102.38

The study showcases the potential of biomimetic 4D printing in various applications, such as smart textiles, robotics, and tissue engineering, highlighting its versatility and promising future prospects. Following this, Pantelopoulos and Bourbakis, 2010 provide a comprehensive survey on wearable sensor-based systems for health monitoring and delve into the transformative potential of these systems in revolutionizing healthcare practices. The document explores how wearable biosensor systems can be embedded in garments to provide comfortable and unobtrusive monitoring solutions. Additionally, the third most cited paper in this field is by Stoppa and Chiolerio, 2014, which explores wearable electronics and smart textiles. The paper discusses how the integration of electronics and textiles can create fabrics capable of sensing, computing, communicating, and actuating. It highlights potential applications in medical, sports, military, and aerospace sectors, emphasizing the importance of materials, manufacturing processes, and energy sources in developing smart textiles. The review showcases recent advancements and addresses the challenges in creating wearable systems that are flexible, ergonomic, energy-efficient, integrated, and autonomous.

4.3 Analysis of Countries and Affiliations

4.3.1 Distribution of Publications per Author's Country

Most of the research publications on Smart Textiles come mainly from authors from China, United States of America and United Kingdom (with 2197, 1614 and 667 frequencies, respectively), followed by South Korea, Germany, and India (with 577, 517, and 479 frequencies, respectively). The rest of the contributions originated predominantly in some European countries, followed by Asia and Oceania.

Table 4.3: Most relevant countries in Smart Textiles (by number of articles published by authors of that country).

Country	Continent	Frequency	Country	Continent	Frequency
China	Asia	2197	Australia	Australia	251
United States	North America	1614	Turkey	Europe/ Asia	215
United Kingdom	Europe	667	Japan	Asia	213
South Korea	Asia	577	Taiwan	Asia	195
Germany	Europe	517	Belgium	Europe	183
India	Asia	479	Portugal	Europe	177
Italy	Europe	348	Spain	Europe	163
Hong Kong	Asia	291	Singapore	Asia	155
France	Europe	266	Sweden	Europe	153
Canada	North America	255	Poland	Europe	145

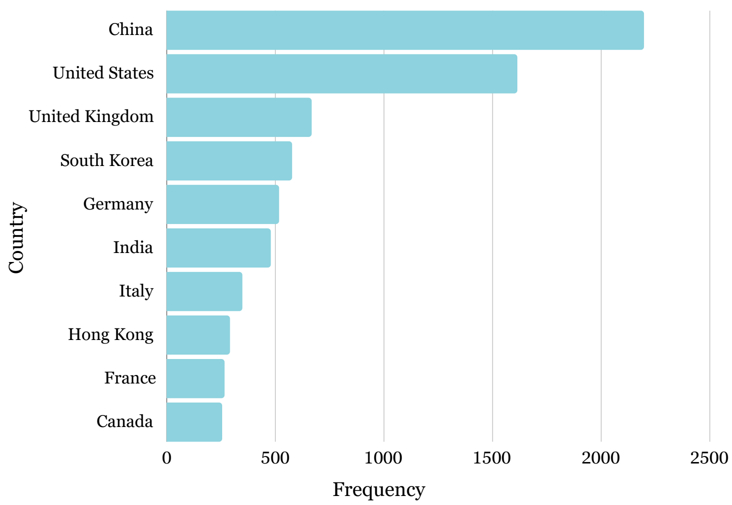

Figure 4.2: Top 10 Countries in terms of Authors' Research Contributions

It is noteworthy that China has not always led in smart textile research production 4.4. Until 2017, the United States held the top position. However, since then, China has rapidly increased its output, achieving exponential growth and surpassing the United States. To further analyze this shift, country production was examined before and after 2017. From 1982 to 2017, the top three countries were the United States, China, and Argentina, with 736, 497, and 271 publications respectively. This indicates the rapid growth in the field, as the number of publications more than doubled when comparing the periods from 2017 to 2023. During this latter period, China and the United States remained the top producers with 1805 and 979 publications, respectively, followed by the UK with 459.

Table 4.4: Top 10 author's countries contribution through the years.

Countries	Number of publications (1980–2023)	Number of publications (1980–2017)	Number of publications (2017–2023)
China	2197	497	1805
United States	1614	736	979
United Kingdom	667	255	459
South Korea	577	210	404
Germany	517	271	286
India	479	191	310
Italy	348	166	202
Hong Kong	291	139	163
France	266	125	161
Canada	255	94	172

4.3.2 Analysis of Most Relevant Organizations

In addition, the organisations that contributed most to the research were mostly located in China, followed by the United States. The top 3 organisations were the Ministry of Education of the People's Republic of China, Donghua University and Chinese Academy of Sciences.

Table 4.5: Most relevant affiliations in Smart Textiles (by number of articles published).

Affiliation	Country	Results
Ministry of Education of the People's Republic of China	China	809
Donghua University	China	472
Chinese Academy of Sciences	China	446
The Hong Kong Polytechnic University	China	326
Jiangnan University	China	193
Georgia Institute of Technology	United States	176
Soochow University	Taiwan	175
National University of Singapore	Singapore	173
University of Chinese Academy of Sciences	China	173
University of Southampton	United Kingdom	162

4.3.3 Analysis of Country Collaborations

Collaborating to generate new scientific information is the focus of research collaboration (Katz & Martin, 1997). While there are several different kinds of research collaboration, the most popular ones involve authors, organisations, and countries working together. Recognising the active countries in the study area is done through country collaboration (Sarker & Bartok, 2024). The collaboration world map shows the country-based affiliations of authors. The color intensity on the map represents the strength of these relationships, with darker colors indicating stronger connections and lighter colors signifying weaker ones. Countries with no collaborative connections are

Table 4.6: Country Collaboration frequency in the field of Smart Textiles.

From	To	Frequency
China	USA	190
China	Hong Kong	105
China	United Kingdom	85
China	Singapore	79
China	Australia	69
USA	Korea	65
USA	United Kingdom	45
China	Germany	35
China	Canada	33
China	France	32

shown in gray. The country collaboration map depicted in Figure 4.3 illustrates the prominent role of China and the United States in international research partnerships. These two nations are identified as having the highest number of collaborative efforts with other countries. Notably, the most frequent bilateral collaboration is between the United States and China, underscoring the significant research synergy and cooperation between these two leading scientific powerhouses. This extensive collaboration reflects their dominant influence and active engagement in advancing global research in the field.

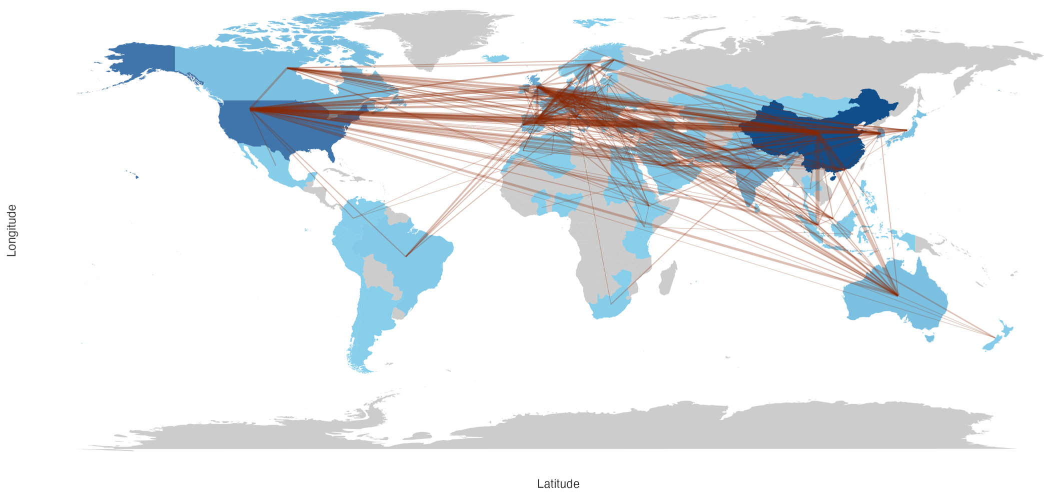

Figure 4.3: Country Collaboration Map in the field of Smart Textiles.

To provide a clearer understanding, Table 4.6 presents the frequency of the top ten most frequent international research collaborations. As previously mentioned, the collaboration between China and the United States ranks first, with a frequency of 190 instances. This is followed by the partnership between China and Hong Kong, with 105 instances, and the collaboration between China and the United Kingdom, with 85 instances.

Table 4.7: Top 10 Most Productive Authors and their Affiliations.

Author	Number of articles	Current Institution
Beeby, S.	100	University of Southampton (U.K.)
Wang, Z.L.	86	Chinese Academy of Sciences (China)
Torah, R.	68	University of Southampton (U.K.)
Koncar, V.	62	ENSAIT Ecole Nationale Supérieure des Arts et Industries Textiles (France)
Van Langenhove, L.	55	Universiteit Gent (Belgium)
Tudor, J.	54	University of Southampton (U.K.)
Wagih, M.	47	University of Glasgow (Scotland)
Kafai, Y.B.	46	University of Pennsylvania (U.S.A.)
Virkki, J.	45	Tampere University (Finland)
De Rossi, D.	44	Università di Pisa (Italy)

4.4 Analysis of Authors

The top contributors in the field of Smart Textiles (seen in Table 4.7), as identified by the number of publications, highlight significant research activity from various leading institutions. Stephen Beeby, with 100 articles, is the most prolific author and is affiliated with the University of Southampton. Zhong Lin Wang, with 86 publications, represents the Chinese Academy of Sciences, underscoring China's significant contributions to the field. Russel N. Torah, also from the University of Southampton, with 68 articles, further emphasizes this university's role as a major hub for Smart Textiles research. And Vladan Koncar, affiliated with ENSAIT (Ecole Nationale Supérieure des Arts et Industries Textiles), has 62 publications, showcasing contributions from French institutions. Other notable contributors include Lieva Van Langenhove from Universiteit Gent (55 articles), M. John Tudor from the University of Southampton (54 articles)and Wagih, M. from the University of Glasgow (47 articles).

4.5 Analysis of Sources

Table 4.8 lists the top 10 publication sources of Smart Textiles researches. The top 3 sources are ACS applied materials & interfaces (204), Textile Reseach Journal (196) and Proceedings of SPIE - The International Society for Optical Engineering (107) tied with Sensors for third place, which are all journals. The top 10 publication sources are diversified in their disciplines, which includes not only just materials science, chemical engineering and mathematics, but also computer science, physics and chemistry and multi-discipline publications.

Table 4.8: Most relevant sources in Smart Textiles (by number of articles published).

Sources	Articles
ACS APPLIED MATERIALS AND INTERFACES	204
TEXTILE RESEARCH JOURNAL	196
PROCEEDINGS OF SPIE - THE INTERNATIONAL SOCIETY FOR OPTICAL ENGINEERING	107
SENSORS (SWITZERLAND)	107
JOURNAL OF THE TEXTILE INSTITUTE	105
FIBERS AND POLYMERS	102
PROCEEDINGS - INTERNATIONAL SYMPOSIUM ON WEARABLE COMPUTERS, ISWC	98
POLYMERS	88
CONFERENCE ON HUMAN FACTORS IN COMPUTING SYSTEMS - PROCEEDINGS	87
IEEE SENSORS JOURNAL	87

4.6 Analysis of Subjects

The research domains of materials science (22.4%), engineering (21.9%), and computer science (11.4%) are the top research domains of Smart Textiles research.

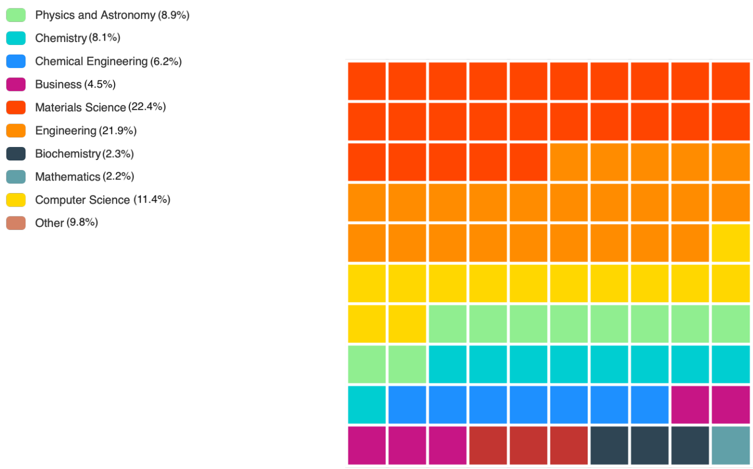

Figure 4.4: Most relevant sources in Smart Textiles (by number of articles published).

Materials Science focuses on the development and characterization of new materials, such as fibers, polymers, and nanocomposites, that can be integrated with electronic components. This area is crucial for advancing the fundamental properties and functionalities of smart textiles. Engineering is integral to the design and manufacturing of smart textiles, encompassing the integration of sensors, actuators, and electronic systems into textile materials, as well as the innovation of new fabrication techniques. Computer Science highlights the importance of software development, data processing, and the creation of algorithms necessary for smart textile applications. This includes developing wearable computing systems and processing data collected from textile-based sensors.

4.7 Analysis of Publication Type

Figure 4.5 illustrates the distribution of publication types within the collected data. Among all records, articles account for 62.4% (5820), followed by conference papers at 29.6% (2760). The remaining publications consist of reviews (6.5%, 606) and conference reviews (1.5%, 139).

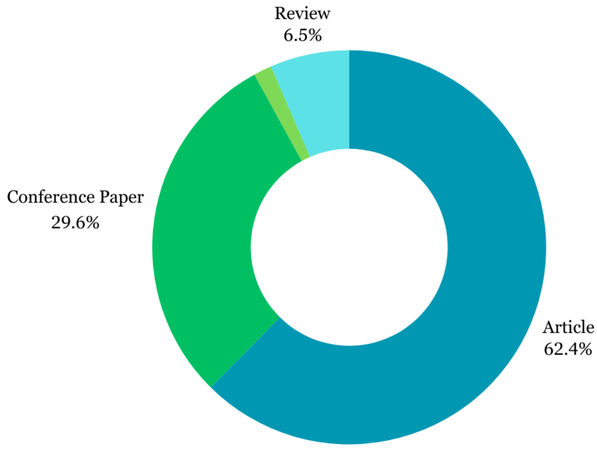

Figure 4.5: Most relevant sources in Smart Textiles (by number of articles published).

4.8 Analysis of Keywords

4.8.1 Analysis of High-Frequency Keywords

Keywords reflect the core focus and themes of research articles, providing insights into the prevalent trends and priorities of the scientific community. By examining the frequency and context of these keywords, we can discern which aspects of smart textiles are receiving the most attention, such as specific technologies, applications, or materials. Keywords Plus has been chosen for this thesis over Author Keywords due to its ability to capture an article's content with greater depth and variety. Generated by an automatic computer algorithm, Keywords Plus provides a more comprehensive view of the research landscape, enabling a richer and more nuanced analysis (J. Zhang et al., 2016). The most frequently used keywords are '*smart textiles*', appearing 2691 times, '*textiles*', with 2511 occurrences, and '*wearable technology*' with 1170 occurrences. These terms are general descriptors for the field of smart textiles. Some other frequent keywords are yarn, fibers and cotton which represent the fundamental building blocks of textile materials. These elements are crucial in the development and functionality of smart textiles. Yarn and fibers are essential components in creating fabric structures that integrate smart technologies, while cotton, as a widely used natural fiber, offers unique properties and advantages in smart textile applications (Dias, 2015).

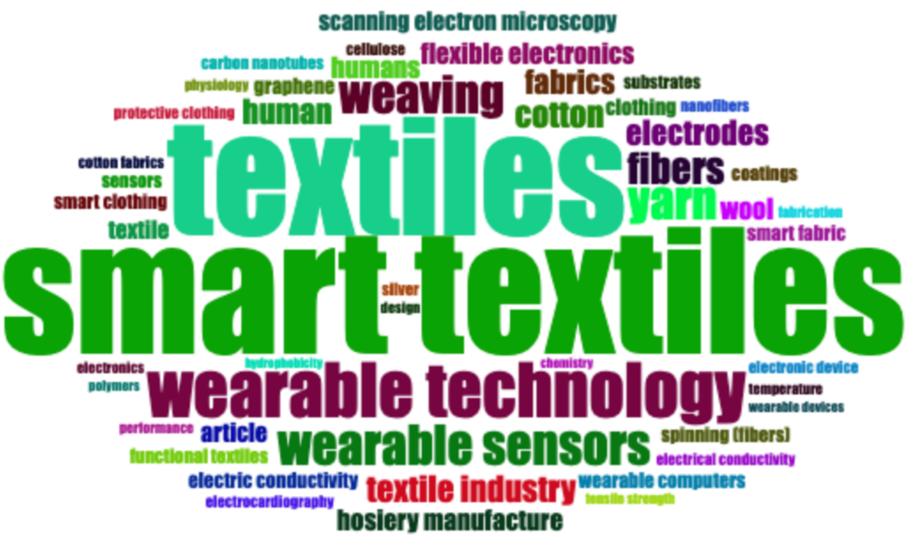

Figure 4.6: Most common keywords in the field of Smart Textiles.

It is crucial to analyze the evolution of keywords over time to understand the shifts in research focus and emerging trends 4.7. For this purpose, I have categorized the most prevalent keywords into three distinct periods: 1980-2000, 2000-2010, and 2010-2023. This temporal division allows us to examine the progression and transformation of keywords across these intervals, thereby highlighting the changing landscape of the research field. To enhance the accuracy of the analysis, a CSV (Comma Separated Values) file was created containing keywords and their synonyms, such as plurals or similar words, to filter out redundant terms. The overall trend of the field can be seen in Figure 4.7. There is a noticeable increase in the frequency of all terms starting around the early 2000s, which continues to rise steeply towards 2023. This indicates a growing interest and research activity in the field of smart textiles. The steep rise in the frequency of high-tech terms such as '*smart textiles*', '*wearable sensors*', and '*wearable technology*' post-2010 highlights a significant shift towards integrating advanced technologies within textiles. On the other hand, the sustained but slower growth of traditional textile terms ('*cotton*', '*weaving*', '*yarn*') suggests that while foundational materials and techniques remain important, the focus of research is increasingly on innovation and integration of new technologies.

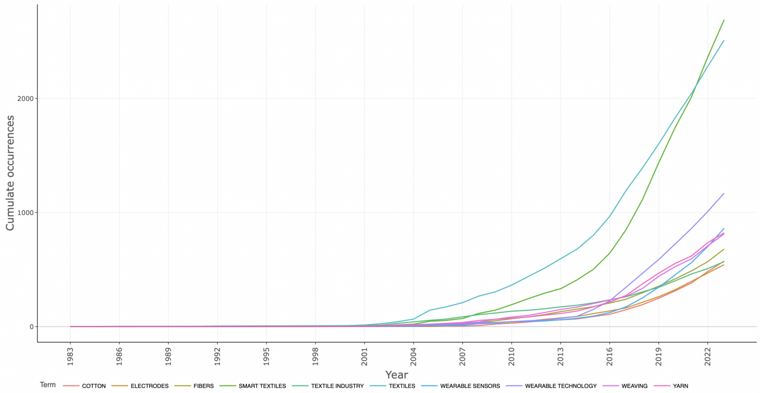

Figure 4.7: Evolution of the most common keywords in the field of Smart Textiles.

4.8.1.1 Most common keywords from 1980 until 2000

The keywords from 1980 to 2000 highlight a foundational period in smart textiles research, with a balanced focus on human interaction, material science, and technological integration. The keyword '*human*' appears most frequently (6%), indicating a significant focus on human-related aspects, encompassing studies on how smart textiles interact with and impact human users. '*Clothing*' (5%) is also prominent, reflecting the core focus of the field on wearable textiles and garments. Additionally, '*fabrics*' (4%) is a crucial term, underscoring the importance of material science in the development of smart textiles. There is also a clear emphasis on developing smart textiles for practical applications, such as sportswear, medical textiles, and protective clothing (seen in the keywords '*sportswear*', '*technical textiles*' and '*medical textile*'), while also considering user comfort and demographic-specific needs.

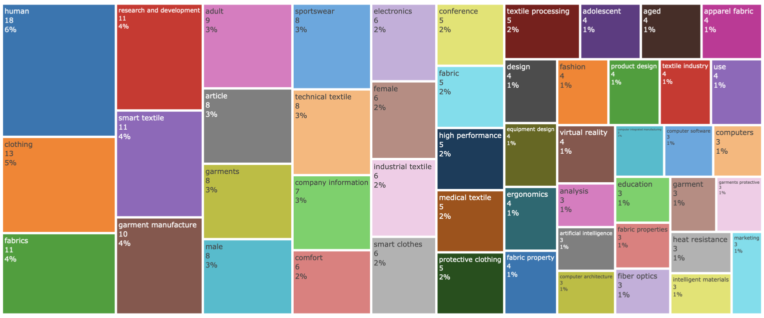

Figure 4.8: Most common keywords between the years of 1980 and 2000 in the field of Smart Textiles.

4.8.1.2 Most common keywords from 2000 until 2010

Apart from the reoccurring words '*smart textile*', '*fabric*' and '*smart fabric*', there are keywords such as 'nanotechnology', 'fibers' and 'telemedicine' which indicate an interdisciplinary approach, combining materials science, healthcare, and advanced technologies. The presence of terms like '*sensors*' (128 occurrences), '*electronics*' (102 occurrences), and '*equipment design*' (67 occurrences) points to the integration of electronic components into textiles. Keywords such as '*methodology*', '*article*' and '*research and development*' reflect a focus on advancing the research process itself where the smart textiles field started to be studied.

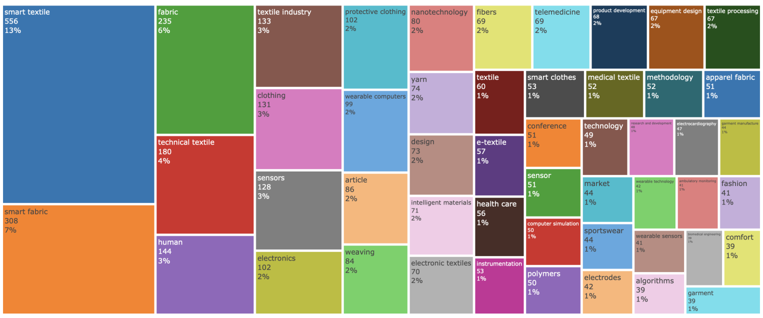

Figure 4.9: Most common keywords between the years of 2000 and 2010 in the field of Smart Textiles.

4.8.1.3 Most common keywords from 2010 until 2023

In recent years, the same key terms persist. Some changes can be seen in the diversity of keywords such as '*scanning electron microscopy*' (381 mentions, 2%), '*electric conductivity*' (311 mentions, 1%), '*hydrophobicity*' (205 mentions, 1%), and '*energy harvesting*' (206 mentions, 1%) highlights a broad spectrum of research areas, from material properties to energy-related applications. Furthermore, the inclusion of keywords like '*electrocardiography*' (218 mentions, 1%), and 'physiology' (210 mentions, 1%) indicates that the focus on biomedical applications has been constant through the years. The importance of the foundational components and manufacturing techniques are also a recurring theme with terms such as '*yarn*' and '*weaving*'.

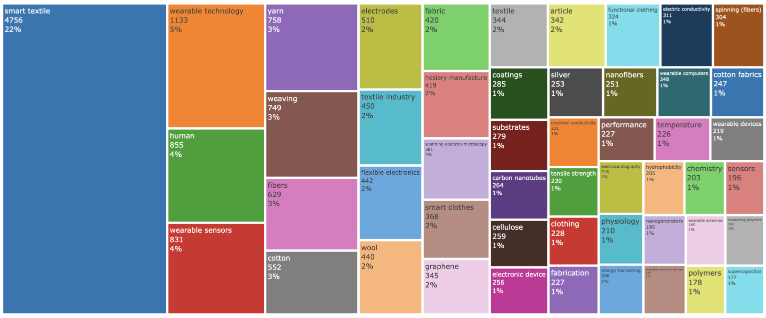

Figure 4.10: Most common keywords between the years of 2010 and 2023 in the field of Smart Textiles.

4.8.2 Co-word Analysis

In 1983, Michelle Cullen introduced the concept of co-word analysis. This method involves measuring the strength of associations by counting the number of times different subject words or keywords co-occur. Specifically, it entails calculating the co-occurrence frequency of these terms within a set of texts, constructing a co-occurrence matrix, and performing distance statistics and network analysis to interpret the relationships (Callon et al., 1983). By using co-word analysis it is possible to find connections between the different topics and better understand the research field. A total of 42891 keywords identified by VOSViewer were used for the co-occurrence analysis of the keywords. When using a minimum of 5 occurrences, a total of 4658 keywords were identified but for a more interpretable graph the limit of occurrences was changed to 10 and the result of 335 keywords can be seen in image 4.11.

Figure 4.11 presents the distribution of keywords according to Average Publication Year (APY), which indicates the average publication year of the documents in which a keyword occurs (van Eck & Waltman, 2018). The lighter the color of the keywords, the more recent their average year of appearance, indicating that they represent more contemporary topics. Early research topics included passive textiles such as '*thermal comfort*' and '*protective clothing*', as well as active textiles like '*healthcare monitoring*'. The appearance of the term '*fashion*' suggests that some early smart textiles were designed primarily for visual appeal, such as the animated sweatshirt created by Md Raihan Hossain and Alam, 2023. At the center of the network is the keyword '*smart textiles*', which is unsurprising given its central role in the field. This is accompanied by other general terms like '*textile*', '*e-textile*', and '*smart garment*'. More recent topics, which may indicate future trends in the field, are represented by keywords in yellow. These include '*fiber electronics*', '*self-healing*', '*liquid metal*', among others. These keywords represent

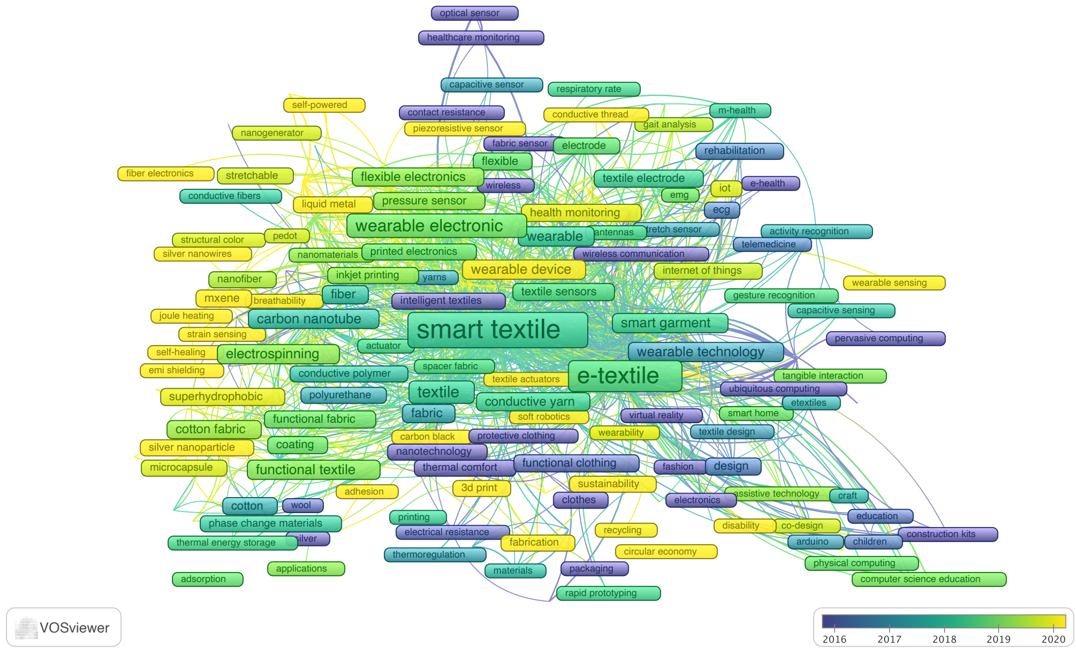

Figure 4.11: Co-word association of keywords in the field of Smart Textiles.

more advanced technologies that have emerged in recent years, reflecting the evolving complexity and innovation within the field of smart textiles.

4.8.3 Analysis of Keyword Clusters

The map in figure 4.12 presents a detailed visualization of keyword co-occurrence in the field of smart textiles, highlighting the relationships and common themes within the research literature. To enhance the comprehensibility of the graph, the minimum occurrence threshold for keywords was set to 110. This resulted in the identification of 131 keywords, which were subsequently organized into 5 distinct clusters. The map is divided into several clusters, each representing different areas of focus within the field.

4.8.3.1 Green Cluster: Smart Textile Applications and Technologies

The green cluster predominantly focuses on the applications of smart textiles, particularly in wearable technology and healthcare. Keywords such as ‘smart textile’, ‘wearable technology’, ‘e-textile’, ‘textile sensors’, ‘smart clothes’, ‘smart garment’, ‘wearable computing’, ‘health monitoring’ and ‘physiology’ indicate significant interest in integrating textiles with electronic devices. This cluster reflects the core of smart textiles research, emphasizing the development and utilization of intelligent fabrics in practical, wearable solutions.

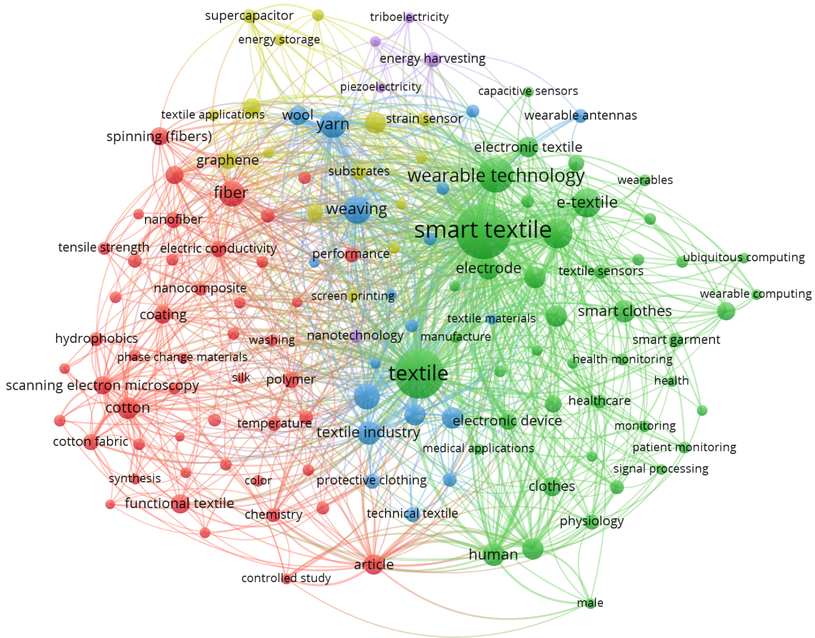

Figure 4.12: Keyword Clusters in the field of Smart Textiles.

4.8.3.2 Red Cluster: Materials and Fabrication

The red cluster is centered around the materials science aspect of smart textiles. Keywords such as ‘fiber’, ‘nanofiber’, ‘tensile strength’, ‘nanocomposite’, ‘cotton’, ‘functional textile’ and ‘synthesis’ suggest a focus on the development and characterization of fibers and nanocomposites. These materials are fundamental to creating advanced textiles. The presence of terms like ‘tensile strength’ and ‘scanning electron microscopy’ indicates an emphasis on the mechanical properties and microscopic analysis of these materials.

4.8.3.3 Blue Cluster: Traditional Textile Techniques and Integration

The blue cluster highlights traditional textile techniques and their integration into smart textiles. Keywords such as ‘wool’, ‘yarn’, ‘weaving’, ‘performance’ and ‘protective clothing’ indicate the use of conventional textile manufacturing methods.

4.8.3.4 Yellow Cluster: Energy and Functionalization

The yellow cluster focuses on the energy aspects and functionalization of smart textiles. Keywords such as ‘supercapacitor’, ‘energy storage’ and ‘strain sensor’ point towards research on energy storage solutions and methods for energy harvesting. These functionalities are crucial for powering smart textiles and integrating advanced electronic capabilities. Techniques like 'screen printing' suggest methods for embedding functionalities onto textiles.

4.8.3.5 Purple Cluster: Niche Applications and Specific Technologies

The small purple cluster represents niche applications and specific technologies within smart textiles. Keywords such as 'triboelectricity', 'nano technology', 'energy harvesting' and 'piezoeletricity' highlight specialized research areas. This cluster underscores the innovative use of smart textiles in unique applications and the development of specialized technologies that enhance the functionality and performance of smart textiles.

4.8.3.6 Overall Cluster Analysis

The network of keywords and their interconnections provide a comprehensive overview of the current research landscape in smart textiles. The clusters highlight the multidisciplinary nature of the field, involving materials science, traditional textile techniques, and advanced applications in wearable technology and healthcare. The visualization also indicates areas of significant research activity and emerging trends. For instance, the emphasis on healthcare applications and energy harvesting methods suggests a growing interest in creating sustainable and health-oriented smart textile solutions.

4.9 Analysis of Trend Topics

In Figure 4.13, the progression of research articles over time is depicted through the analysis of keywords. The timeline from 1987 to 2023 shows the evolution and increasing complexity of the field.

Initially, research concentrated on basic textile applications and properties as can be seen by the trend topic '*garments*' which represents the starting point of smart textile research. Terms like '*eletronics*' and '*smart clothing*' span over many years showing the foundational importance of these topics in the evolution of smart textiles. The term '*protective clothing*' consistently appears throughout the timeline, indicating the emergence of a new breed of 'smart' garments. These innovative textiles are characterized by the integration of wearable sensors and electronics, including sophisticated features like textile antennas (Curone et al., 2007; Hertleer et al., 2007). This evolution underscores a shift towards functional textiles designed not only for comfort and aesthetics but also for enhanced safety and performance in various environments. However, the most crucial insight obtained from this graph are the latest trend topics and their implications for future research. To further understand these trends, the focus will be on analyzing the top five terms from 2023 and 2022. These terms are particularly significant for future trend analysis, as they represent the cutting-edge developments and directions in the field.

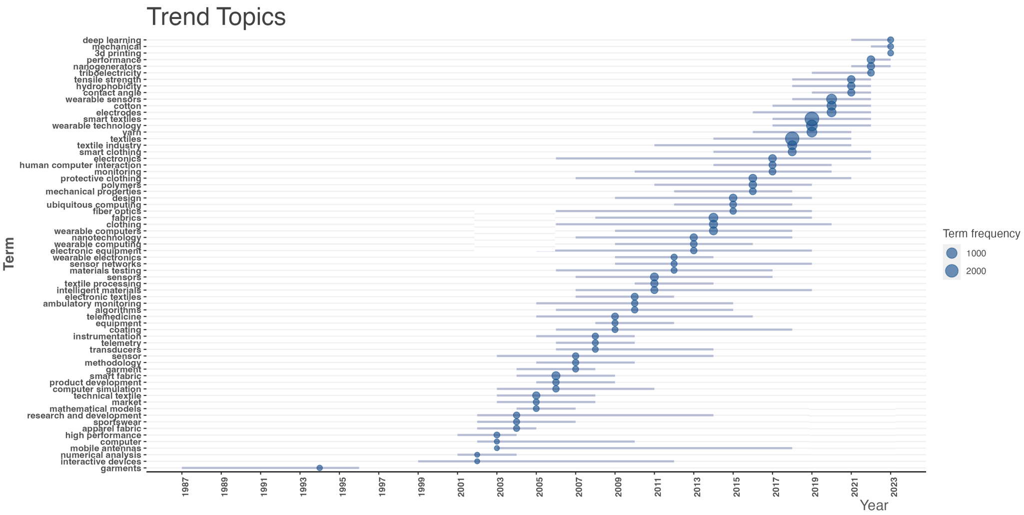

Figure 4.13: Trend topics by year in the field of Smart Textiles.

Deep Learning signifies the growing importance of artificial intelligence and machine learning in textile research, as can be observed in many other industries where deep learning is becoming dominant (Akinosho et al., 2020; Lilhore et al., 2021). Deep learning algorithms integrated with textile sensors enhance sensing capabilities by analyzing complex data patterns, improving recognition of signals like pressure, proximity, and temperature. Additionally, deep learning enables object recognition and classification based on sensor data, allowing smart textiles to identify shapes, patterns, and movements for applications in gesture recognition, sign language translation, and object detection (Zhao et al., 2023). Deep learning also optimizes energy harvesting from body motions, enhances data privacy and security, and opens up possibilities for personalized healthcare solutions (Z. Zhang et al., 2020).

Mechanical refers to the study and enhancement of the physical properties and behavior of textile materials. This includes ensuring durability and strength, maintaining flexibility and comfort while integrating electronic components, and the seamless incorporation of mechanical elements such as sensors and actuators (Di et al., 2016; Guo et al., 2016; Persson et al., 2018b; Yin et al., 2024).

3D Printing technology plays a crucial role in the development and advancement of smart textiles. By integrating 3D printing with smart textiles, innovative solutions are created that combine functionality, customization, and design. This technology can be used to add functional elements to smart textiles, such as creating stretchable fibers with tactile sensors, energy collection capabilities, and intelligent patterns on clothing textiles (Wu et al., 2022). This innovative technique addresses the common shortcomings of traditional smart textiles, such as complex preparation processes and rigid structures, by offering a more streamlined and flexible approach. By developing stretchable elastic fibers with a coaxial core-sheath structure, 3D printing facilitates the integration of conductive and insulative materials, enhancing the mechanical properties and functionality of the textiles (Y. Chen et al., 2021; Eutionnat-Diffo et al., 2020).

Performance refers to the enhanced functional capabilities that these advanced fabrics can provide like responsiveness, durability and functionality. There are numerous examples highlighted in the study, such as smart e-textiles designed for biomedical applications. These advanced textiles offer various functional capabilities that allow them to monitor and enhance healthcare. They can track vital signs and activities, providing real-time data to healthcare professionals and users. Additionally, sensors have been incorporated to detect various physiological parameters, including heart rate, temperature, motion, and muscle activity (Cesarelli et al., n.d.).

Nanogenerator is a term used to describe a small electronic chip that can generate electricity from the mechanical movements of the body (Alam et al., 2023). With the support of these lightweight, self-sufficient wearable intelligent systems, individuals can easily acquire and efficiently utilize electrical energy. This will pave the way for future advancements in artificial intelligence and human-centric wearable electronics (Dong et al., 2021, 2022). The integration of nanogenerators into smart textiles paves the way for a new class of self-sustaining wearable devices that can continuously monitor and interact with the environment and the wearer's body.

5 Conclusion

5.1 Summary

The objective was to provide a comprehensive overview of the research conducted in the field of Smart Textiles from 1980 to 2023. Through multiple rounds of searching and screening, the most prolific countries, authors, sources and affiliations in this field were identified. The key takeaways are:

1. **Trends in Publications**: The progression of Smart Textiles research has evolved through distinct stages. From 1982 to 1998, publication numbers were low and stable, indicating limited interest in the field. From 1998 to 2014, there was a gradual increase in publications, reflecting growing interest and advancements. The period from 2014 to 2018 saw significant growth, and since 2018, there has been an exponential rise in publications, culminating in a peak by 2023. Recent years have seen the highest number of publications, indicating increased attention and rapid development in this field.

2. **Global Distribution**: Research outputs are mainly concentrated in Asia and North America, with China at the forefront with 2,197 publications, followed by the United States with 1,614. Other notable contributors include the United Kingdom, South Korea, Germany, and India. Despite the high volume of research, cross-national collaborations, especially beyond the primary contributors, remain limited.

3. **Key Publication Sources**: Prominent journals and conference proceedings in the field include *ACS Applied Materials & Interfaces* (204 articles), *Textile Research Journal* (196 articles), and both *Proceedings of SPIE* and *Sensors* (107 articles each). These sources reflect the interdisciplinary nature of Smart Textiles, encompassing materials science, engineering, and applied physics.

4. **Major Collaborations**: The most significant international collaborations are between China and the United States, with additional notable partnerships involving Hong Kong and the United Kingdom. These collaborations highlight crucial

bilateral relationships essential for advancing Smart Textiles research.

5. **Leading Research Institutions**: Key institutions driving research include the Ministry of Education of the People's Republic of China, Donghua University, and Chinese Academy of Sciences. These institutions are central to innovation and research advancements in Smart Textiles.

6. **Clusters**: The keyword cluster analysis in the field of Smart Textiles identified five significant thematic groupings: Smart Textile Applications and Technologies, focusing on wearable technology and healthcare; Materials and Fabrication, emphasizing the development and characterization of advanced fibers and nanocomposites; Traditional Textile Techniques and Integration, highlighting the use of conventional manufacturing methods; Energy and Functionalization, centered on energy storage and harvesting solutions; and Niche Applications and Specific Technologies, representing innovative uses in specialized areas.

7. **Research Focus and Future Directions**: Frequently occurring keywords in Smart Textiles research include 'wearable technology', 'conductive textiles', and 'e-textiles'. Future research is expected to explore **new materials and technologies**, enhance the functionality and integration of smart textiles and address commercialization challenges. Given the growing interest in healthcare applications of smart textiles, further research could focus on developing advanced **healthcare monitoring systems** integrated into textiles. Also, according to the trend topics, research in smart textiles will likely focus on integrating artificial intelligence and machine learning, particularly through the application of **deep learning** to enhance functionality. Efforts to improve the mechanical properties of textiles will ensure durability and comfort while incorporating advanced electronic components. The use of **3D printing** will enable seamless integration of electronics, creating highly functional and innovative garments. Enhanced **performance** capabilities will be pursued for applications in sports, military, and healthcare, emphasizing advanced functionalities like thermal regulation and moisture management. The development of self-powered textiles using **nanogenerators** will be a key area, allowing energy harvesting from body movements to power embedded electronics.

In conclusion, this study provides a comprehensive overview of the Smart Textiles research landscape, highlighting key trends, contributors, and future research directions. The significant increase in publications, along with strong international collaborations and leading contributions from major institutions, underscores the dynamic and rapidly evolving nature of this field. Future research is likely to emphasize interdisciplinary approaches, innovative materials, and sustainable practices to advance the development and application of Smart Textiles.

5.2 Limitations

It is important to note some of the limitations faced in this study. Firstly, one notable limitation of this thesis is the exclusion of grey literature from the analysis. Grey literature, which includes documents such as reports, thesis, government publications, and other materials not formally published through traditional academic channels, can provide valuable insights and data that are often not captured in peer-reviewed journals. By not including grey literature, the study may overlook important findings and perspectives that could contribute to a more comprehensive understanding of the research topic. Secondly, the search query was created using words that are general and which may not identify all documents related to the topic. There can also be studies who were relevant but not included as they were not in the English language or in the other screening criteria chosen. Future research can expand the search scope to explore additional relevant studies, thereby enhancing the existing literature.

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Annex 1

The full search query used in Scopus.

(TITLE-ABS-KEY ("e textile") OR TITLE-ABS-KEY ("e textiles") OR TITLE-ABS-KEY ("e cloth") OR TITLE-ABS-KEY ("e clothes") OR TITLE-ABS-KEY ("e clothing") OR TITLE-ABS-KEY ("e fabric") OR TITLE-ABS-KEY ("e fabrics") OR TITLE-ABS-KEY ("e garment") OR TITLE-ABS-KEY ("e garments") OR TITLE-ABS-KEY ("e apparel") OR TITLE-ABS-KEY ("e thread") OR TITLE-ABS-KEY ("e threads")) OR (TITLE-ABS-KEY ("smart textile") OR TITLE-ABS-KEY ("smart textiles") OR TITLE-ABS-KEY ("smart cloth") OR TITLE-ABS-KEY ("smart clothes") OR TITLE-ABS-KEY ("smart clothing") OR TITLE-ABS-KEY ("smart fabric") OR TITLE-ABS-KEY ("smart fabrics") OR TITLE-ABS-KEY ("smart garment") OR TITLE-ABS-KEY ("smart garments") OR TITLE-ABS-KEY ("smart apparel") OR TITLE-ABS-KEY ("smart thread") OR TITLE-ABS-KEY ("smart threads")) OR (TITLE-ABS-KEY ("intelligent textile") OR TITLE-ABS-KEY ("intelligent textiles") OR TITLE-ABS-KEY ("intelligent cloth") OR TITLE-ABS-KEY ("intelligent clothes") OR TITLE-ABS-KEY ("intelligent clothing") OR TITLE-ABS-KEY ("intelligent fabric") OR TITLE-ABS-KEY ("intelligent fabrics") OR TITLE-ABS-KEY ("intelligent garment") OR TITLE-ABS-KEY ("intelligent garments") OR TITLE-ABS-KEY ("intelligent apparel") OR TITLE-ABS-KEY ("intelligent thread") OR TITLE-ABS-KEY ("intelligent threads")) OR (TITLE-ABS-KEY ("responsive textile") OR TITLE-ABS-KEY ("responsive textiles") OR TITLE-ABS-KEY ("responsive cloth") OR TITLE-ABS-KEY ("responsive clothes") OR TITLE-ABS-KEY ("responsive clothing") OR TITLE-ABS-KEY ("responsive fabric") OR TITLE-ABS-KEY ("responsive fabrics") OR TITLE-ABS-KEY ("responsive garment") OR TITLE-ABS-KEY ("responsive garments") OR TITLE-ABS-KEY ("responsive apparel") OR TITLE-ABS-KEY ("responsive thread") OR TITLE-ABS-KEY ("responsive threads")) OR (TITLE-ABS-KEY ("electronic textile") OR TITLE-ABS-KEY ("electronic textiles") OR TITLE-ABS-KEY ("electronic cloth") OR TITLE-ABS-KEY ("electronic clothes") OR TITLE-ABS-KEY ("electronic clothing") OR TITLE-ABS-KEY ("electronic fabric") OR TITLE-ABS-KEY ("electronic fabrics") OR TITLE-ABS-KEY ("electronic garment") OR TITLE-ABS-KEY ("electronic garments") OR TITLE-ABS-KEY ("electronic apparel"

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