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Review

Smart Textiles: A Review and Bibliometric Mapping

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Abstract: According to ISO/TR 23383, smart textiles reversibly interact with their environment and respond or adapt to changes in the environment. The present review and bibliometric analysis was performed on 5810 documents (1989–2022) from the Scopus database, using VOSviewer and Bibliometrix/Biblioshiny for science mapping. The results show that the field of smart textiles is highly interdisciplinary and dynamic, with an average growth rate of 22% and exponential growth in the last 10 years. Beeby, S.P., and Torah, R.N. have published the highest number of papers, while Wang, Z.L. has the highest number of citations. The leading journals are *Sensors*, *ACS Applied Materials and Interfaces*, and *Textile Research Journal*, while *Advanced Materials* has the highest number of citations. China is the country with the most publications and the most extensive cooperative relationships with other countries. Research on smart textiles is largely concerned with new materials and technologies, particularly in relation to electronic textiles. Recent research focuses on energy generation (triboelectric nanogenerators, thermoelectrics, Joule heating), conductive materials (MXenes, liquid metal, silver nanoparticles), sensors (strain sensors, self-powered sensors, gait analysis), speciality products (artificial muscles, soft robotics, EMI shielding), and advanced properties of smart textiles (self-powered, self-cleaning, washable, sustainable smart textiles).

Keywords: smart textiles; bibliometric analysis; science mapping; research trends; hotspots

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1. Introduction

1.1. Definition and Characteristics of Smart Textiles

The interdisciplinary research of textile technology with materials science, chemistry, physics, microelectronics, computer science, biomedicine, optics, and other technologies has led to the development of technologically advanced textiles and garments based on advanced smart materials [1,2]. The concept of intelligent or smart materials was defined in 1990 by Takagi [3] as "materials which respond to environmental changes at the most optimum conditions and manifest their own functions according to the changes". The same author set a clear differentiation of structural and functional materials versus intelligent materials.

Various definitions of smart textiles appear in the literature, and different terms have been used for similar textile products, such as smart textiles, smart fabrics, smart clothing, smart garments, as well as functional textiles, functional clothing, intelligent textiles, interactive textiles, etc. [1,4,5]. For instance, one definition of smart fabric from NASA [4] was "a traditional fabric with integrated active functionality". Some authors even equated the terms smart and functional textiles, such as "smart textiles or functional textiles are demarcated as textile constituents that are capable of changing their characteristic behaviour with response to the inspiration of peripheral features or technical stimuli from the surrounding environment" [6]. Meena et al. [7] defined smart textiles as fabrics derived from intelligent or responsive materials that sense stimuli and enable information transmission. However, most authors agreed that smart textiles can sense the environment (sensing function), act upon it (actuating function), and adapt their behaviour accordingly (adaptive function) [2,8] and that they have evolved from simpler to more complex over the three generations [2,8–10]:

- The first generation of smart textiles are referred to as **passive smart textiles**, with a sensing function only—their materials perceive external stimuli;
- The second generation is called **active smart textiles**, with an actuating function—they sense a stimulus from the environment and respond to it;
- The third generation is called **advanced**, **very smart**, or **ultra-smart textiles**—they perceive, respond, and adapt to changes in the environment.

In 2020, the terminology, technical definitions, categorisation, and applications of smart textile products were finally defined by the International Standard organisation. The Technical Report ISO/TR 23383 [11] provided a better understanding of new terms and a clear differentiation between functional and smart textiles. In functional textiles (Figure 1), the functionality is over and above the normal textile function, is pre-defined [12], and is added by means of material, composition, and construction of finishing [11]. Smart textiles (also named intelligent or interactive textiles) interact reversibly with their environments or respond/adapt to stimuli or changes in the environment (Figure 2) [11]. Examples of some specific relationships between environmental stimuli and corresponding response effects in smart textiles are presented in Figure 3.

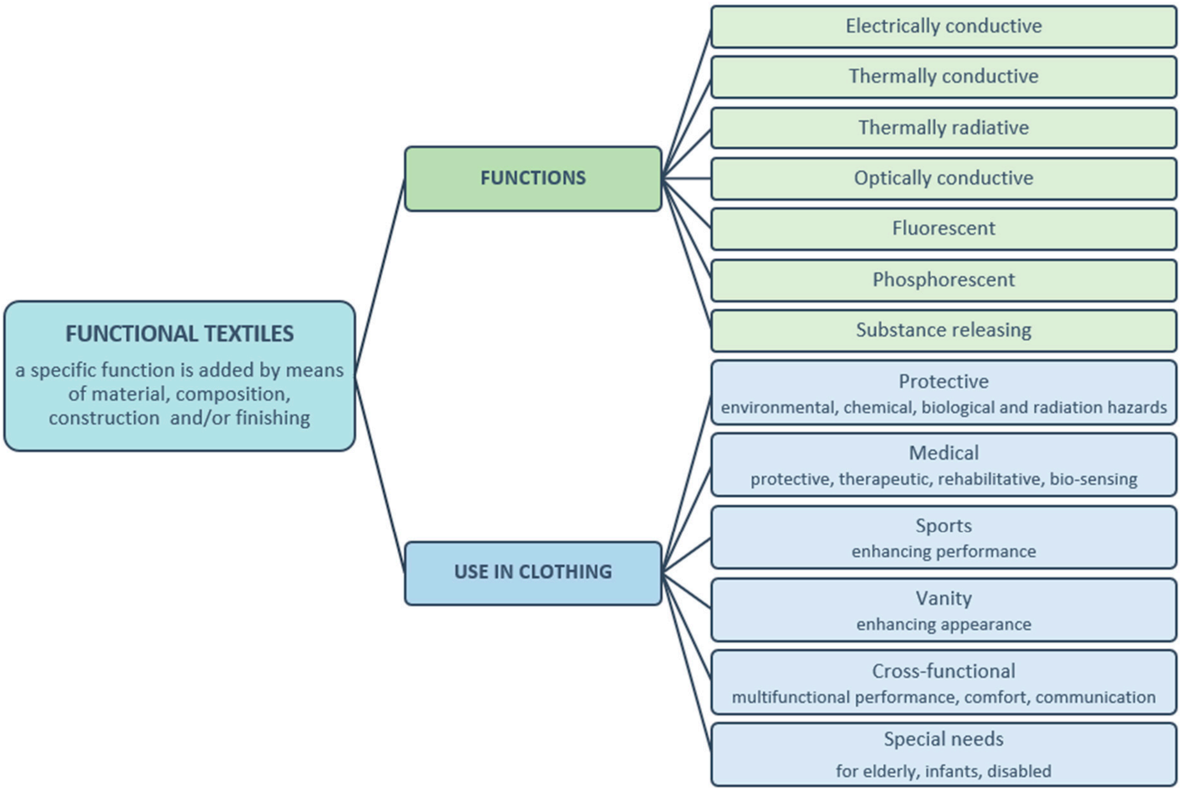
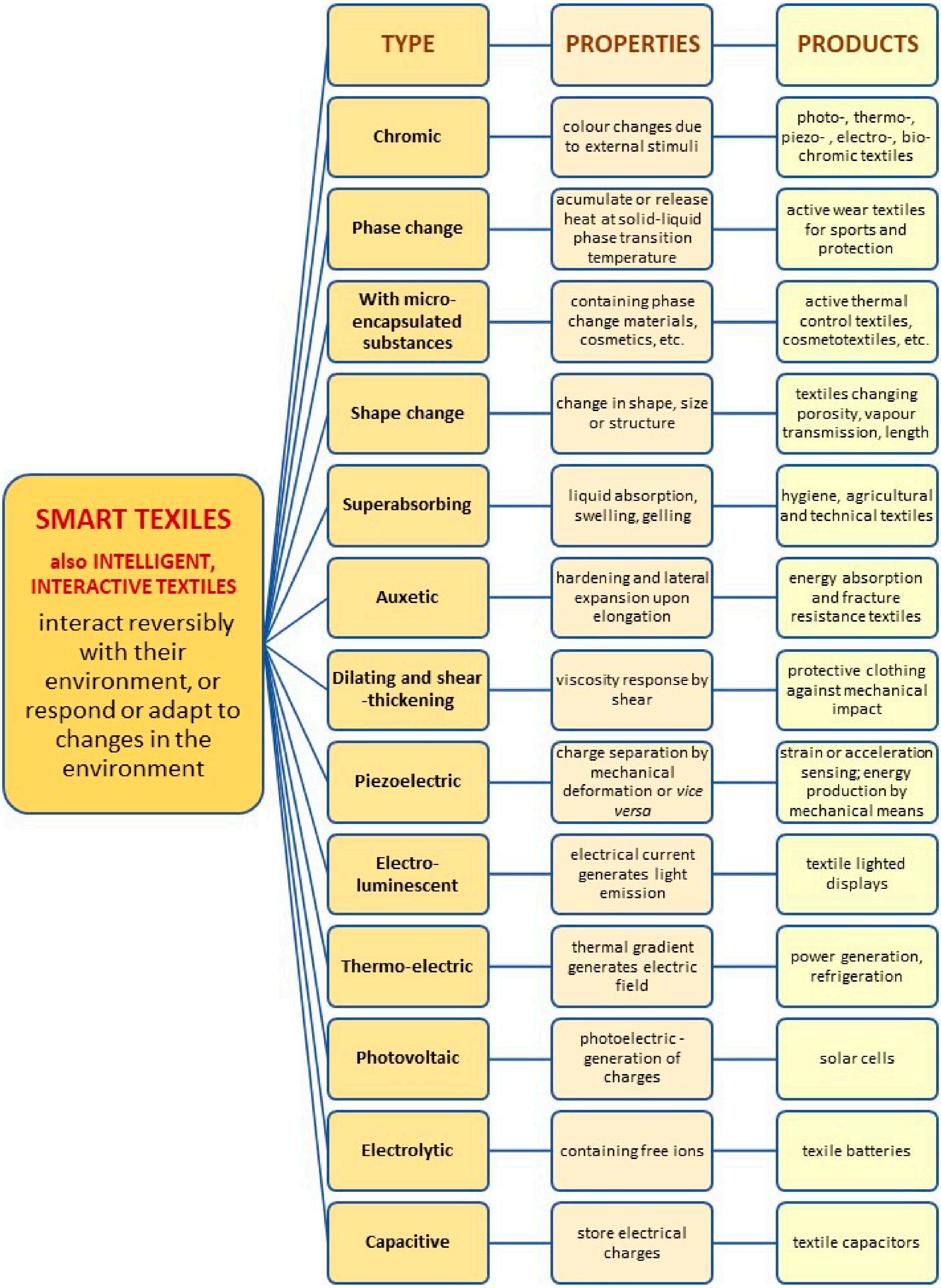


Figure 1. Functional textile products, data from [11,12].



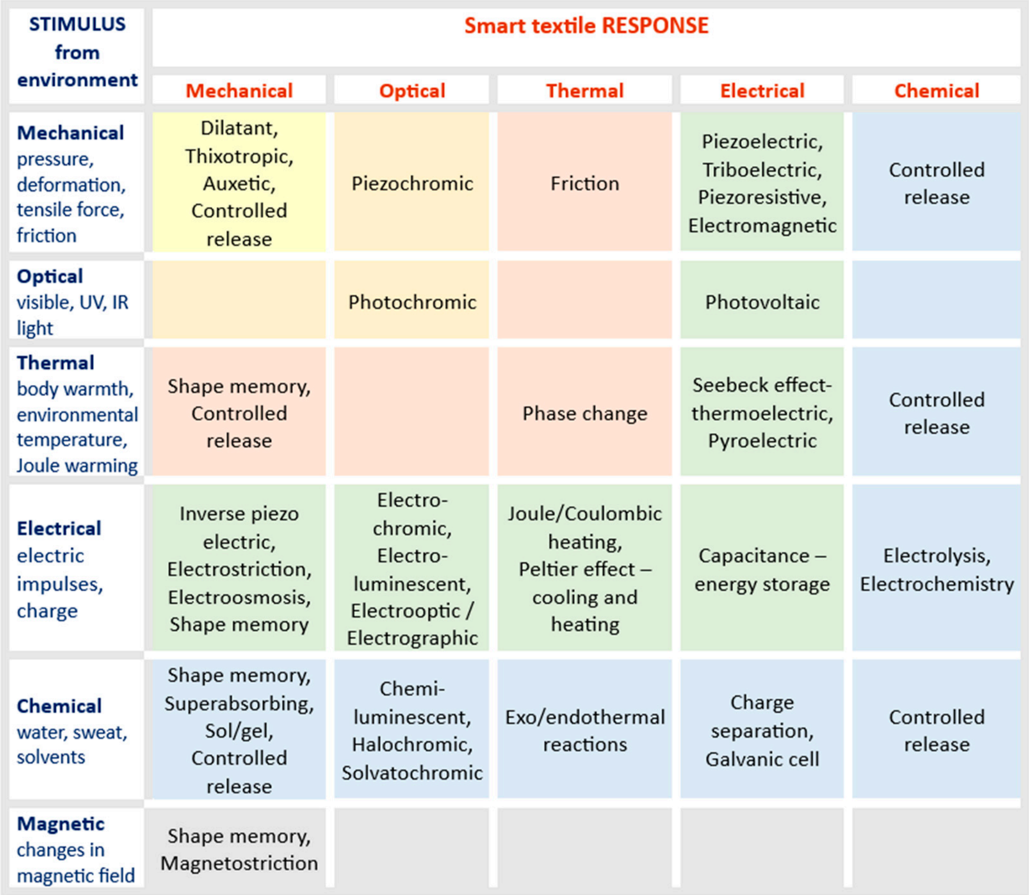
SMART TEXILES

also INTELLIGENT, INTERACTIVE TEXTILES

interact reversibly with their environment, or respond or adapt to changes in the environment

TYPE	PROPERTIES	PRODUCTS
Chromic	colour changes due to external stimuli	photo-, thermo-, piezo- , electro-, bio-chromic textiles
Phase change	acumulate or release heat at solid-liquid phase transition temperature	active wear textiles for sports and protection
With micro-encapsulated substances	containing phase change materials, cosmetics, etc.	active thermal control textiles, cosmetotextiles, etc.
Shape change	change in shape, size or structure	textiles changing porosity, vapour transmission, length
Superabsorbing	liquid absorption, swelling, gelling	hygiene, agricultural and technical textiles
Auxetic	hardening and lateral expansion upon elongation	energy absorption and fracture resistance textiles
Dilating and shear -thickening	viscosity response by shear	protective clothing against mechanical impact
Piezoelectric	charge separation by mechanical deformation or *vice versa*	strain or acceleration sensing; energy production by mechanical means
Electro-luminescent	electrical current generates light emission	textile lighted displays
Thermo-electric	thermal gradient generates electric field	power generation, refrigeration
Photovoltaic	photoelectric - generation of charges	solar cells
Electrolytic	containing free ions	texile batteries
Capacitive	store electrical charges	textile capacitors

Figure 2. Smart (intelligent) textile types, properties, and products as described by technical report ISO/TR 23383, data from [11].



STIMULUS from environment	**Smart textile RESPONSE**				
	Mechanical	**Optical**	**Thermal**	**Electrical**	**Chemical**
Mechanical pressure, deformation, tensile force, friction	Dilatant, Thixotropic, Auxetic, Controlled release	Piezochromic	Friction	Piezoelectric, Triboelectric, Piezoresistive, Electromagnetic	Controlled release
Optical visible, UV, IR light		Photochromic		Photovoltaic	
Thermal body warmth, environmental temperature, Joule warming	Shape memory, Controlled release		Phase change	Seebeck effect-thermoelectric, Pyroelectric	Controlled release
Electrical electric impulses, charge	Inverse piezo electric, Electrostriction, Electroosmosis, Shape memory	Electro-chromic, Electro-luminescent, Electrooptic / Electrographic	Joule/Coulombic heating, Peltier effect – cooling and heating	Capacitance – energy storage	Electrolysis, Electrochemistry
Chemical water, sweat, solvents	Shape memory, Superabsorbing, Sol/gel, Controlled release	Chemi-luminescent, Halochromic, Solvatochromic	Exo/endothermal reactions	Charge separation, Galvanic cell	Controlled release
Magnetic changes in magnetic field	Shape memory, Magnetostriction				

Figure 3. Examples of stimulus–response effects in smart textiles, data from [1,11,13].

Two aspects need to be considered when designing smart textiles: the selection of a suitable smart material and the technology to incorporate the smart material into the textile structure, e.g., by braiding, chemical treatments, coating/laminating, embroidering, knitting, printing, sewing, spinning, or weaving [2]. Smart textiles enable specific functions and applications, such as in clothing and/or technical textiles (thermal insulation, barrier properties, signal sensing, monitoring, displaying, energy generation, energy storage, responsive actuating, leak detection, self-repairing, self-cleaning, treatment), security (identification, monitoring, data processing, localisation), and decoration (changes in colour, luminance, transparency, morphology, shape; light emission), etc. [1,8,14,15]. Major sectors of smart textiles applications include military and security, aerospace, environmental engineering, industrial protective clothing, biomedical and healthcare, cosmetics, sports and fitness, vehicle safety and comfort, fashion and entertainment, computing and electronics, buildings and interiors, and others [1,2].

According to the International Market Analysis Research and Consulting Group [16], the global market for smart textiles reached the amount of USD 3.8 billion in 2022. Experts predict that the market will reach USD 15.9 billion by 2028, with a compound annual growth rate of 24.6% between 2023 and 2028. Due to the ageing population on a global scale, the development and deployment of smart textiles in the medical sector is promising, as people proactively take care of their own health.

1.2. Related Works

1.2.1. Reviews on Smart Textiles

Due to the vast area of smart textiles, only a few publications provided reviews on the entire field of smart textiles [17]. Most reviews have been limited to certain aspects of smart textiles, e.g., on **production methods** [18–20], **applications** [20,21] of specific

materials, such as nanomaterials [9,10,22,23], fibre optics [24], piezofibres [25], actuator materials [26,27], phase change materials (PCMs) [28], $Ti_3C_2T_x$-based MXenes [7], and perovskite materials [29], used specifically in smart textiles. Other review articles have been devoted to selected **application areas** of smart textiles. In **medicine and healthcare**, reviews have covered smart textiles in health [30], for monitoring health/physiological parameters [31–34], for personalized healthcare [13], healthcare and sustainability [35], and smart textiles in relation to the COVID-19 pandemic [36,37]. In the **electronics** domain, reviews have been published on electrically conductive textiles [38], smart textiles for electricity generation [39], energy harvesting materials and structures for smart textiles [40], smart textile triboelectric nanogenerators [15,41,42], smart electronics-based textiles [43,44], smart textiles in relation to wearable electronics [45–48]. Other reviews have presented smart textiles for personalized **thermoregulation** [49], **protection** [50], visible and IR **camouflage** [51], and **chromic** smart textiles [52].

1.2.2. Bibliometric Mapping in the Field of Textiles

Bibliometric analysis is a useful tool for searching the intellectual structure of a specific research area, for dealing with large amounts of scientific data, and for producing high-impact research papers.

Only a few bibliometric mapping studies have been published in the domain of functional/smart textiles. A research article by Liu et al. [2] presented a bibliometric study and mapping in the area of **smart textiles** based on 2647 papers collected from the Web of Science core collection database, time span 1996–2021. The study was conducted using a search query "smart textile", and CiteSpace software was applied for information visualisation and mapping. For **functional clothing**, Li et al. [53] conducted a bibliometric analysis and mapping of a set of 4153 literature sources from the Web of Science Core Collection database using the CiteSpace tool. De-la-Fuente-Robles et al. [54] studied **wearable technologies for healthcare** and performed a bibliometric analysis and mapping of 600 original articles and reviews from the Scopus database using the VOSviewer tool. Popescu and Ungureanu [23] reviewed green nanomaterials for smart textiles dedicated to environmental and biomedical applications and used VOSviewer to present a map of data extracted from the Web of Science database. Tian et al. [55] performed knowledge mapping of **protective clothing** research over the last 20 years on 1735 articles from the Web of Science using the visualisation software CiteSpace combined with Google Earth. Halepoto et al. [56] analyzed 2898 articles regarding **antibacterial textiles** obtained from the Web of Science Core Collection, published from 1998 to 2022. Bibliometrix sub-tool Biblioshiny was applied to conduct the performance and science mapping analyses. Bataglini et al. [57] focussed on a narrow field of **3D printing** technology applied in the textile industry using SciMAT (Science Mapping Analysis Tool) software.

1.3. Aims and Research Questions

The scientific research literature on smart textiles and related products has become very extensive, but it is fragmented, scattered, and difficult to manage and track. Due to the rapid development of materials, technologies, products, and applications in the field of smart textiles, as well as the diverse and still inconsistently used terminology, we aimed to investigate the field using bibliometric methods and mapping and to interpret the results in accordance with the terminology introduced by ISO, which distinguishes between functional and smart textiles. Specifically, the goal of the research was to conduct a publication analysis and visualise the structure of the smart textiles field through mapping in order to answer the following research questions:

- RQ1: What are the global research outputs and publication trends?
- RQ2: What are the most relevant/influential documents, authors, sources, and countries in the field of smart textiles?
- RQ3: What have been the main research topics, and what might be the focal points for future research?

- RQ4: What is the pattern of scientific collaboration on smart textiles at the country level?

2. Materials and Methods

Bibliometric analysis is one of the three major review methods besides meta-analysis and systematic literature review [58]. Two types of bibliometric techniques can usually be used for bibliometric analysis: performance analysis and science mapping analysis (SMA) [59–62]. Performance analysis is descriptive in nature and is used to evaluate the contributions of different scientific actors/research constituents, such as researchers, institutions, countries, etc., based on publications and citation data [63–65]. Performance analysis is widely used because its metrics are easy to understand and can be calculated for each research component either as an aggregate (per research component, e.g., documents, authors, institutions, countries, sources) or specifically (e.g., research component per publication, per year, or per period) [59]. On the other hand, science mapping or bibliometric mapping examines the relationships between research constituents [60,64–67]; it aims to visually represent and show the conceptual, social, or intellectual structures of scientific research, as well as its evolution, development, and dynamics [67–70] using citation analysis, co-citation analysis, bibliographic coupling, co-word analysis, and co-authorship analysis. Science maps are usually generated based on the analysis of large collections of scientific documents, and the construction of a science map follows a general workflow described by [68,71–73].

This study follows the science mapping methodology previously implemented in other bibliometric analyses [59,70,74–78]. In the first phase of the bibliometric analysis, a preliminary literature search and analysis of documents was conducted that identified themes and keywords of the research topic [1,5,11]. Keywords were selected based on the terminology defined in the standard ISO/TR 23383 [11] and the most frequently used terms in the literature, including their various forms and synonyms. The terms selected to extract the document sample for the bibliometric analysis and used in the search query were (smart or intelligent or interactive) in combinations with (cloth or clothes or clothing or textile or textiles or garment or garments or apparel or apparels or fabric or fabrics).

Phrase searching (keywords between quotation marks) was conducted using the Boolean operator OR between search terms. Initial searches were conducted in the Scopus and Web of Science (WoS) databases, using the TITLE-ABS-KEY search fields (based on title, abstract, and keywords) in Scopus and the TS–topic search (based on title, abstract, keywords, and keywords plus) in the WoS database. An example of a search query in the Scopus database is:

((TITLE-ABS-KEY (“smart fabrics”)) OR (TITLE-ABS-KEY (“smart fabric”)) OR (TITLE-ABS-KEY (“smart apparels”)) OR (TITLE-ABS-KEY (“smart apparel”)) OR (TITLE-ABS-KEY (“smart garments”)) OR (TITLE-ABS-KEY (“smart garment”)) OR (TITLE-ABS-KEY (“smart textiles”)) OR (TITLE-ABS-KEY (“smart textile”)) OR (TITLE-ABS-KEY (“smart clothing”)) OR (TITLE-ABS-KEY (“smart cloth”)) OR (TITLE-ABS-KEY (“smart clothes”))) OR ((TITLE-ABS-KEY (“intelligent fabrics”)) OR (TITLE-ABS-KEY (“intelligent fabric”)) OR (TITLE-ABS-KEY (“intelligent apparels”)) OR (TITLE-ABS-KEY (“intelligent apparel”)) OR (TITLE-ABS-KEY (“intelligent garments”)) OR (TITLE-ABS-KEY (“intelligent garment”)) OR (TITLE-ABS-KEY (“intelligent textiles”)) OR (TITLE-ABS-KEY (“intelligent textile”)) OR (TITLE-ABS-KEY (“intelligent clothing”)) OR (TITLE-ABS-KEY (“intelligent clothes”)) OR (TITLE-ABS-KEY (“intelligent cloth”))) OR ((TITLE-ABS-KEY (“interactive fabrics”)) OR (TITLE-ABS-KEY (“interactive fabric”)) OR (TITLE-ABS-KEY (“interactive apparels”)) OR (TITLE-ABS-KEY (“interactive apparel”)) OR (TITLE-ABS-KEY (“interactive garments”)) OR (TITLE-ABS-KEY (“interactive garment”)) OR (TITLE-ABS-KEY (“interactive textiles”)) OR (TITLE-ABS-KEY (“interactive textile”)) OR (TITLE-ABS-KEY (“interactive clothing”)) OR (TITLE-ABS-KEY (“interactive clothes”)) OR (TITLE-ABS-KEY (“interactive cloth”))).

The validity of the search strategy was manually verified by checking the titles and abstracts of the 100 most frequently cited documents to ensure that all documents were relevant to the topic of the study. In case of ambiguity, the full texts were reviewed by an expert in the research field to make a final decision.

The final search was conducted in June 2023. Since the data for 2023 were still incomplete, it was reasonable to exclude them from the analysis, so we performed analyses for the period up to 2022. The retrieved documents were narrowed down by document type to journal articles, reviews, and conference papers. Figure 4 shows a flowchart illustrating how data were collected.

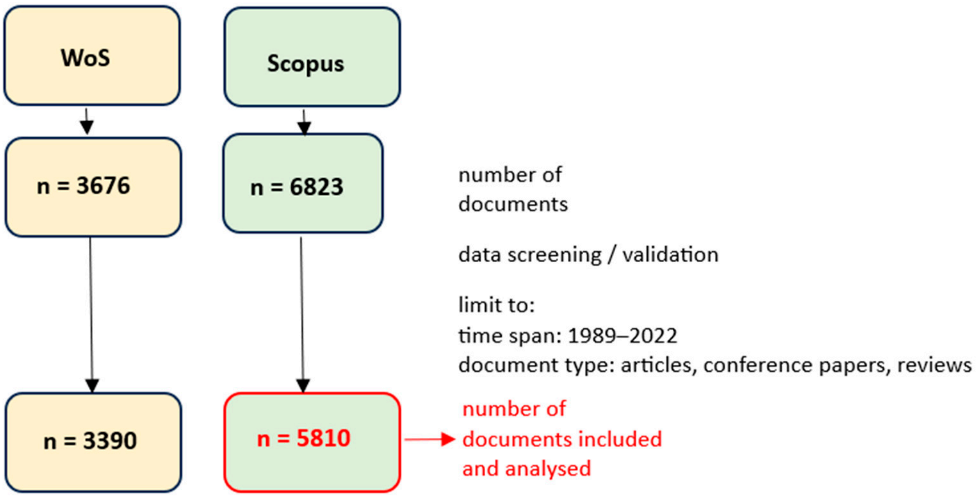


Figure 4. Flowchart of the search in the WoS (Topic search) and Scopus database (Title–Abstract–Keyword search).

The Scopus database returned a larger number and more relevant documents than Web of Science, and it appears to be more relevant and better suited to the requirements of the bibliometric analysis of our research. The selection of the Scopus database was also justified by the fact that it is a larger database compared to other competing databases such as Web of Science [79,80]. A large data file in Scopus, containing 5810 documents, was exported to a csv format, containing the complete data set and cited references.

After obtaining all relevant bibliometric data on smart textiles research from Scopus, various bibliometric approaches and software tools were applied. Scopus bibliometric tools, Microsoft Excel, and Bibliometrix (v4.1.3) [72] were used for basic statistical analyses and the visualisation of bibliometric results. VOSviewer (v1.6.19) software was utilized to create and analyse networks of authors' keywords connected by co-occurrence links and to create, visualise, and explore bibliographic maps [81] and Bibliometrix/Biblioshiny for the country collaboration map.

To improve the quality of the original raw data set for the science mapping analysis, the **preprocessing** phase was essential. We created the VOSviewer thesaurus file to merge terms, such as singular and plural (e.g., "biosensor" and "biosensors"), synonyms (e.g., "e-textiles" and "electronic textiles"), different spellings (e.g., "fibre" and "fiber"), abbreviated and full terms (e.g., "FBG" and "Fibre Bragg Grating"), and author names or source titles (e.g., Tröster Gerhard, Troester G., Troster G. and Tröster G.). The same thesaurus file was also used to ignore terms (e.g., general terms such as "conclusion", "abstract", "method", "graphical abstract").

After preprocessing the data set, a co-occurrence **network** of authors' keywords as the unit of analysis was created.

During the **normalisation** process, similarities of the items (e.g., authors' keywords, etc.) were measured. By default, VOSviewer applies the association strength normalisation, described in detail by van Eck and Waltman [81].

Once the normalisation was complete, the VOS ("visualisation of similarities") **mapping** technique of the VOSviewer software was applied to create science maps.

Co-word **analysis** was then performed to examine the actual content of the publications and co-authorship analysis was used to study intellectual connections between scholars in different countries. The resulting maps were analysed and presented in the form of network **visualisations**, with items represented by their labels and, by default, also by a circle. The label size and the circle size of an item were determined based on the item's weight: the greater the weight of an item, the larger the label and the circle of the item. The colour of an item was determined by the cluster to which the item belonged. The lines between the items represent the links and their strength.

The final step was the **interpretation** of the science maps, which required close collaboration among experts in the mapped area, with the goal of not only quantitatively counterpart the qualitative knowledge of domain experts but also providing new insights and useful knowledge for research and science policy purposes, as suggested by [82,83]. The workflow of the science mapping methodology applied in this study is shown in Figure 5.

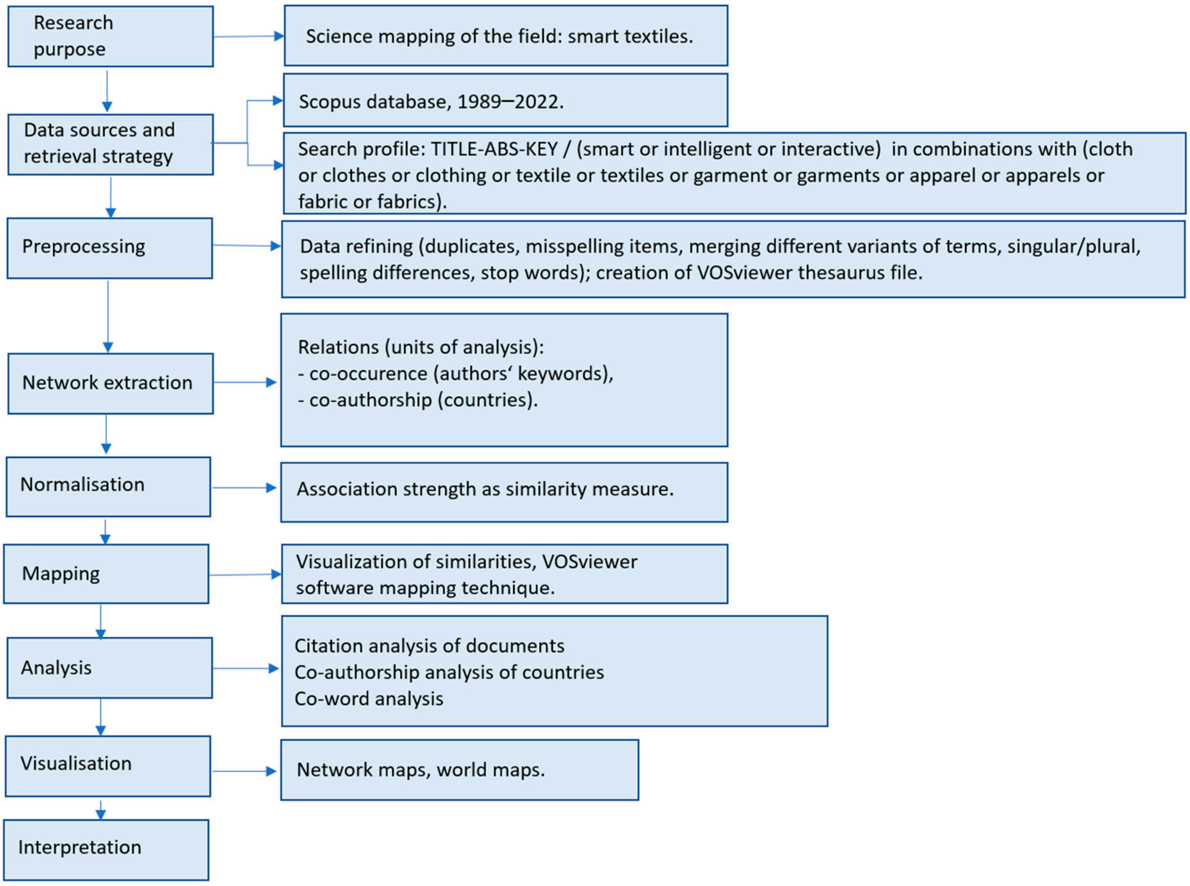


Figure 5. Workflow of the science mapping applied in this study.

3. Results and Discussion

In the following section, the results of the bibliometric analysis of the literature on smart textiles are presented (Figure 6). First, the results of the performance analysis with production and influential aspects of documents, authors, sources, and countries are described. The second part contains the results of the science mapping analysis, including a co-occurrence network of authors' keywords, different clusters indicating the main research topics in smart textiles research, and the intensity of countries' collaboration through co-authorship analysis of countries. Finally, the newest hotspots as potential directions for future smart textiles research and development are presented.

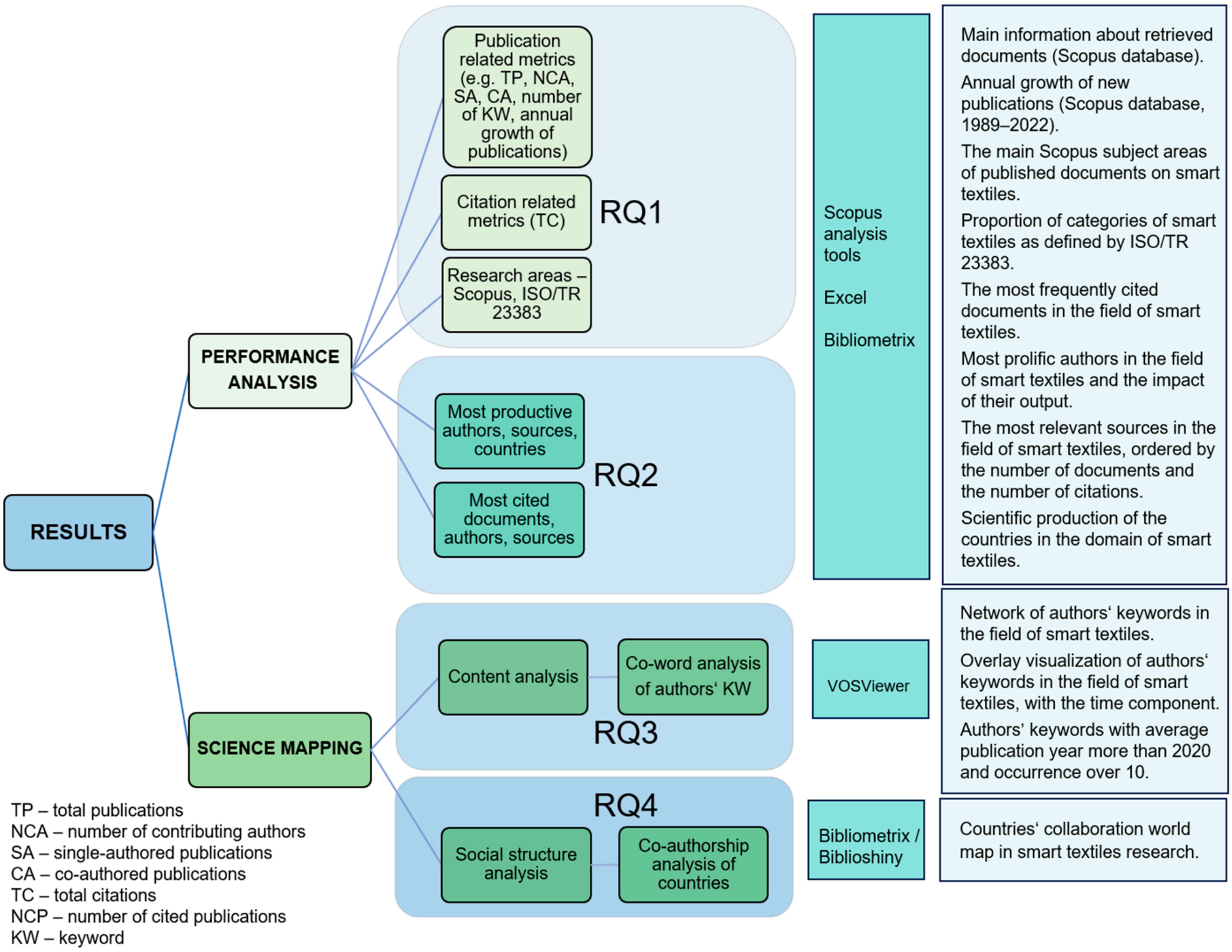


Figure 6. Presentation of results.

3.1. Performance Analysis

3.1.1. Overview of Retrieved Documents and Trends

A total of 5810 documents from 1739 sources published between 1989 and 2022 were obtained from the Scopus database; the main characteristics of retrieved documents are listed in Table 1.

The annual growth of publications on smart textiles and the cumulative citations per year are presented in Figure 7. During the period 1989–2022, the average increase in published documents was more than 22% per year. Most research publications were published in the last ten years.

The retrieved documents were distributed among more than twenty Scopus subject areas (Figure 8), reflecting the highly interdisciplinary nature of the field. Another sixteen subject areas with less than 2% of documents are grouped under Other (9.1%).

Figure 9 shows the proportion of smart textile types according to the categories ISO/TR 23383 (see Figure 2 [11]), based on the number of publications retrieved by the advanced search in Scopus. Shape change, capacitive, and piezoelectric smart textiles are the three most propulsive groups, followed by chromic, photovoltaic, electrolytic, phase change, and thermo-electric types of smart textiles.

Table 1. Main information about retrieved documents (Scopus database).

Bibliometric Items	Findings
Timespan	1989–2022
Sources (journals, proceedings, etc.)	1739
Documents	5810
Annual growth rate %	22.36
Average citations per document	22
References	166,487
DOCUMENT CONTENTS	
Keywords Plus (ID)	23,347
Authors' Keywords (DE)	10,502
AUTHORS	
Authors	12,314
Authors of single-authored documents	538
AUTHORS COLLABORATION	
Single-authored documents	683
Co-authors per document	4.33
International co-authorships %	18.24
DOCUMENT TYPES	
Articles	3560
Conference papers	1879
Reviews	371

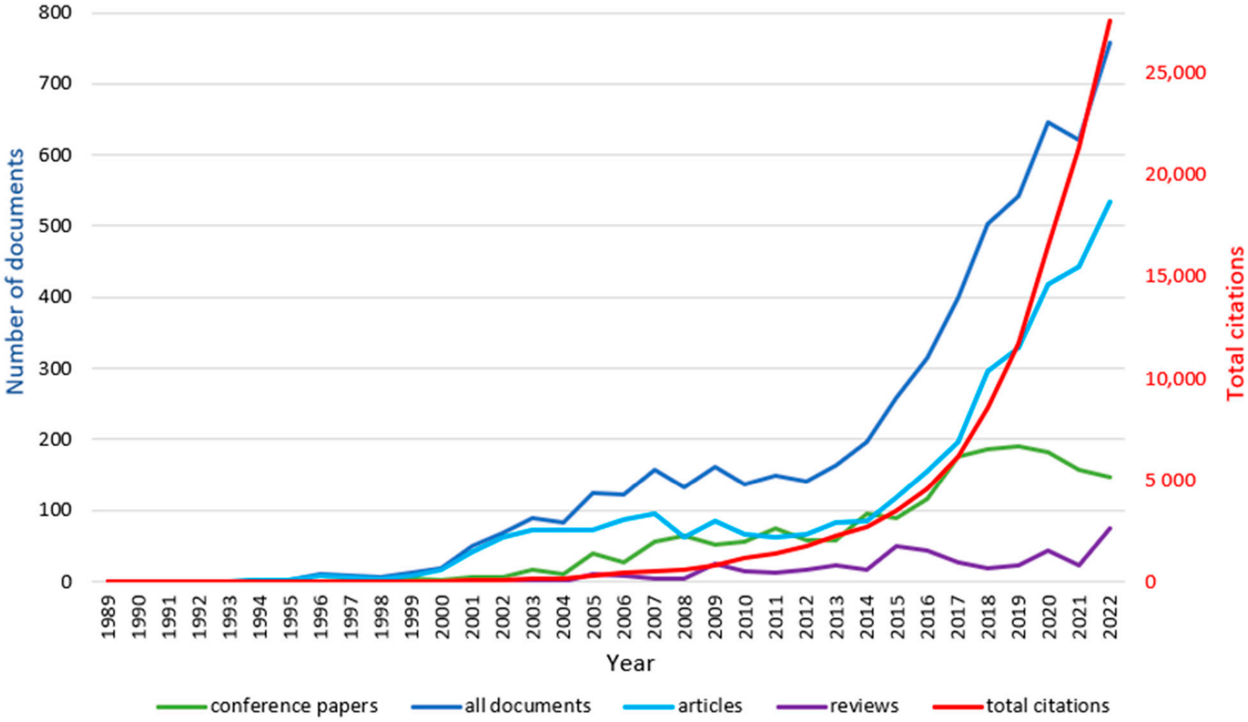


Figure 7. Annual growth of new publications (Scopus database, 1989–2022).

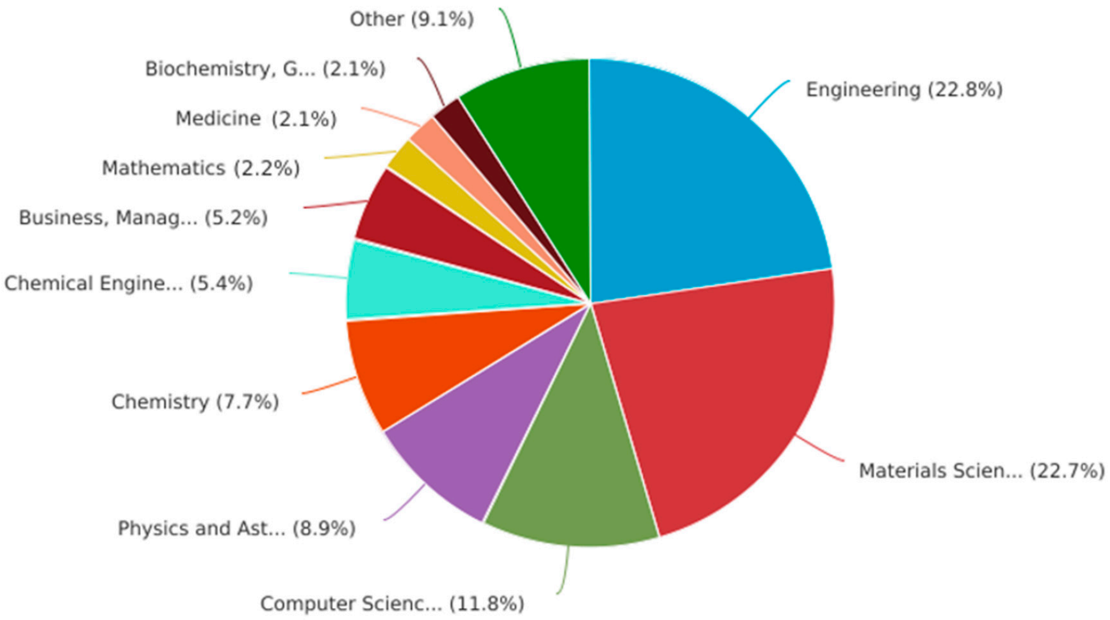


Figure 8. The main Scopus subject areas of published documents on smart textiles.

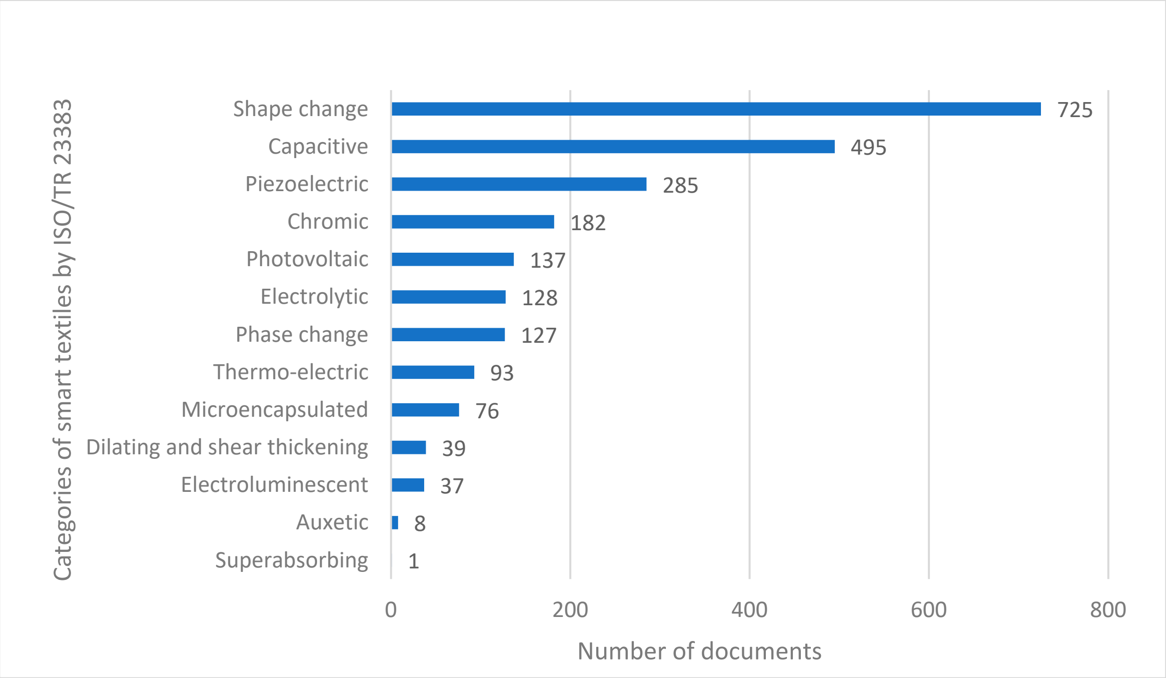


Figure 9. Proportion of categories of smart textiles as defined by ISO/TR 23383, measured by the number of publications found in the Scopus database.

3.1.2. Analysis of Oldest and Most Cited Documents

The **oldest** paper related to smart textiles published in the Scopus database dates back to 1989. A detailed review of the ten earliest articles [84–93] showed that the research topics of these publications had little to do with smart textiles as they are defined today, yet indirectly provided the seeds for smart production of smart textiles in the future. They dealt with computer-aided design and technology in the garment industry [84,85], the use of powerful measurement technologies for fabric properties during sewing [87,90,91,93], and the simulation of textile images through the joint use of a yarn editor, a textile editor, and a texture mapper [89]. These approaches to developing and integrating new technologies led to improvements in production efficiency, flexibility, quality, and design features in the garment industry. Two articles [86,88] had more to do with functional textiles than smart textiles, as they examined the use of Tencel and Lycra in the design of more comfortable sportswear [86] and how fabric structure, colour, and surface appearance affected the price of intelligent fabrics [88]. In 1996, Steve Mann [92] pointed out the potential of wearable textiles and the benefits of their use in modern society. It should be emphasised that only this article had a direct reference to smart textiles.

The **most frequently cited** documents in the field of smart textiles are presented in Table 2.

Table 2. The most frequently cited documents in the field of smart textiles.

Rank	Document	Total Citations	Ref. No.
1	Gladman Sydney, A., Matsumoto, E. A., Nuzzo, R. G., Mahadevan, L., and Lewis, J. A. (2016). **Biomimetic 4D printing**. *Nature Materials*, 15(4), 413–418. doi:10.1038/nmat4544	1.982	[94]
2	Pantelopoulos, A. and Bourbakis, N. G. (2010). **A survey on wearable sensor-based systems for health monitoring and prognosis**. *IEEE Transactions on Systems, Man and Cybernetics Part C: Applications and Reviews*, 40(1), 1–12. doi:10.1109/TSMCC.2009.2032660	1.715	[95]
3	Stoppa, M., and Chiolerio, A. (2014). **Wearable electronics and smart textiles: A critical review**. *Sensors* (*Switzerland*), 14(7), 11957–11992. doi:10.3390/s140711957	1.454	[45]
4	Leng, J., Lan, X., Liu, Y., and Du, S. (2011). **Shape-memory polymers and their composites: Stimulus methods and applications**. *Progress in Materials Science*, *56*(7), 1077–1135. doi:10.1016/j.pmatsci.2011.03.001	1.239	[96]
5	Mondal, S. (2008). **Phase change materials for smart textiles-an overview**. *Applied Thermal Engineering*, *28*(11–12), 1536–1550. doi:10.1016/j.applthermaleng.2007.08.009	935	[28]
6	Chen, J.; Huang, Y.; Zhang, N.; Zou, H.; Liu, R.; Tao, C.; Fan, X.; Wang, Z.L. (2016). **Micro-cable structured textile for simultaneously harvesting solar and mechanical energy**. *Nature Energy*, 1(10) doi:10.1038/nenergy.2016.138	786	[97]
7	Boulos, M. N. K., Wheeler, S., Tavares, C., and Jones, R. (2011). **How smartphones are changing the face of mobile and participatory healthcare: An overview, with example from eCAALYX**. BioMedical Engineering Online, 10 doi:10.1186/1475-925X-10-24	767	[98]
8	Xue, J., Xie, J., Liu, W., and Xia, Y. (2017). **Electrospun nanofibers: New concepts, materials, and applications**. *Accounts of Chemical Research*, 50(8), 1976–1987. doi:10.1021/acs.accounts.7b00218	716	[99]
9	Majumder, S., Mondal, T., and Deen, M. J. (2017). **Wearable sensors for remote health monitoring**. *Sensors* (*Switzerland*), 17(1) doi:10.3390/s17010130	687	[100]
10	Chan, M., Estève, D., Fourniols, J.-Y., Escriba, C., & Campo, E. (2012). **Smart wearable systems: Current status and future challenges**. *Artificial Intelligence in Medicine*, 56(3), 137–156. doi:10.1016/j.artmed.2012.09.003	664	[101]

Among the ten most cited articles [28,45,94–101], review papers prevail; one is an original scientific paper, while the most cited document is categorised as a letter focused on biomimetic 4D printing. It summarises the latest scientific knowledge and technological solutions and describes the fabrication of mesoscale bilayer architectures with programmable anisotropy using appropriate printing parameters (filament size, orientation, and spacing) [94]. New materials, such as shape memory polymers (SMPs), that have the ability to regain their original shape after severe deformation when exposed to external stimuli (Joule heating, light, magnetism, or moisture) are presented in [96]. Stimuli-responsive materials can be used to form shape memory fibres for the development of smart textiles that respond to thermal stimuli. Such smart fibres can be used for novel sensors [96]. PCMs have the ability to change from solid to liquid state and vice versa under the influence of temperature [28]; they are used in the production of thermoregulated smart textiles. Promising PCMs for textile applications are linear long-chain hydrocarbons and polyethylene glycol, with melting points of 15–35 °C. For textile applications, PCMs are microencapsulated. Although the development of PCMs dates back to 1980, when they were developed for spacesuits and gloves, researchers are still struggling to achieve adequate durability of PCMs under repeated use for consumer products [28]. New processes such as electrospinning provide for the formation of nanofibres that have secondary structures, such as a porous, hollow, or core–sheath structures, and can be further functionalised with molecular species or nanoparticles during or after the electrospinning process [99]. Furthermore, they can be used for energy storage, sensors, or wearable/flexible electronics. The development of smart textiles that generate electric power from ambient sunshine and mechanical motion could be the next generation of wearable electronics [97]. The hybrid power textile combines triboelectric nanogenerators, which convert human biomechanical motion into electricity, and a photovoltaic textile, which gathers power from absorbed solar irradiance. Such hybrid power textiles ensure simultaneous harvesting of solar and mechanical energy [97]. The development of health and healthcare-related apps for smartphones supports healthcare and public health interventions by collecting important data for healthcare research, which is also sought by wearable health monitoring systems [98]. Several of the most frequently cited documents are reviews on both commercially available and research prototypes of wearable health monitoring systems [45,95,100,101]. Biosensors can measure various physiological parameters, such as heart rate, blood pressure, body and skin temperature, oxygen saturation, respiration rate, electrocardiogram, etc., in a non-invasive and unobtrusive way. Sensor modules can be integrated into clothing or embedded in garments [95]. Stoppa et al. [45] looked at the materials and manufacturing process in the production of smart textiles and highlighted a possible trade-off between flexibility, ergonomics, low power consumption, integration, and autonomy. Several issues arose in the use of textile sensors, such as energy harvesting, the use of a wearable power supply, washability, and the change in tactile properties of textiles, such as stretch recovery, drape, shear, and handle [45,100], but the major issues in wearable healthcare systems remain privacy and security of the user's sensitive medical data, reliable communication links, robust data compression algorithms and energy efficiency [100], as well as the development of intelligent signal processing, data analysis and interpretation, interoperability of communication standards, efficiency of electronic components, and energy supply [101]. In a comprehensive examination of the most cited documents, it is noticeable that the sustainability aspect of smart textiles is missing.

3.1.3. Analysis of Authors

Table 3 lists the ten most productive authors and their citation impact. Together, they published 398 (8.5%) papers of the total output on smart textiles. **Beeby**, **Stephen P.**, from the University of Southampton, published the highest number of papers (61 papers, 1.05%), which were cited 1300 times. His broad area of research focuses mainly on electronic textiles, flexible electronics, smart materials, printed electronics, and energy harvesting [102]. Similarly, the research interests of **Torah**, **Russel N.**, also from the University of Southampton (58 papers, cited 1023 times), include the development and fabrication of smart textiles, particularly in the areas of electronic textile (e-textile) technologies, triboelectric nanogenerators, and biomedical applications [103]. Beeby and Torah have coauthored more than 50 publications on smart textiles, such as [104–109]. It should be noted that the authors listed in the table have a higher total number of publications, but only documents matching our search query on smart textiles were considered and are listed in Table 3.

Table 3. Most prolific authors in the field of smart textiles and the impact of their output.

Author	Institution	Number of Documents	Number of Citations
Beeby, Stephen P.	University of Southampton, UK	**61**	1300
Torah, Russel N.	University of Southampton, UK	**58**	1023
Tudor, M. John	University of Southampton, UK	45	895
Koncar, Vladan	ENSAIT Ecole Nationale Supérieure des Arts et Industries Textiles, Roubaix, France	43	1151
van Langenhove, Lieva	Universiteit Gent, Belgium	42	1757
Tröster, Gerhard	ETH Zürich, Switzerland	32	1185
Tao, Xiaoming	Hong Kong Polytechnic University, Hong Kong	30	1036
Yang, Kai	University of Southampton, UK	30	709
Wang, Zhong Lin	Chinese Academy of Sciences, Beijing, China	29	**6556**
Dunne, Lucy E.	University of Minnesota Twin Cities, Minneapolis, USA	28	371

Wang, Zhong Lin from the Chinese Academy of Sciences, Beijing, China, stands out in terms of the number of citations and also a large production of publications in the present time. He is a Chinese-American physicist, materials scientist, and engineer specializing in nanotechnology, energy science, and electronics [110]. Dr. Wang pioneered the nanogenerators field for distributed energy, self-powered sensors, and large-scale blue energy [111]. His most contributed topics in the Scopus database (2018–2022) are nanogenerators, piezoelectrics, and energy harvesting. His recent publications in the field of smart textiles cover the topics of energy harvesting with triboelectric nanogenerators [42,112–118], as well as related topics of self-charging wearable textile systems [119–121], advanced sensors for monitoring physiological or motion signals [122–125], and smart textiles for electromagnetic interference shielding (EMI shielding) in human–machine interaction [126].

3.1.4. Analysis of Sources

Document sources analysis was employed to identify the key important sources relevant to the research of smart textiles. This analytical approach is useful to researchers to find relevant literature and select the most appropriate journal to publish their own research findings. A total of 1739 different publication sources in the field of smart textiles were identified. The sources were ranked according to the number of documents and number of citations, as presented in Table 4.

Table 4. The most relevant sources in the field of smart textiles ordered by the number of documents (left) and the number of citations (right).

Rank	Source	Number of Documents	Rank	Source	Number of Citations
1	**Sensors**	**139**	1	**Advanced Materials**	**6488**
2	**ACS Applied Materials and Interfaces**	**132**	2	ACS Applied Materials and Interfaces	5985
3	**Textile Research Journal**	**121**	3	Sensors	5323
4	Proceedings–International Symposium on Wearable Computers, ISWC *	70	4	ACS Nano	5055
5	Proceedings of SPIE–The International Society for Optical Engineering *	67	5	Advanced Functional Materials	4495
6	IEEE Sensors Journal	66	6	Nano Energy	2521
7	Conference on Human Factors in Computing Systems–Proceedings *	62	7	Textile Research Journal	2298
8	ACM International Conference Proceeding Series *	60	8	Sensors and Actuators, A: Physical	2043
9	Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics) *	59	9	Smart Materials and Structures	1997
10	Journal of The Textile Institute	56	10	IEEE Sensors Journal	1877

* conference proceedings.

Scientific meetings are known to provide high-quality new information on research developments in a short time in smart textiles research. Among the top ten most prolific sources contributing to smart textiles, half were conference proceedings. However, articles published in scientific journals in the field of smart textiles, particularly in the areas of advanced materials, sensors, and nanotechnologies, had a higher citation value. In many scientific environments, higher citation counts and international visibility are perceived as higher scientific excellence. From this point of view, scientific articles outweighed conference papers.

3.1.5. Geographic Distribution of the Publications

Figure 10 shows the geographic origin of the institutions contributing to the research on smart textiles; a darker blue colour represents a larger number of publications. In total, authors from 86 countries contributed papers. The most prolific countries for smart textile-related publications are China (28.3%), followed by the USA (12.65%), South Korea (6.36%), the UK (6.05%), and Germany (5.46%).

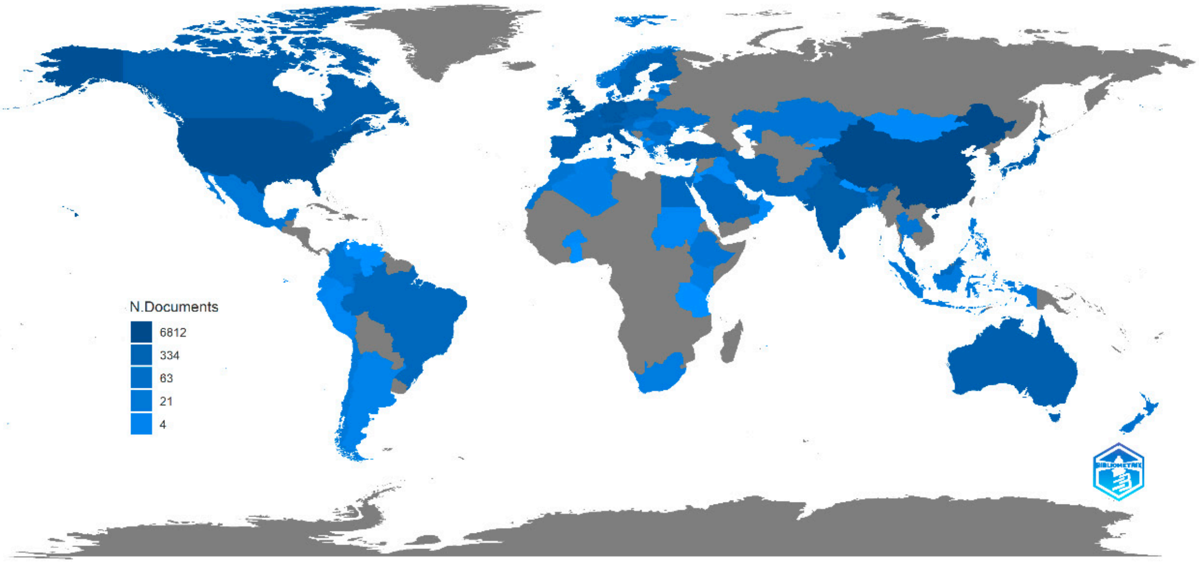


Figure 10. Scientific production of the countries in the domain of smart textiles.

3.2. Science Mapping

3.2.1. Co-Word Analysis

Co-word analysis was used to recognize (a) the conceptual structure of the smart textile literature, (b) the most frequently used keywords used by researchers, and (c) the main research areas and trends in the research field.

The co-word analysis is based on the assumption that "words that frequently occur together have a thematic relationship". For the co-occurrence analysis, the authors' keywords were chosen as the unit of analysis because they are considered the most concise and reliable source that reflects the content of the publications [58]. A total of 10,502 authors' keywords were identified in the raw data set of 5810 documents. After cleaning in the preprocessing phase, 10,221 were used in an analysis. Authors' keywords that occurred at least 7 times were taken into account for further analysis, and 329 KW met this threshold. The network was created based on the weight attribute "occurrence". The **nodes** (circles) represented the authors' keywords, so their **size** was proportional to the occurrence of each keyword (larger size means higher occurrence). Each colour represented a thematic cluster, and the colour of the circle was determined by the cluster to which the authors' keyword belonged. For a given keyword, the **links** attribute indicated the unique number of times a keyword co-occurred with each of the other keywords. The **strength** of the link between two keywords indicated the number of publications in which the two keywords co-occurred (co-occurrence). The distance between two authors' keywords roughly indicated the relatedness of the authors' keywords in terms of co-occurrence links. In general, the closer two authors' keywords are located to each other, the more strongly they are related [81].

Figure 11 shows the network of authors' keywords grouped into five thematically similar clusters. For some keywords, the label was not shown to avoid overlap. The leading keywords of each cluster were additionally tagged. The resulting clusters can be used to identify main research areas within the field of smart textiles.

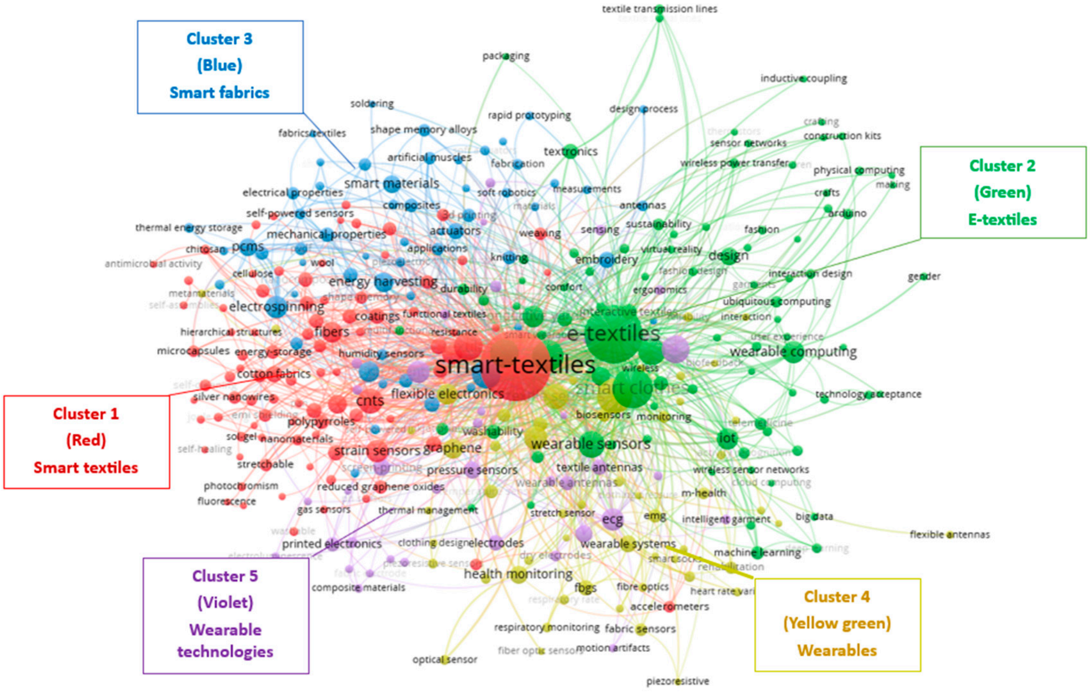


Figure 11. Network of authors' keywords in the field of smart textiles.

Clusters of KW as indicators of research areas

Cluster 1 (Red) was formed around the keyword **SMART TEXTILES** (occurrence 1021), with 294 links and a total link strength of 842, which is the highest among all the authors' keywords. Overall, this leading term is closely linked to core terms in four other clusters. The red cluster is rather general and thematically covers smart textile materials, technologies, applications, and properties. Examples of keywords with high occurrence (>10) in this cluster are textiles, carbon nanotubes (CNTs), MXenes, strain sensors, supercapacitors, conductive textiles, conductive polymers, polyaniline (PANI), polypyrroles, reduced graphene oxides, graphene fibres, nanocomposites, nanoparticles, nanomaterials, nanotechnologies, energy storage, Joule heating, silver nanovires, silver nanoparticles, EMI shielding, shape memory, stretchable electronics, accelerometers, microcapsules, liquid-crystals, hydrogels, sol-gel, flexibility, flexible devices, and washable.

The content analysis shows that among the materials, those that ensure the conductivity of the textiles through the use of nano-sized particles or through the use of nanotechnologies predominate. The applications are very broad and range from sensors (heart rate, pH, gas, monitoring human movements) to energy storage devices, EMI shielding, and flexible displays. The properties depend on the type of smart textiles and their capability; flexibility and washability are often emphasised. Some properties in this cluster are related to functional textiles rather than smart textiles, such as flame retardant, UV protection, self-cleaning, antibacterial, and antimicrobial. The reason may be historical, due to confusing terminology and incomplete standards for defining basic terms, namely smart and functional textiles, in the early stages of research and development of new materials and technologies in this field.

Cluster 2 (Green) is focussed on the keyword **E-TEXTILES** (occurrence 665), with 237 links and a total link strength of 573. The cluster presents smart electronic textiles, their constitutive parts, such as sensors and conductive yarns, their design, and their placement in computer networks for specific applications. Examples of specific keywords with high occurrence (>10) in this cluster include wearable electronics, textile electronics, wearable computers, sensors, wearable sensors, wearable computing, ubiquitous computing, physical computing, internet of things (IoT), body area network, body sensor networks, machine learning, artificial intelligence, deep learning, conductive yarns, conductive threads, textile transmission lines, wireless power transfer, textronics, health-care, telemedicine, e-health, activity recognition, capacitive sensing, radio frequency identification (RFID), prototyping, fashion, technology acceptance, washability, durability, and sustainability.

This cluster is more structurally distinct and narrow. Keyword analysis identifies materials for the production of e-textiles, such as conductive fibres, conductive yarns, conductive threads, conductive materials, and CNT fibres. They are applied in textile body sensors, wearable sensors, sensor networks, wireless sensor networks, thermistors, and RFID. During the operation of an e-textile, data are collected from sensors that monitor various body parameters and transmitted to body area networks and the IoT using microprocessors, physical computing interactive systems, displays, and other user interfaces. Large amounts of data are processed using machine learning, deep learning, and other artificial intelligence methods. The emergence of e-textiles in the market is already impacting Industry 4.0, as well as e-health and telemedicine, by solving complex medical challenges and improving healthcare. Great efforts have already been made to improve the durability and washability of e-textiles, but there is still room for improvement by coating delicate parts of e-textiles with flexible and thin coatings that are resistant to moisture, water, wrinkling, and creasing during wear and textile care.

Cluster 3 (Blue) is organised around the keyword **SMART FABRICS** (occurrence 136), with 104 links and a total link strength of 106. The cluster presents smart fabric items that are designed for clothing from the viewpoints of textile technologies, specialized smart technologies and materials, as well as the design and properties of products. Examples of specific keywords with high occurrence (>10) include electrospinning, triboelectric nanogenerators, energy harvesting, actuators, soft actuators, poly(3,4-ethylenedioxythiophene) (PEDOT), poly(3,4-ethylenedioxythiophene)–poly(styrenesulfonate) (PEDOT:PSS), antennas, self-powered sensors, humidity sensors, thermoelectrics, thermal energy storage, embroidery, knitting, 3D printing, microencapsulation, smart materials, PCMs, nanofibres, conductive fibres, conducting polymers, artificial muscles, soft robotics, shape-memory alloys, shape-memory polymers, polyvinylidene difluoride (PVDF), liquid metal, piezoelectric, self-powered, photoluminescence, electrical properties, thermoregulation, thermal comfort, rapid prototyping, design process, and innovation.

Cluster 3 is oriented toward smart fabrics, which are only one of the segments of smart textiles. Fabrics can be woven, knitted, or non-woven, and thus, technologies such as knitting, weaving, electrospinning, embroidery, and 3D printing can be used to create smart fabrics. Advanced materials, such as conductive yarns or wires made from shape-memory alloys, can be incorporated into the fabric structure, while shape-memory polymers (SMPs) can be used to produce shape-memory fibres, shape-memory yarns or shape-memory fabrics. The latter may also be made by coating a shape-memory emulsion or shape-memory film. SMPs and their composites deform back to their original shape after severe deformation due to Joule heating, magnetism, moisture, light, or solutions. The response of SMP composites depends on the type of filler (carbon particles, CNTs, a mixture of CNTs and PVDF, carbon fibres, electromagnetic fillers, hybrid fibres) or the embedding of an optical fibre. Conductive polymers such as PEDOT or PEDOT:PSS can be used to make physical sensors for humidity, temperature, pressure, and strain. Piezoelectric plastic materials such as PVDF can generate electrical charge when mechanically deformed. They are often used for health monitoring. The application of PCMs to textiles usually requires microencapsulation of the PCMs and then the application of microcapsules to the fabric by coating or printing. Such a fabric responds to temperature and enables a thermoregulatory effect that ensures the thermal comfort of the wearer. Smart textiles require energy to maintain the sensors and actuators. An alternative device for energy harvesting is the triboelectric nanogenerator, a mechanical harvester based on triboelectricity that harvests electrical energy from the mechanical energy of the environment. The advantages of triboelectric nanogenerators are high instantaneous output power, an environmentally friendly, low-cost manufacturing process, and different operating modes tailored to target applications. In addition, the use of self-powered sensors or self-powered devices can reduce the need for additional devices for energy harvesting.

Cluster 4 (Yellow green) is focused on **WEARABLES** (occurrence 210), with 151 links and a total link strength of 193. This cluster presents products at a cross-section of wearables (a broader term for all items that can be worn) and smart textiles, as reflected in typical keywords with high occurrence (>10): wearable devices, wearable system, flexible electronics, smart shirt, smart socks, textile sensors, flexible sensors, temperature sensors, biosensors, fabric sensors, optical sensors, piezoresistive sensors, capacitive sensors, stretch sensors, strain sensing, textile pressure sensors, FBGs (Fibre Bragg gratings), health monitoring, m-health (mobile health), electromyography (EMG), rehabilitation, monitoring, respiratory monitoring, respiratory rate, heart rate variability, vital signs, gait analysis, and sports.

The wearables cluster contains publications on various sensors and other devices that can detect physiological changes and are used in close contact with the body in smart clothing such as shirts, socks, sportswear, belts, etc. Ideally, wearable sensors should be resistant to mechanical, chemical, and thermal impacts. Sensor concepts based on chemical, physical, and thermal mechanisms of action are suitable for application in smart textiles to detect various parameters such as forces, displacements, thermal energy, humidity, chemicals, UV radiation, etc. Stretch sensors are used to monitor body parameters because the fabric is in direct contact with the skin over a large area of the body. Therefore, monitoring occurs at several points on the body. Pressure sensors are used either as switches and interfaces to electronic devices or also to monitor the user's vital signs. Textile piezoelectric resistance sensors are used to detect movement and respiration. Fabric biosensors can be used to record the electrical signal from the heart—electrocardiogram (ECG); muscle response or electrical activity in response to stimulation of the muscle by a nerve (EMG), brain activity—electroencephalography (EEG); and general vital signs such as heart rate, blood pressure, body and skin temperature, respiratory rate, and oxygen saturation. Constant control over an individual's health and fitness through daily monitoring of vital signs can contribute to proactive care for healthy living in the treatment of chronic diseases, rehabilitation after surgery, progress in sports training, or simply for general preventive monitoring of the user's condition.

Cluster 5 (Violet) is grouped around the keyword **WEARABLE TECHNOLOGIES** (occurrence 124), with 89 links and a total link strength of 104. The cluster presents electronic technologies that are integrated into textiles to be worn on the body. Among the keywords with the highest occurrence (>25) in this cluster are intelligent textiles, ECG, electrodes, textile electrodes, textile antennas, wearable antennas, pressure sensors, printed electronics, and screen printing. Other specific terms with occurrence >10 include dry electrodes, sensing, wireless communications, structural health monitoring, conductive ink, melt spinning, multi-material fibres, composite materials, and ergonomics.

Although the fourth and fifth clusters are closely related, the fifth cluster focuses more on technologies that support the production of wearables. These are electronic devices embedded into textile clothing worn by individuals that are responsible for collecting, analysing, and transmitting personal data, usually with the specific aim of providing healthcare. The production of robust and rigid sensors is now being replaced by new materials that are stretchable, flexible, and resistant to chemicals, so new materials and new technologies are receiving more attention. Printed electronics are made with screen or inkjet printing of conductive inks. Melt spinning is often used to spin highly stretchable and electrically conductive filaments. Composites and multi-material fibres are gaining acceptance in the manufacture of sensors due to their specific advantages over single fibres/materials. The use of dry electrodes, which include textile electrodes, is more suitable for daily and long-term use, as dehydration due to electrolyte deficiency does not occur. These types of electrodes are especially desirable for EMG recording. The classic antenna on textiles is nowadays replaced by a textile antenna whose task is to communicate between the sensor and the external device. Wearable antennas must be flexible, lightweight, washable, and robust. They enable wireless communication between the body network, where the user's physiological data is collected, and the health centre.

An overview of new trends—the latest concepts and propulsive research topics

When considering the time dimension, certain general keywords seem to be more important and used more frequently at the beginning of the observed period (e.g., wearable computing, smart materials, protective clothing), while specific terms such as wearable sensors, wearable electronics, and textile electrodes became typical in the middle of the observed period. Research topics such as liquid metal, MXenes, textile electronics, and triboelectric nanogenerators have gained importance in recent years. The overlay visualisation of the authors' keywords is shown in Figure 12, where the colour of the circles is determined by the average publication year of the documents in which the authors' keyword appears. A colour bar displayed in the lower right corner of the visualisation ranges from blue (oldest average publication year) to green and yellow (newest average publication year).

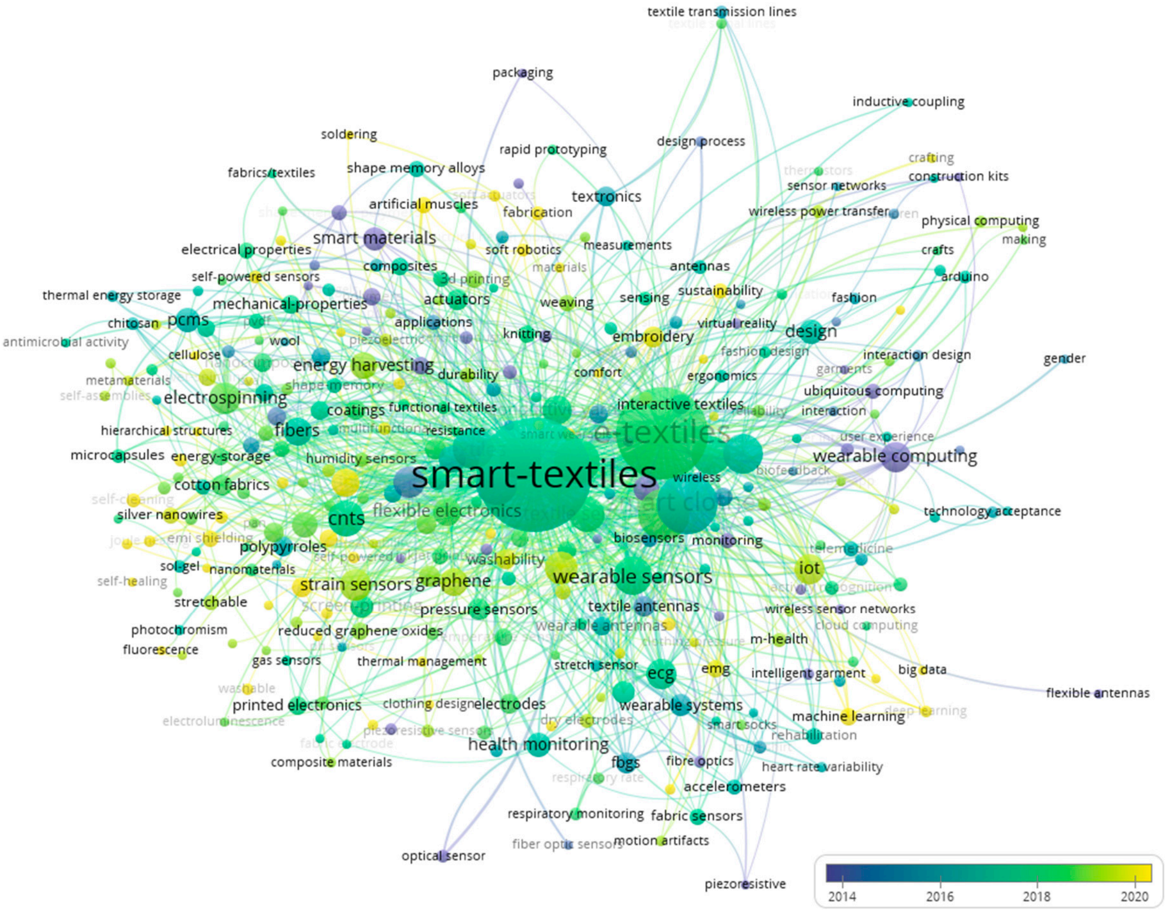


Figure 12. Overlay visualisation of authors' keywords in the field of smart textiles, with the time component.

To further explore trends in the field of smart textiles, the most recent keywords with an average publication year younger than 2020 were identified and further examined in new scientific publications. The most recent keywords with at least 10 occurrences are listed in Table 5 and are presented in the following text as **hotspots of recent research**.

Table 5. Authors' keywords with an average publication year younger than 2020 and occurrence of more than 10 that can be considered as new propulsive research areas for smart textiles.

Authors' Keywords	Average Publication Year	Occurrence
liquid metal	2021.45	11
MXenes	2020.94	33
textile electronics	2020.92	13
self-powered	2020.83	12
EMI shielding	2020.64	22
self-powered sensors	2020.53	15
silver nanoparticles	2020.47	15
strain sensing	2020.40	10
sustainability	2020.39	18
artificial muscles	2020.22	23
joule heating	2020.18	11
washable	2020.18	11
thermoelectrics	2020.18	11
triboelectric nanogenerators	2020.16	63
gait analysis	2020.07	14
self-cleaning	2020.06	17
fabrication	2020.00	16
soft robotics	2020.00	13

Liquid metal. Liquid metals possess unique properties in ambient environments, such as fluidity, high conductivity, and intrinsic stretchability. In smart textiles, they have been applied in chemical sensors, wearable electronics, and stretchable devices [127]. Elastic liquid metal-based triboelectric fibres can harvest mechanical energy via the triboelectric effect and have been applied as power sources for wearable electronics and functional textiles [128]. Conductance-stable liquid metal sheath–core microfibres are appropriate for the production of stretchy smart fabrics and self-powered sensing [129]. Liquid metals can be 3D printed to produce interconnects in stretchable electronics [130].

MXenes. MXenes are two-dimensional inorganic nanomaterials consisting of atomically thin layers of transition metal carbides, nitrides, or carbonitrides. Due to their excellent electrical conductivity, enriched surface functionalities, and large surface area, MXenes have been used as building blocks for next-generation wearable electronics, flexible electronics, and in combination with fibres, yarns, fabrics, and smart textiles. MXenes enable wearable smart textiles for energy storage, power generation, strain and humidity sensing, EMI shielding, Joule heating, healthcare, and biomedical applications [7,131].

Textile electronics. Textile electronics contain fibres or fibre assemblies with electronic functions for the generation, transmission, modulation, and detection of electrons. Their characteristics include high performance, light weight, handiness, flexibility, comfort, and low strain under severe deformation [132]. A new generation of 1D fibre-shaped electronics has been applied in devices for energy harvesting, energy storage, light emission, and sensing. They are small in diameter, lightweight, flexible, and can be fabricated into soft textile electronics [133].

Self-powered. One of the great challenges for smart textiles research and development is sustained self-powered textile-based devices that can also be used as elements of the Internet of Things and the Metaverse as its emerging successor. Mechanical energy harvesting technologies such as triboelectric nanogenerators, piezoelectric nanogenerators, and electrochemical mechanical generators have been used to convert mechanical energy directly into electrical power [14]. Other energy sources have also been considered for conversion into electricity, such as photovoltaics, thermoelectric generators, electromagnetic generators, magnetoelastic generators, and pyroelectric and hydrovoltaic systems [21,40,134]. Examples of achievements include highly integrated composite core/shell fibres for weaving triboelectric nanogenerators that can be used in self-powered smart textiles whose fibres are stretchable, conductive, with good pliability and high resistance–strain sensitivity [135]; washable smart textiles based on triboelectric nanogenerator arrays used as bedsheets for real-time and self-powered sleep behaviour monitoring [136]; self-powered smart gloves based on the triboelectric effect and electrostatic induction, which can be used for a variety of purposes, including gesture recognition, sign language translation, human–machine interfaces, advanced robotic control, user identification, and object recognition [137].

EMI shielding. Digital and electronic devices cause interference of electromagnetic waves that negatively affect nearby electronic devices, communication signals, and human health. Textile materials, such as cotton, silk, polyester, nylon, spandex, polyethylene terephthalate, etc., can be modified by various methods and techniques with conductive materials such as silver nanowires, liquid metals, Cu nanoparticles, CNTs, graphene, graphene oxide, MXene, polypyrrole, or PEDOT to perform the function of protection from EM waves to provide EMI shielding [138]. Examples of new research include durable EMI-shielding ramie fabrics with flame-retardant and self-healing properties consisting of an ammonium polyphosphate/polyethyleneimine layer, MXene sheets, and a polycaprolactone layer [139], highly conductive textiles with bark-like morphology composed of MXene microstructure and porous textile, with improved flexibility, durability, breathability, and EMI shielding performance [140], and the development of titanium carbide (Ti_3C_2Tx) MXene nanosheets with improved stability and enhanced connectivity, containing Ti_3C_2Tx/PANI composites with 3D nanoflower structures. With the addition of GaIn liquid metal nanoparticles and carbon fabric substrates, flexible, stable, conductive composite fabrics for EMI shielding were obtained [141].

Self-powered sensors. Self-powered sensors constitute an important sub-class of self-powered products. Based on innovative self-powering technologies, they harvest energy directly from the working environment to ensure long-term sustainable operation. In addition, their output voltage and current are additional readout signals, so they can simultaneously serve as self-powered sensors for content creation and energy supply [21]. Examples of smart textiles as self-powered sensing platforms include a textile thermoelectric generator for monitoring body temperature [142], a smart bedsheet for monitoring human sleep [143], smart textile socks as a human–computer interface in a virtual reality space [144], a smart textile glove for human sign language recognition [145], a textile magnetoelastic generator for monitoring cardiovascular parameters [146], piezoelectric smart textiles for sensing heartbeats and speech [147], a textile biofuel cell that can generate electricity from sweat enzymes to monitor the concentration of ions in sweat [148].

Silver nanoparticles. In functional textiles and in older generations of smart textiles, silver nanoparticles have been traditionally used for antibacterial, antifungal, antistatic, free-radical scavenging, catalytic, electronic, water treatment, sun protection, and air treatment purposes [10,149]. Solution immersion, layer-by-layer deposition, and sonochemical processes are established methods to deposit silver nanoparticles on various textile materials [149]. In the third generation of smart textiles, silver nanoparticles offer new functions, such as the production of smart stimuli-responsive textiles with simultaneous moisture management and controlled antimicrobial activity by embedding silver nanoparticles into temperature- and pH-responsive microgels applied to cotton fabrics [150], conductive inks for e-textiles and screen printing of silver inks for the production of washable, electrically conductive materials for printed circuit boards and RFID tags [22], production of conductive fabrics by dipping and dry coating with silver nanoparticles for applications in EMI shielding, lightweight batteries, and molecular electronic devices [151], use of PVDF nanofibres coated with nonpolar silver nanoparticles as electrodes for piezoelectric sensors [152], and fabrication of textile-based triboelectric nanogenerators consisting of an active layer of graphite carbon nitride nanosheets loaded with silver nanoparticles on carbon fibres for use as wearable power sources [153].

Strain sensing. Mechanisms for detecting mechanical deformation in strain sensing are based on resistive, capacitive, piezoelectric, electrical time-domain reflectometry, and triboelectric effects [154]. Signal transmission in new flexible strain sensors is structurally dependent on the conductive material deposited on the substrate material. Flexible base substrates are synthetic or natural textile polymers, while the conductive materials can be metallic (silver nanoparticles), carbon (CNTs, graphene, carbon black nanoparticles), or conductive polymeric materials (PANI, polypyrrole (PPy), polythiophene (PTH), such as PEDOT or PEDOT:PSS, MXenes, ionic gels, or hydrogel fibres) [20,154–157]. Desirable properties of strain sensors include flexibility, stretchability, minimal hysteresis, high sensitivity, wide sensing range, fast response, reliability, light weight, long-term stability and durability, comfort, and industrial mass production capability [20,154]. Moreover, they can be self-powered [155] or self-healing [156]. Strain sensing technologies are used in wearable sensors for personal healthcare (ECG, respiration, pulse, blood pressure, gait measurement, motion monitoring), physiological monitoring, sign-to-speech translation, and human–machine interaction [20,154,155]. Examples of recent research include development of flexible textiles with improved strain sensing properties composed of conductive nanomaterials of Ti_3C_2Tx MXene/carbon nanotubes, immersion-deposited onto thermoplastic polyurethane nonwoven fabrics [158]; multilayer pressure/strain sensors with improved pressure sensitivity and surface roughness, composed of a knitted cotton/spandex textile with a polypyrrole surface on which rose-like silver flowers were produced by electrodeposition [159]; continuous, twisted graphene fibres with high tensile strength, improved breaking strain, and stable electrical and mechanical properties woven into breathable, wettable, and washable strain sensors used to assemble anti-jamming wearable electronics for sensing human motion in the air or underwater [160]; and an integrated and scalable fabrication process for composite, stretchable, and conductive core/shell fibres for weaving TENGs, applied for strain sensors self-powered smart textiles with strain sensors [135].

Sustainability. The issue of sustainability in the context of smart textiles is addressed from two perspectives. First, it addresses the issue of sustainability in the production, recycling, and waste treatment of smart textile products. The sustainability of smart textiles depends on the choice of materials used, the manufacturing processes, and the end-of-life options for the textiles [23]. Researchers are exploring new sustainable and environmentally friendly materials, green manufacturing methods, end-of-the-life processes, and standardized sustainability assessment methods, such as life cycle analysis, recyclability, and biodegradability [23,161,162]. Second, numerous positive contributions of smart textiles to sustainability are highlighted in the following areas [163]: environmental monitoring (temperature and humidity sensors, gas sensors) [164–166]; fresh water purification and harvesting (filtering, mist collection, collection by coalescence or mechanical squeezing) [167–169]; personal protection (warming, cooling, electromagnetic protection, EMI shielding, protection against UV radiation, toxic substances and microorganisms) [35,37,138,170–173]; power supply on the body with energy harvesting and storage (triboelectric nanogenerators [174–180], including thermoelectric generators [134,181,182], photovoltaic textiles [183–185], bio-physicochemical energy harvesting [186], textiles with perovskite solar cells and other perovskite materials [187,188], dry batteries and flexible electrodes [189–192], and wearable all-in-one power sources that integrate energy harvesting and storage capability into one textile [163,193–196].

Artificial muscles. Artificial muscles refer to fibrous materials and devices that can contract, expand, or rotate reversibly in response to external stimuli such as magnetic fields, electricity, irradiation, heat, and atmosphere [197–199]. Materials that convert electrical, chemical, or thermal energy into a shape-change, such as fibres composed of CNT, graphene, organic polymers, shape memory alloys, or their composites, can be used to form artificial muscles [199,200]. More recent inventions are based on sheath-run artificial muscles, in which the material that drives actuation is a sheath on a twisted or coiled core, which may be a low-cost yarn [201,202]. Other examples include woven hydraulic artificial muscles [203], aerogel fibres [204], printed hydrogel artificial muscles [205], and artificial muscles made from hierarchically patterned helically wound yarns that are self-adaptive to ambient humidity and temperature changes and exhibit plant-like tropisms [206]. Artificial muscles can be creatively used in wearable electronics, soft robotics, and medical applications.

Joule heating. The concept of Joule heating, a physical effect in which the passage of current through an electrical conductor generates thermal energy, is used in smart textiles for active warming. Actively heating textiles are made by modifying, coating, or embedding the textile fibre with electroactive materials such as CNTs, graphene, silver nanoparticles, MXene, or PEDOT:PSS [207–213]. The application of Joule heating in smart textiles has applications in personal warming in cold environments and medical thermotherapy.

Washable. Washing is one of the most important processes to ensure the hygiene of textiles and, thus, protect people's health. Therefore, smart garments should be washable. The first studies and produced electronic textiles were based on rigid conventional electronics integrated into textiles, which did not correspond to the stretchability, flexibility, and washability of textiles, so the removal of electronic devices before washing was strongly recommended. Nowadays, new technologies and new materials allow researchers to develop flexible, stretchable, and washable electronics integrated into textiles without losing comfort and wearability. The latest studies show that coating thread material with poydimethylsiloxane [214] and filling hollow silicon fibres, including conductive yarn, with a mixture of silicone rubber and a curing agent [143], coating triboelectric yarn containing conductive CNTs with PVDF fibres deposited by a tailored electrospinning process [215], increase the washability of smart textiles. Thus, encapsulating conductive yarns with polymers or coating textile sensors with superhydrophobic compounds makes smart textiles washable.

Thermoelectrics. Thermoelectric materials generate electricity through the thermoelectric effect when a temperature gradient is applied. In new smart textiles, thermoelectric generators are used as flexible, self-powered solid-state modules that passively harvest energy from the heat of the human body. They operate on three principles: the Seebeck coefficient, the Peltier effect, and the Thomson effect [134]. Examples of inorganic thermoelectrics include metals (silver, copper), chalcogenides (bismuth telluride, antimony telluride), and metal oxides (zinc oxide), while among organic materials, conductive polymers are used, such as polyacetylene, polypyrrole, PANI, PEDOT, and PEDOT:PSS [40,134]. Dopants can be incorporated into a base material such as graphene, graphene oxide, and CNTs to dope conductive polymers and increase the overall electrical conductivity of the system [134].

Triboelectric nanogenerators. Triboelectric energy harvesting is based on mechanical rubbing and electron transfer [40]. Triboelectric nanogenerators are nanodevices that harvest biomechanical energy from human body movement [216,217]; they couple the triboelectric effect and electrostatic induction to convert mechanical energy into electricity [41]. Proper choice of materials and structures enhances performance [216,218,219]. Many designs and combinations of materials have been developed and fabricated. In general, triboelectric nanogenerators consist of substrates, electrode layers, and triboelectric layers [220]. Flexible substrates for triboelectric nanogenerators can be selected from polyimide, polydimethylsiloxane (PDMS), polyurethane, polyethylene terephthalate, or silk fibres. The electrode layer is a conductive material selected from carbon-containing materials (carbon particles, CNTs, graphene, carbon fibres), conductive polymers (polypyrrole, PANI, poly(P-pheylene-vinylene), polyetheretherketone (PEEK), PEDOT:PSS), metallic nanowires (silver, gold, copper nanowires), or conductive fibres, yarns, or fabrics. Negative triboelectric layers include PVDF, polytetrafluoroethylene (PTFE), polyethylene terephthalate (PET), and PDMS, while positive triboelectric materials are mainly nylon 66, silk, and cellulose [40,220]. The main principle of the design of textile triboelectric nanogenerators is to suitably fit two friction surfaces with different properties into a textile. Therefore, triboelectric nanogenerators can have different structures, such as (a) a thread with a tubular structure, e.g., elastomeric material and a spiral inner electrode adhered to a tube with the dielectric layer and the outer electrode; (b) a modified fabric containing surfaces with microstructures of different materials; (c) a fibre with a core–shell structure with a conductive core and an insulated shell, e.g., a silicone rubber coated stainless-steel thread sewn onto an elastic textile with a serpentine shape; (d) a triboelectric nanogenerator based on a three-dimensional textile [41]. Textile triboelectric nanogenerators' basic modes of operation include single-electrode mode, lateral-sliding mode, vertical contact-separation mode, and free-standing triboelectric layer mode, each of which has its application possibilities and ranges [15]. Potential approaches to improve mechanical-to-electrical conversion and increase the power output of textile triboelectric nanogenerators include surface/interface physical treatments, chemical modifications at the atomic level, structural optimization, control of the working environment, and integrated energy management [42].

Gait analysis. Gait analysis is the systematic study of locomotion, analysing parameters such as body movements, body mechanics, and muscle activity. Soft wearable electronic technologies used for gait analysis consist of flexible sensors, microcontrollers, and power supply units. Flexible, stretchable, lightweight, mechanically and temperature stable, and body-compatible materials are used, such as textile polymers, conductive organic polymers, inorganic MXenes, nanomaterials, metals, ionic liquids, and hydrogels [221]. Smart textiles for gait analysis include smart socks, smart shoes and shoe insoles, smart trousers, exosuits, knee pads, skin-mounted textile sensors, and whole-body networks [120,144,221–228]. Gait analysis is essential in medicine (medical diagnostics, rehabilitation or prevention in orthopaedics, physiotherapy, neurology, psychiatry, gerontology), sports (performance improvement, rehabilitation after injuries), biometrics (identification, authentication, surveillance of persons, criminal investigation), and virtual reality and game controllers [144,222,225,226,229].

Self-cleaning. The term self-cleaning in smart textiles refers to coatings that work with two mechanisms [185]. The first mechanism is based on the lotus effect, which is achieved by alkyl- and fluoroalkyl-substituted silanes and fluorine in the form of fluorocarbon polymers. This type of self-cleaning surface is based on the superhydrophobic properties of coated surfaces, which can be achieved by introducing micro nanostructures on a surface, together with the use of low surface energy materials. The lotus leaf has a low surface free energy due to its specific surface structure and composition, which translates into low adhesion between the surface and water droplets. On such a surface, the water forms spherical droplets with a contact angle of more than 150°. In this case, the water droplet rolls down the surface, picks up dirt from the surface, and cleans it. Hydrophobic surfaces with self-cleaning properties can be achieved using fluorinated polymers, such as poly(pentafluorostyrene) and poly(pentafluorophenyl acrylate) [230]. Fluorocarbon resin-coated phase change conductive fibres show excellent hydrophobic and self-cleaning properties [231]. It should be emphasised that fluorinated compounds are being used less and less in coating systems due to possible risks to human health and the environment. Therefore, fluorine-free silicone elastomer coatings have been synthesised, such as polymethyl siloxane (PMS), PDMS, hexadecyltrimethox-ysilane (HDTMS), noctyltriethoxysilane (OTES), octadecyltrimethoxysilane (ODTMS), trichloro(octadecyl)silane (OTS), aminosilicone emulsions, and polyvinylsilsesquioxane (PVSQ) [232–234]. Plant polyphenols were also used to enhance the superhydrophobic properties of polyamide fabric to achieve self-cleaning [235]. The second mechanism is based on photocatalysis, in which the oxidative decomposition of organic dirt and contaminants adsorbed on the surface of textiles takes place under electromagnetic radiation. The residues are then removed by washing. Photo-catalytic activity is demonstrated by coatings with nanoparticles of TiO_2, ZrO_2 nano-composite, TiO_2/SiO_2 composite, ZnO, etc., applied to textiles using sol-gel technology [232].

Fabrication. The term fabrication refers to the production or invention of individual components that make up larger assemblies or end products. In the case of smart textiles, the term is often used in the context of smart textiles that contain miniature parts, such as elements for wearable electronic textiles [231], sensors [236,237], textile-based triboelectric nanogenerators [39], miniaturized energy storage systems composed of micro-flexible supercapacitors [238], miniaturized platforms for autonomous and interconnected textiles applied in personalized healthcare [13], twisted coiled polymer actuators for artificial muscles [239], or embedding optical fibre technology in textile fabrics [240].

Soft robotics. Soft robots aim to be as flexible as living organisms [241]. Soft robotics is inspired by the movement of living organisms and features excellent adaptability and accuracy in performing tasks [242]. Textiles are used in soft robotics either as passive or active soft materials. Passive robust textile auxiliary materials in the form of fibres, yarns, and fabrics reinforce the conventional soft materials to transmit forces and improve anisotropy [241], while active smart textiles in soft robotics in the form of fibres, yarns, or fabrics are used as soft actuators, sensors, or self-powered elements [241,242]. Soft actuators can be actuated by mechanisms such as changes in electricity–voltage, charge, current (electrical actuation), light (optical actuation), temperature (thermal actuation), humidity (solvent and vapour actuation), magnetism (magnetic actuation), or pressure (pneumatic actuation) [242,243]. Reversible deformation (e.g., elongation, contraction, bending, or rotation) is based on changes in the volume, distance, or order of the material [241,242]. Soft robotics with flexible actuators can be used in medical robots (surgery, drug delivery, motion assistance, rehabilitation), actively deformable garments (functional compression), soft human–machine interfaces (wearable manipulation devices, haptic feedback), bioinspired robots (humanoid, animal, or plant-like soft robots), and technical robots for remote sensing and manipulation [241–243].

Based on the results of the above analysis, it can be stated and deduced that, from a technical point of view, modern smart textiles bring together at least two major research and industrial sectors and their multidisciplinary know-how: smart chemical/textile materials and smart miniaturised electronic technologies. In this regard, smart textile materials have mainly evolved toward organic, nano, composite, conductive, or semiconductive, while electronics aim to be miniaturised, wearable, washable, wireless, fibre- or yarn-based, flexible, stretchable, printable, and integrated. Development has also been driven by innovative combinations of new materials, their unique structures, new technologies, and better integration of components.

Smart functionalities and utilities of innovative smart textiles offer amazing new opportunities in the fields of medicine and health management, sensing and monitoring, environmental protection, personal safety, soft robotics, Internet of Things, Industry 4.0 and 5.0, as well as sports and leisure, fashion, decoration, and entertainment. New conductive yarns, miniaturised textile sensors, actuators, connectors, and nanotechnologies for energy harvesting enable the discrete integration of electronic components into wearable clothing and other smart textile products. Signals sensed by the sensors are wirelessly transmitted to local or global networks. Textile-based EMI shielding solutions have become available to consumers.

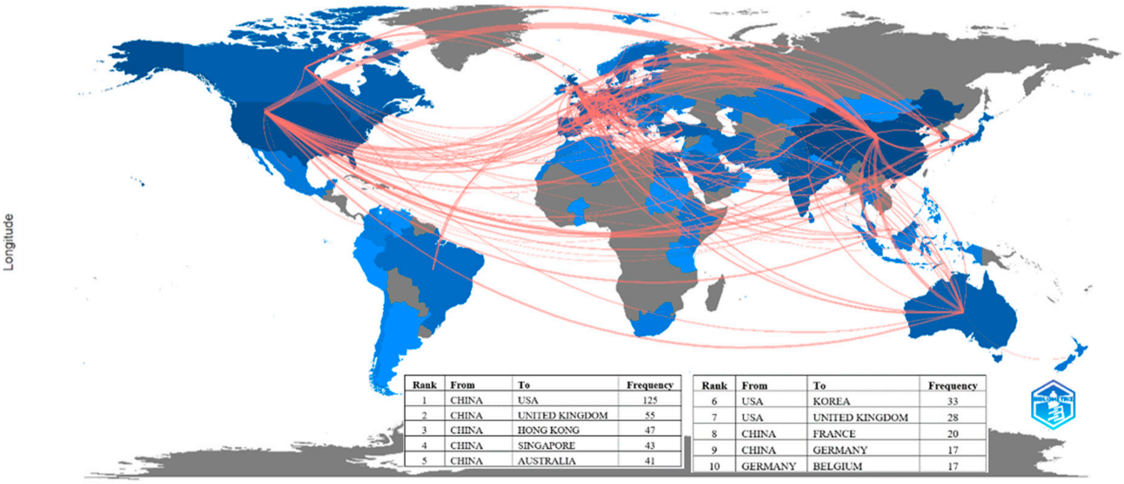
Energy supply has become one of the most important issues and research challenges of our time. Smart textiles with embedded microsystems, such as triboelectric nanogenerators, thermoelectric nanogenerators, or photovoltaics, offer promising possibilities for energy harvesting. Moreover, self-powered textile-based sensors, actuators, and other devices can become energetically sustainable elements of global networks.

Scientific research that indicates technological feasibility, however, does not automatically lead to commercial success. Despite recent advances, there is a significant gap between commercial needs and the academic state of the art. Numerous prototypes and exciting research results have been described, but exploitation and commercialization still seem problematic. Therefore, efforts should be made to select the best viable solutions, improve their reliability, robustness, fabrication, sustainability, and scalability, and produce them in larger quantities at acceptable prices.

It seems that the focus of smart textiles remains on the technological level. Higher levels of intelligence have already been achieved through the integration of various micro and nanomaterials and technologies into individual products. However, the sustainability and recycling of complex elements of smart textiles appears to be one of the remaining and under-researched issues. Little research has been conducted to find solutions for environmentally sustainable design, production, and end-of-life management of smart textile products. Further study and development of environmentally sustainable solutions for smart textiles are urgently needed. Therefore, recycling, reuse, or remanufacturing of complex smart textiles, as well as eco-design strategies, development of renewable natural materials, and application of circular economy principles to smart textiles, are interesting opportunities for future research. These issues, along with international standardisation and legislation, should be resolved soon, as the global market for advanced smart textiles is growing rapidly.

3.2.2. Co-Authorship Analysis of Countries

When authors from two or more countries contribute to a given article, the authors' countries are considered as collaborating countries; the countries are linked based on the number of publications they have co-authored [58]. Figure 13 shows the country collaboration map on smart textiles literature around the world. The USA and China top the list with 125 co-authored publications, followed by China and the UK with 55, China and Hong Kong with 47, China and Singapore with 43, and China and Australia with 41 collaborations.



Rank	From	To	Frequency
1	CHINA	USA	125
2	CHINA	UNITED KINGDOM	55
3	CHINA	HONG KONG	47
4	CHINA	SINGAPORE	43
5	CHINA	AUSTRALIA	41

Rank	From	To	Frequency
6	USA	KOREA	33
7	USA	UNITED KINGDOM	28
8	CHINA	FRANCE	20
9	CHINA	GERMANY	17
10	GERMANY	BELGIUM	17

Figure 13. Countries' collaboration world map in smart textiles research.

The analysis of country cooperations reveals that in the field of smart textiles, China has the most extensive cooperative relationships with other countries in the world.

3.3. Originality and Limitations of the Study

To the best of our knowledge, this study is the first attempt to provide a comprehensive bibliometric analysis in the domain of smart textiles, using terminology, definitions, and categorization of different types of smart textiles and textile products according to the standard ISO/TS 23383. This served as the basis for the selection of keywords for further analyses, for the extraction of the document sample from the Scopus database, for the bibliometric analyses using VOSviewer (v1.6.19) and Bibliometrix (v4.3.0)/Biblioshiny (v4.1) as tools for science mapping, and for content analysis and review.

Accordingly, the novelty and value of this paper is to provide a new comprehensive overview of the smart textiles research field, to better understand the core knowledge structure of the research domain, to highlight the key research areas and directions, to provide researchers with a broader insight into new technologies, materials, and products, to identify knowledge gaps and develop new research ideas, and to position their own research contributions in the smart textiles landscape.

It is important to mention some limitations to the present study. First, a science map cannot represent more than what is contained in the data on which it is based. The literature data sources for this study were, after several search queries in different databases, limited to the Scopus database. The inclusion of other databases, such as Web of Science, Google

Scholar, or patent databases like Espacenet, could have potentially uncovered further insights not included in this study. Second, we may have missed some articles that did not use searched keywords in the abstract, title, or keyword fields. In addition, we did not include grey literature or articles published in languages other than English in our analysis.

The nature of the bibliometric methodology is also a limitation in itself. In particular, because bibliometric analysis is quantitative in nature, the qualitative conclusions of bibliometrics can be quite subjective, and the relationship between quantitative and qualitative results may be unclear [244].

Petrovich [82] discussed the objectivity of science maps. The creation of science maps involves several methodological and technical decisions from the science cartographer, such as the unit of analysis, the mapping technique, the normalisation method, the visualisation approach, the clustering algorithm, and so on, and each decision affects the results [82]. These decisions in the science map workflow should be transparent in order to warrant the reproducibility of science maps [245].

Several authors [58,59,246] also recommended using co-word analysis in combination with co-citation analysis (past) or bibliographic coupling (present) to enrich understanding and interpretations of thematic clusters, to gain additional insights into the dynamics of the field and to predict forthcoming trajectories.

However, in this study, we have considered and used as many recommendations from authors in the field of bibliometrics as possible, so we consider the presentation to be comprehensive and integrated.

4. Conclusions

For historical reasons and due to the rapid development in this field, the terminology and definitions for smart textiles have only recently been harmonised and standardised. According to ISO/TR 23383, smart textiles must reversibly interact with their environment and respond or adapt to changes in the environment. Therefore, the term smart textiles has been distinguished and separated from the term functional textiles, in which the functionality exceeds the normal textile function but is pre-defined. In the early stages of development, the terms were used rather inconsistently, which is also reflected in the literature.

In accordance with the research questions and the results of the analyses, the following conclusions are drawn.

RQ1: What are the global research outputs and publication trends?

According to the Scopus database search, a total of 5810 documents on smart textiles were published in 1739 different journals and conference proceedings from 1989 to 2022, with an average growth rate of 22%. There has been exponential growth in the last 10 years, and most of the papers have been published in the last few years. The field of smart textiles is highly interdisciplinary, with engineering, materials science, computer science, chemistry, and physics being the top five disciplines out of more than twenty subject areas. Based on the number of publications in the Scopus database, shape change, capacitive, and piezoelectric smart textiles are the three fastest-growing groups, followed by chromic, photovoltaic, phase change, and thermoelectric types of smart textiles.

RQ2: What are the most relevant/influential documents, authors, sources, and countries in the field of smart textiles?

The ten most cited documents in the field of smart textiles deal with 4D biomimetic printing and shape memory polymers, wearable sensors and other wearable electronic systems, energy-harvesting textiles, and PCMs. The two most prolific authors in the field of smart textiles, Beeby, Stephen P., and Torah, Russel N., are from the University of Southampton, UK. Their research interests include electronic textiles, textile wearables, nanotechnologies for energy harvesting, and biomedical applications. The author with the highest number of citations (6556) is Wang, Zhong Lin from the Chinese Academy of Sciences, Beijing, China. His recent publications in the field of smart textiles are related to energy harvesting, including triboelectric nanogenerators, self-charging textile systems, physiological and motion sensors, and EMI shielding.

In terms of the number of documents, the leading journals are *Sensors*, *ACS Applied Materials and Interfaces*, and *Textile Research Journal*, which are also on the list of most cited sources, while *Advanced Materials* has the highest number of citations. Conferences provide high-quality new information on research developments in a short period of time; among the ten most productive sources in the field of smart textiles research are five conference proceedings.

In absolute numbers, China is the country with the most publications on smart textiles, followed by the USA, South Korea, the UK, and Germany.

RQ3: What have been the main research topics, and what might be the focal points for future research?

Co-word analysis of the authors' keywords reveals five thematic clusters that highlight the following research areas in smart textiles:

- Smart textile materials, technologies, applications, and their properties (smart textiles cluster);
- Electronic textiles, their components, such as sensors and conductive yarns, their design, and their integration into computer networks (E-textiles cluster);
- Smart fabrics for clothing, their special technologies and materials, design and properties of the products (smart fabrics cluster);
- Research at the interface between wearable electronic devices and smart textiles (wearables cluster);
- Electronic devices integrated into textiles to be worn on the body (wearable technologies cluster).

Therefore, research on smart textiles is largely concerned with new materials and technologies related to electronic textiles and electronic components embedded in e-textiles.

Specifically, keywords with a high occurrence and most recent average publication year indicate the following newest research priorities in the smart textiles domain (Figure 14): power generation (triboelectric nanogenerators, thermoelectrics, Joule heating), conductive materials (MXenes, liquid metal, silver nanoparticles, fibres), textile sensors (strain sensors, self-powered sensors, gait analysis), special products (artificial muscles, soft robotics, EMI shielding, fabrication), and advanced properties of smart textiles (self-powered, self-cleaning, washable, sustainable).

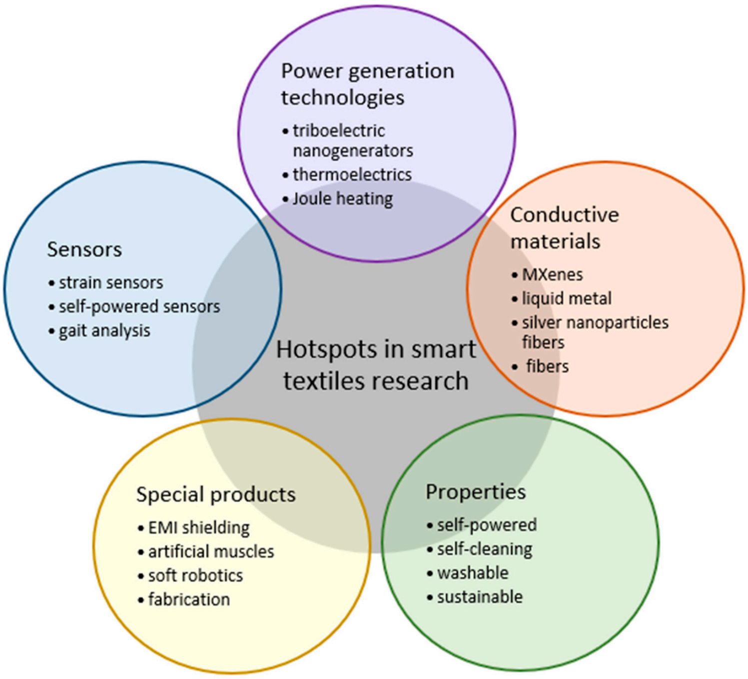


Figure 14. Newest research priorities in the domain of smart textiles.

RQ4: What is the pattern of scientific collaboration on smart textiles at the country level?

Co-authorship analysis of countries shows that China has the most extensive cooperative relationships with other countries in the world, with most publications co-authored with the USA and UK.

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