Review

Smart Textiles: A Review and Bibliometric Mapping

Irena Sajovic * , Mateja Kert , Bojana Boh Podgornik

Posted Date: 6 September 2023

doi: 10.20944/preprints202309.0314.v1

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

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 6 September 2023 doi:10.20944/preprints202309.0314.v1

Review

Smart Textiles: A Review and Bibliometric Mapping

Irena Sajovic *, Mateja Kert and Bojana Boh Podgornik

University of Ljubljana, Faculty of Natural Sciences and Engineering, Department of Textiles, Graphic Arts and Design, Aškerčeva cesta 12, SI-Ljubljana, Slovenia; irena.sajovic@ntf.uni-lj.si, mateja.kert@ntf.uni-lj.si, bojana.bohpodgornik@ntf.uni-lj.si
* Correspondence: irena.sajovic@ntf.uni-lj.si; Tel.: + 386 1 200 32 54

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 5,810 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), specialty 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

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.

Nevertheless, various definitions of smart textiles appeared in 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 are called **active smart textiles**, with an actuating function - they sense a stimulus from the environment and respond to it,
- the third generation is named the **advanced** or **very smart** or **ultra smart textiles** that perceive, respond and adapt to changes in the environment.

In 2020, the terminology, technical definitions, categorisation and applications of smart textiles 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, construction of finishing [11]. Smart textiles (named also intelligent or interactive textiles) interact reversibly by 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.

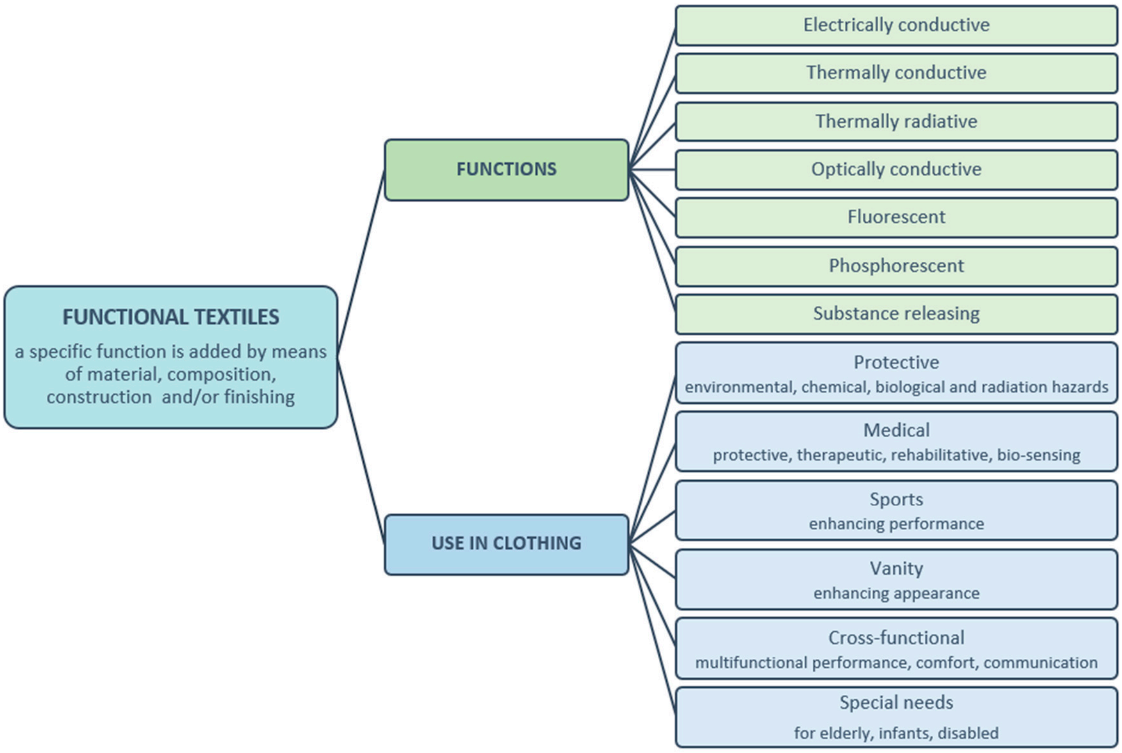


Figure 1. Functional textile products [11,12].

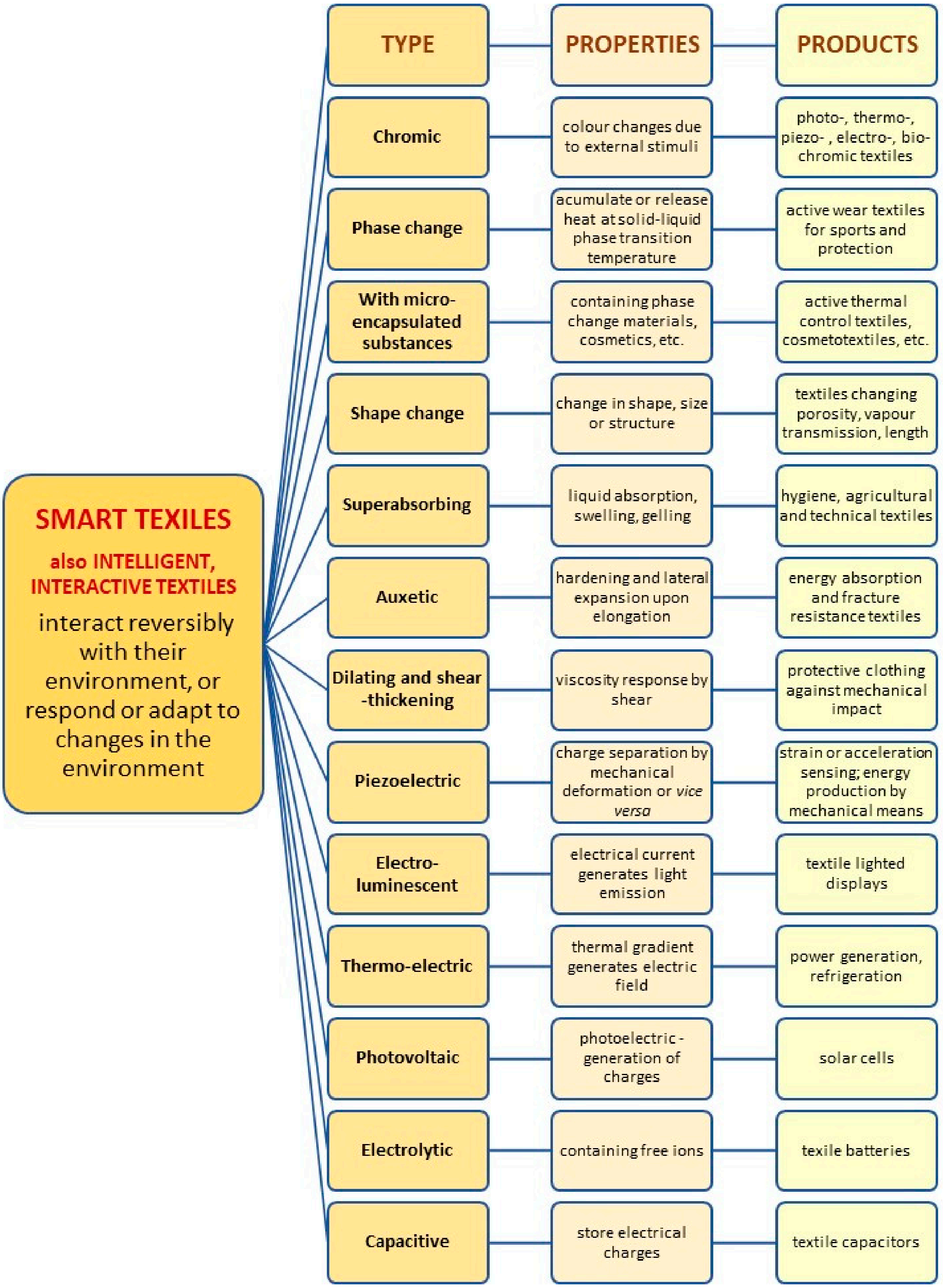
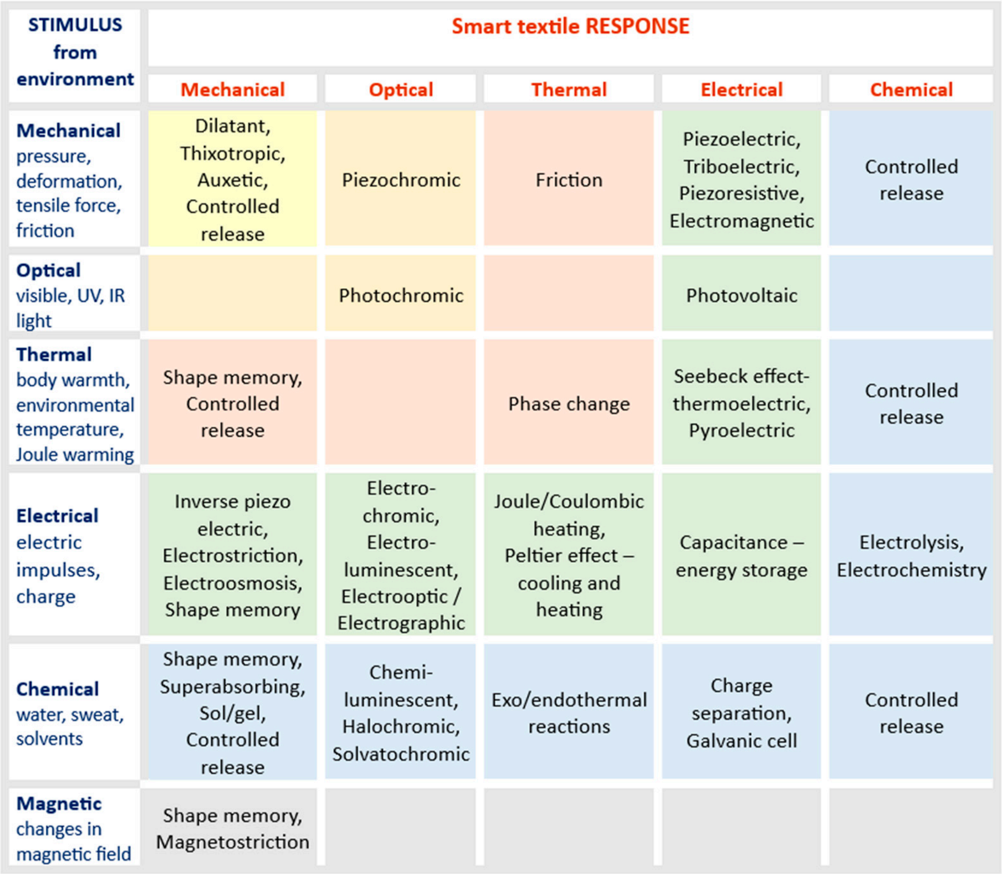


Figure 2. Smart (intelligent) textile types, properties and products as described by technical report ISO/TR 23383 [11].



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 [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), 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 amount of 3.8 billion US dollars in 2022. Experts predict that the market will reach US$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 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] on 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 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 field, handling large amounts of scientific data, and producing high-impact research.

Only 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 the 2,647 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 the Cite Space 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 4,153 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 Scopus database, using the VOSviewer tool. Popescu and Ungureanu [23] reviewed green nanomaterials for smart textiles dedicated to environmental and biomedical applications, and used WOSviever 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 1,735 articles from the Web of Science, using visualisation software CiteSpace, combined with Google Earth. Halepoto et al. [56] analyzed 2,898 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 scattered, fragmented, 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. More specifically, the objectives of the research were to conduct 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 [64]. Two types of bibliometric techniques can typically be used for bibliometric analysis: performance analysis and science mapping analysis (SMA) [65–68]. **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 [69–71]. 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) [65]. On the other hand, **science mapping** or bibliometric mapping examines the **relationships** between research constituents [66,70–73]; it aims to visually represent and show the conceptual, social or intellectual structures of scientific research, as well as its evolution, development and dynamics [73–76] 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 [60,74,77,78].

This study follows science mapping methodology previously implemented in other bibliometric analyses [65,76,79–83]. 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 search query were the following:

(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, 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 checked by an expert in the field to make a final decision.

The final search was conducted in June 2023. Since the data for 2023 were still very 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.

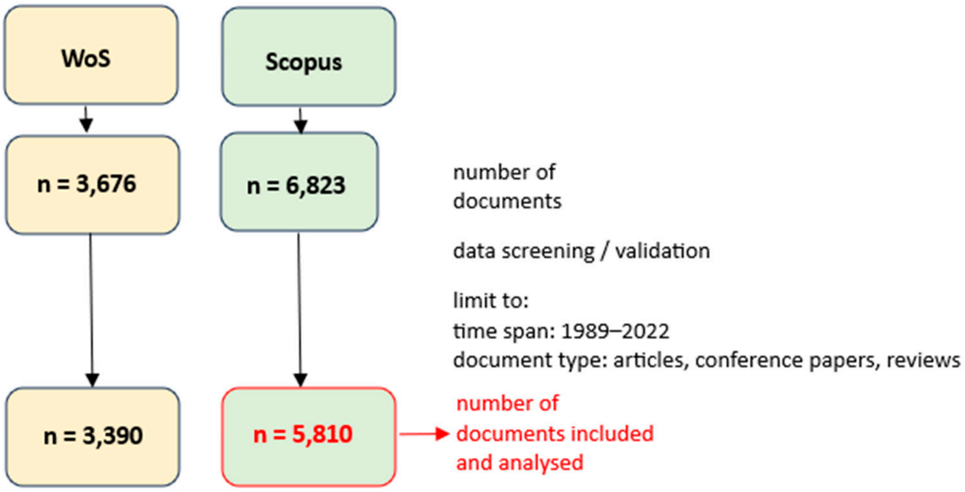


Figure 4. Flowchart of the search in the WoS (Topic search) and Scopus database (Title-Abstract-Keyword search).

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 Scopus** was also justified by the fact that it is a larger database compared to other competing databases, such as Web of Science [58,59]. A large data file in Scopus, containing 5,810 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 [60] were used for basic statistical analyses and the visualisation of bibliometric results. VOSviewer software was utilized to create and analyse networks of authors' keywords connected by co-occurrence links, and to create, visualise and explore bibliographic maps [61], and Bibliometrix/Biblioshiny for the country collaboration map.

To improve the quality of the initial raw data set for the science mapping analysis, the **preprocessing** of initial raw data set was essential. The VOSviewer thesaurus file was created to merge terms, such as singular and plural (e.g., "biosensor" and "biosensors"), synonyms (e.g., "e-textiles" and "electronic textiles"), spelling differences (e.g., "fibre" and "fiber"), abbreviated and full terms (e.g., "FBG" and "Fibre Bragg Grating") and author name or source title (e.g., Tröster Gerhard, Troester G., Troster G. and Tröster G.). The same thesaurus file was also employed 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. VOSviewer applied the association strength normalisation by default, which was described in detail by van Eck and Waltman [61].

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 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 sizes of an item's label and the circle were determined as a function of the item's weight: the higher 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 represented 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 to provide new insights and useful knowledge for research and science policy purposes, as suggested by [62,63]. The workflow of the science mapping methodology applied in this study is shown in Figure 5.

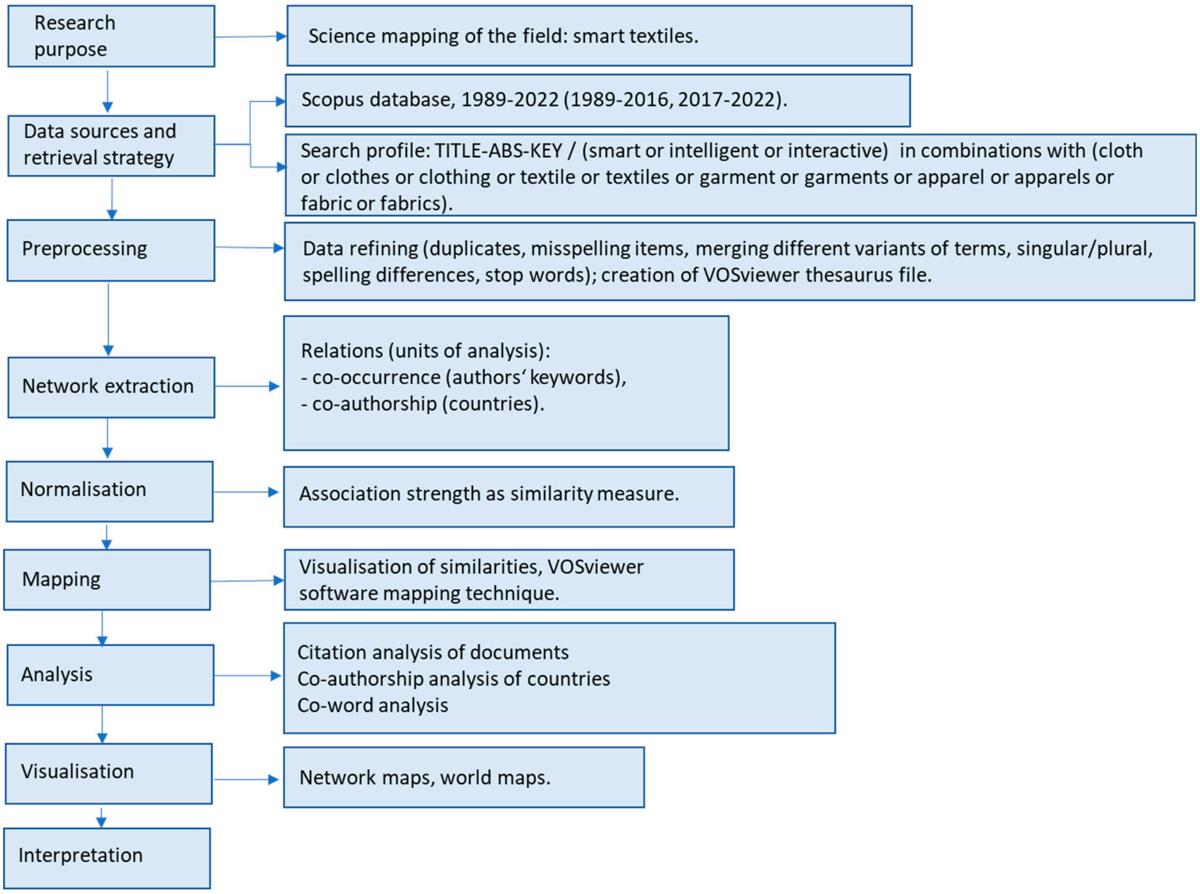


Figure 5. Workflow of science mapping applied in this study.

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.

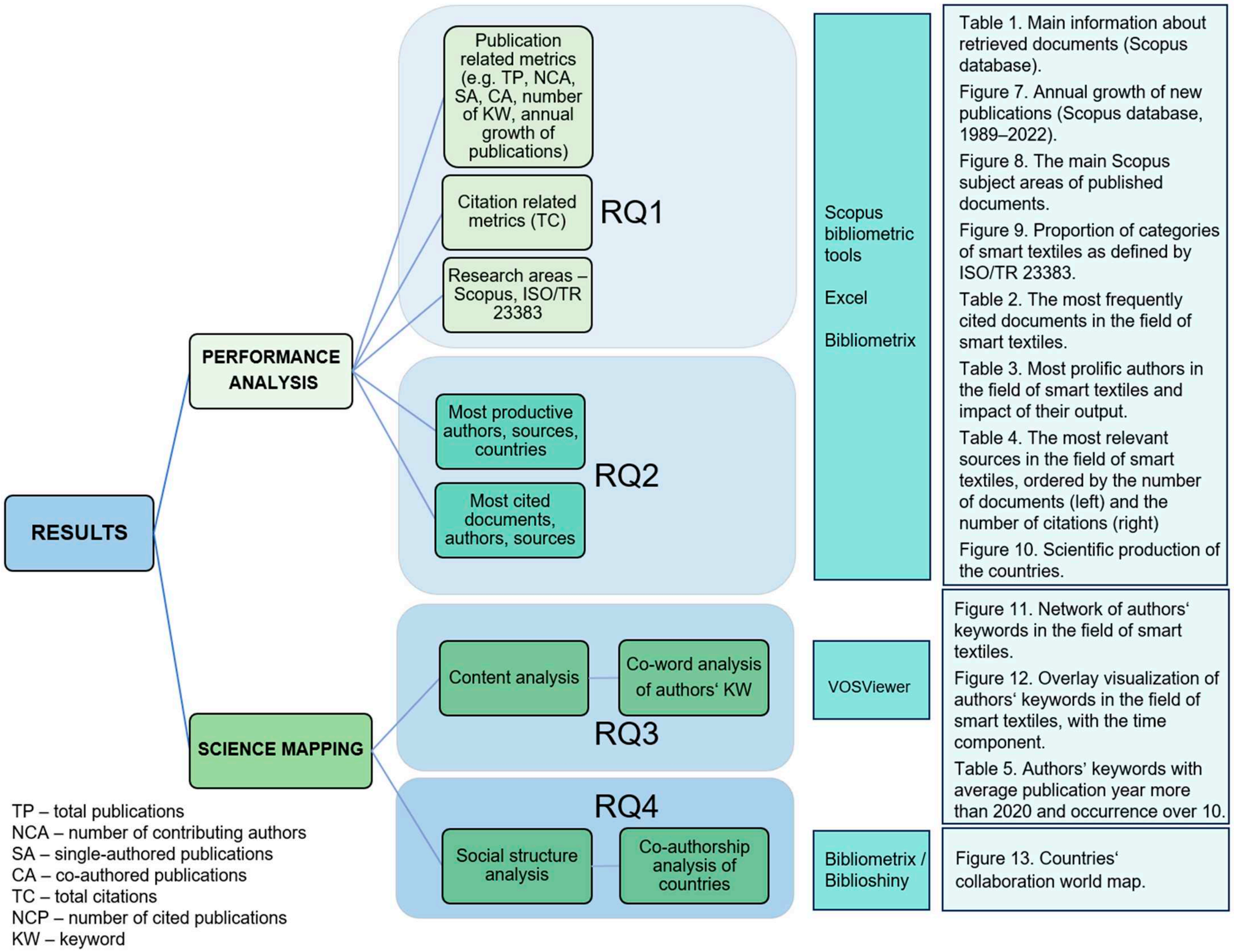


Figure 6. Presentation of results.

3.1. Performance analysis

3.1.1. Overview of retrieved documents and trends

A total of 5,810 documents from 1,739 sources published between 1989 and 2022 was obtained from the Scopus database; main characteristics of retrieved documents are listed in Table 1.

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

Bibliometric items	Findings
Timespan	1989–2022
Sources (journals, proceedings, etc.)	1,739
Documents	5,810
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	3,560
Conference papers	1,879
Reviews	371

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.

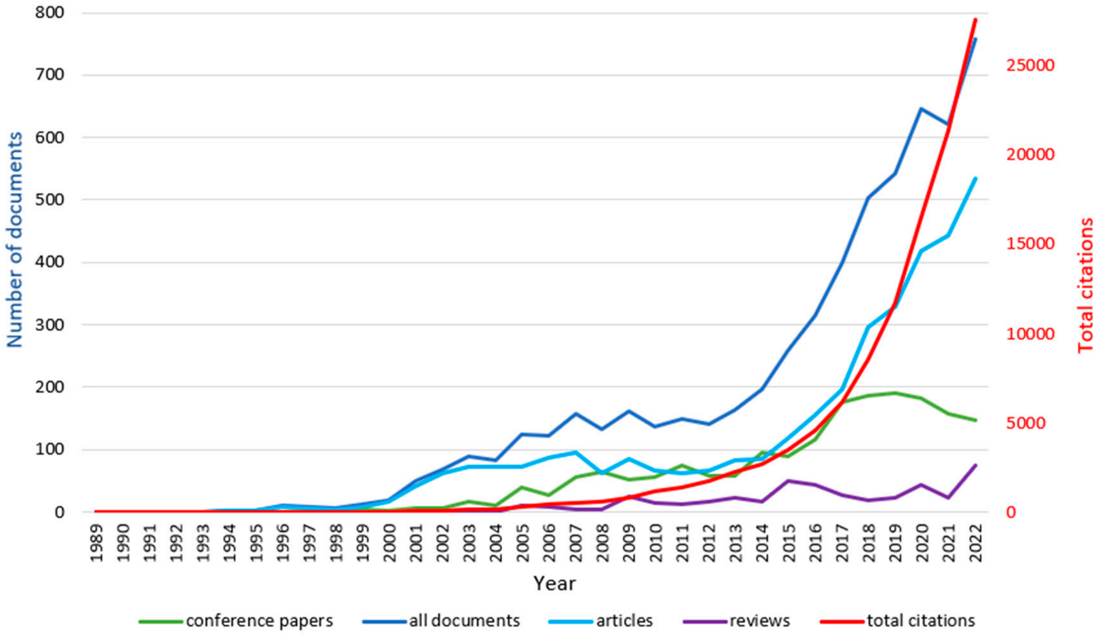


Figure 7. Annual growth of new publications (Scopus database, 1989–2022).

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

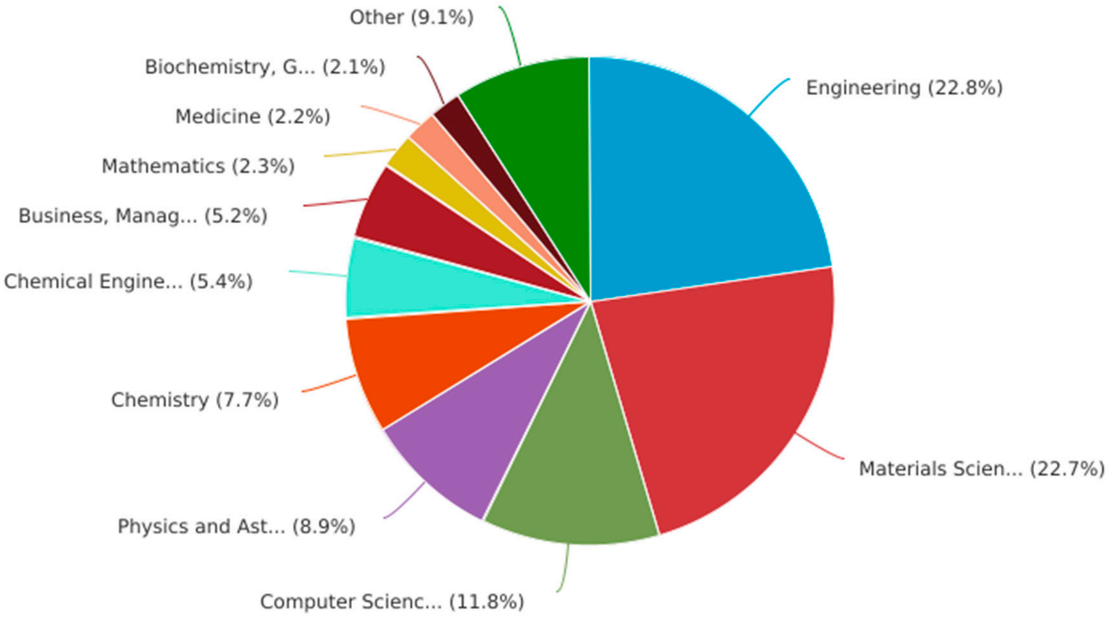


Figure 8. The main Scopus subject areas of published documents on smart textiles.

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.

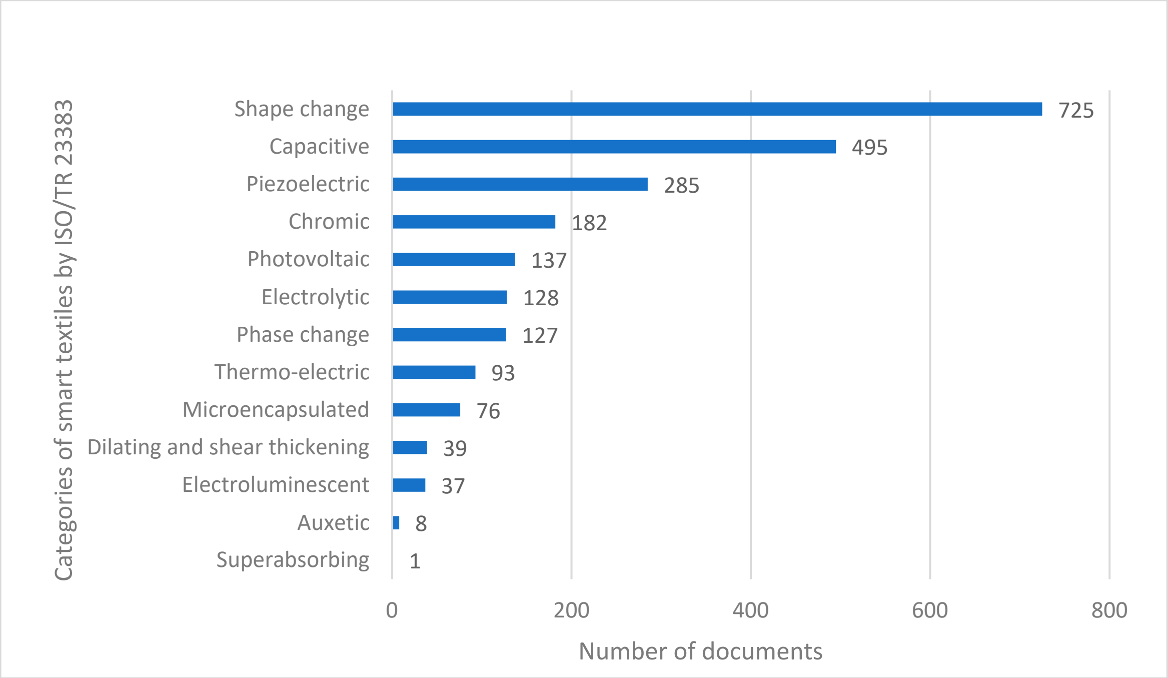


Figure 9. Proportion of categories of smart textiles as defined by ISO/TR 23383, measured by the number of publications found in the Scopus database.

3.1.2. Analysis of oldest and most cited documents

The **oldest** paper related to smart textiles published in 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 lead 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., & Lewis, J. A. (2016). **Biomimetic 4D printing**. Nature Materials, 15(4), 413-418. doi:10.1038/nmat4544	1.982	[94]
2	Pantelopoulos, A., & 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., & 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., & 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., & 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., & 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., & 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] prevail review papers, 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 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 structure, 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 textile assures simultaneously harvesting 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 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] have looked at the materials and manufacturing process in the production of smart textiles, and have 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 1,300 times. His broad area of research focuses mainly on the 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 1,023 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].

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

Author	Institution	Number of documents	Number of citations
Beeby, Stephen P.	University of Southampton, UK	**61**	1,300
Torah, Russel N.	University of Southampton, UK	**58**	1,023
Tudor, M. John	University of Southampton, UK	45	895
Koncar, Vladan	ENSAIT Ecole Nationale Supérieure des Arts et Industries Textiles, Roubaix, France	43	1,151
van Langenhove, Lieva	Universiteit Gent, Belgium	42	1,757
Tröster, Gerhard	ETH Zürich, Switzerland	32	1,185
Tao, Xiaoming	Hong Kong Polytechnic University, Hong Kong	30	1,036
Yang, Kai	University of Southampton, UK	30	709
Wang, Zhong Lin	Chinese Academy of Sciences, Beijing, China	29	**6,556**
Dunne, Lucy E.	University of Minnesota Twin Cities, Minneapolis, USA	28	371

Wang, Zhong Lin from 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 specialized 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 by 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 used to identify the most important sources related to the research of smart textiles. This type of analysis can be helpful for researchers to find relevant literature and select the most appropriate journal to publish their own research findings. A total of 1,739 different publication sources in the field of smart textiles were identified. The sources are 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**	**6,488**
2	**ACS Applied Materials and Interfaces**	**132**	2	ACS Applied Materials and Interfaces	5,985
3	**Textile Research Journal**	**121**	3	Sensors	5,323
4	Proceedings – International Symposium on Wearable Computers, ISWC*	70	4	ACS Nano	5,055
5	Proceedings of SPIE – The International Society for Optical Engineering*	67	5	Advanced Functional Materials	4,495
6	IEEE Sensors Journal	66	6	Nano Energy	2,521
7	Conference on Human Factors in Computing Systems – Proceedings*	62	7	Textile Research Journal	2,298
8	ACM International Conference Proceeding Series*	60	8	Sensors and Actuators, A: Physical	2,043
9	Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*	59	9	Smart Materials and Structures	1,997
10	Journal of The Textile Institute	56	10	IEEE Sensors Journal	1,877

* conference proceedings.

Scientific meetings are known in smart textiles research, providing high quality new information on research developments in a short time. Among the ten most productive sources for smart textiles five 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 their 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 %).

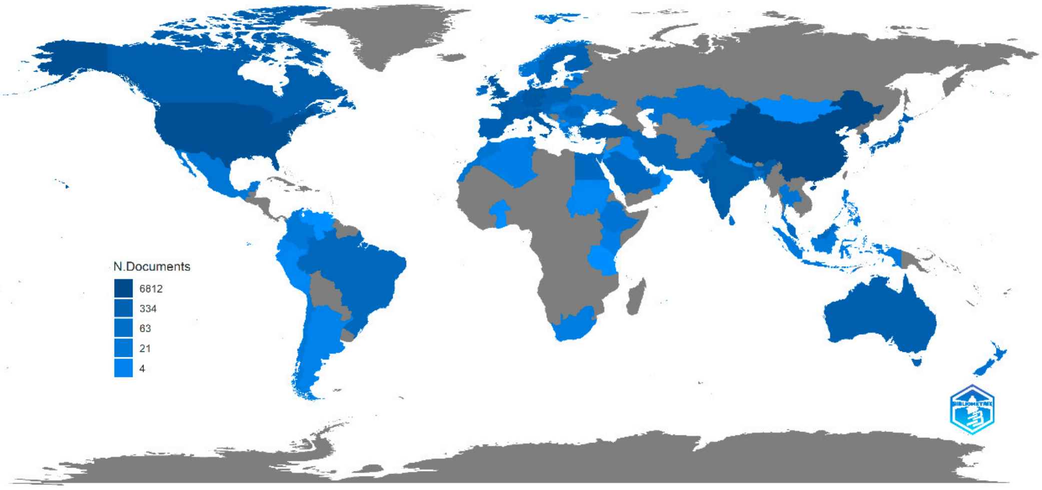


Figure 10. Scientific production of the countries in the domain of smart textiles.

3.2. Science mapping

3.2.1. Co-word analysis

The co-word analysis was used to recognize (a) the conceptual structure of the smart textile literature, (b) most frequently used keywords used by researchers, and (c) 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 [64]. A total of 10,502 authors' keywords were identified in the raw data set of 5,810 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-occurence 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. Resulting clusters may be used as an indicator for the recognition of main research areas within the field of smart textiles.

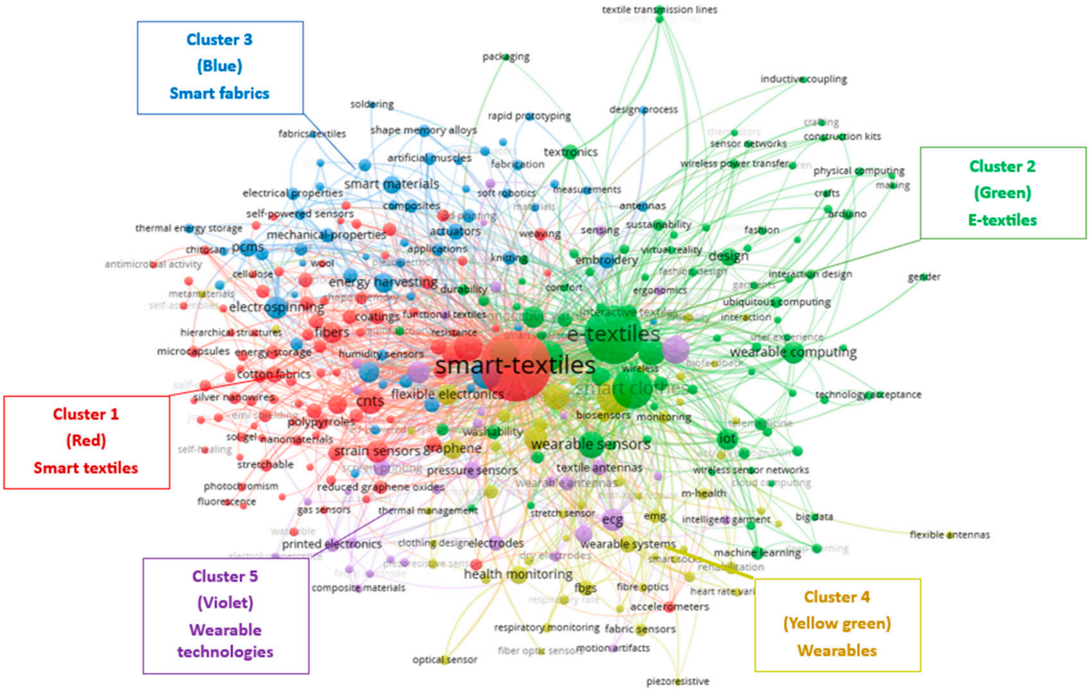


Figure 11. Network of authors' keywords in the field of smart textiles.

Clusters of KW as indicators of research areas

Cluster 1 (Red) was formed around the keyword **SMART TEXTILES** (occurrence 1,021), 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 other four 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, 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, 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 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, 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 is 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 being 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 population 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 fabrics items that are designed for clothing, from the viewpoints of textile technologies, specialized smart technologies and materials, as well as 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, innovation.

Cluster 3 is oriented towards 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 and electrospinning can be used to create smart fabrics, in addition to embroidery and 3D printing. 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, 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. The 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, 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 the 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), as well as 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 keywords with highest occurrence (>25) in this cluster are intelligent textiles, ECG, electrodes, textile electrodes, textile antennas, wearable antennas, pressure sensors, printed electronics, 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, 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 in 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 used and 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, textile electrodes became typical in the middle of the observed period. Research topics such as liquid metal, MXenes, textile electronics, triboelectric nanogenerators, have gained importance in the last 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).

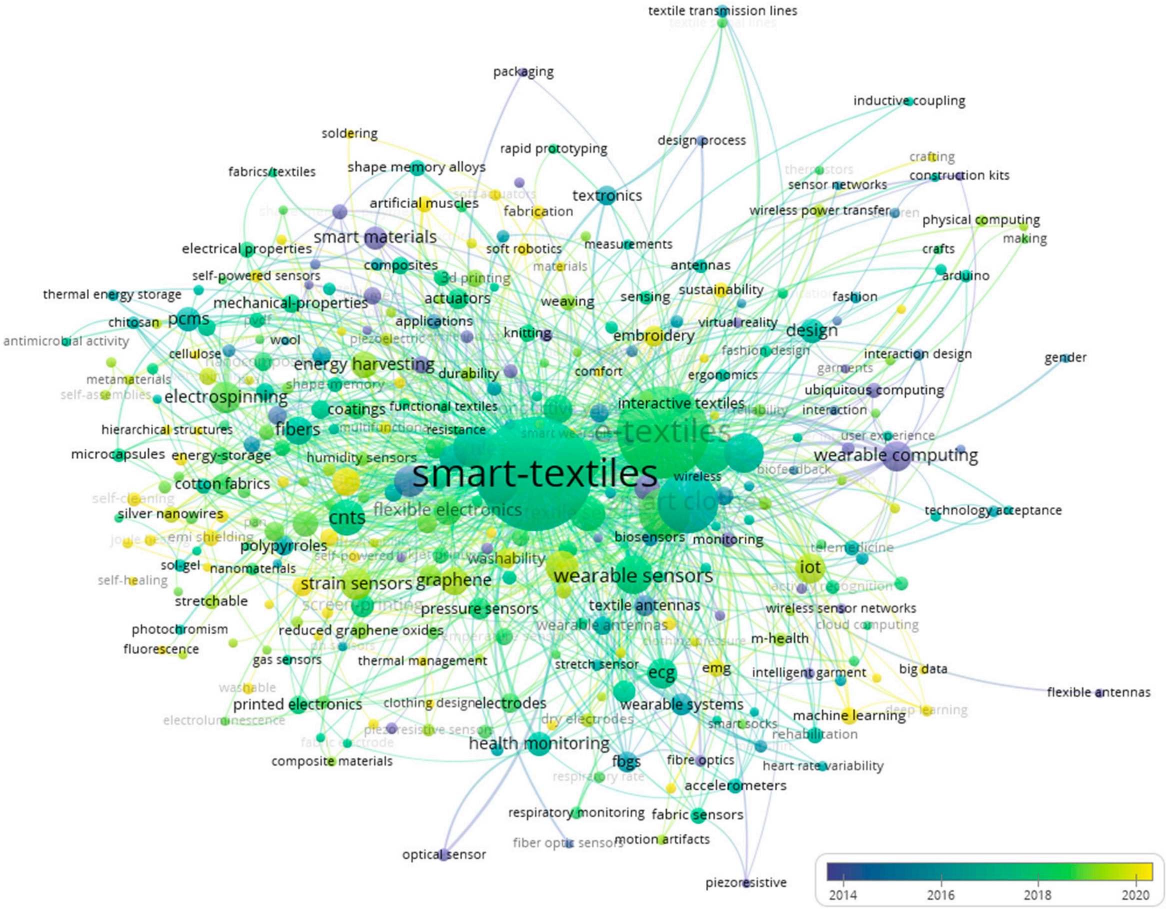


Figure 12. Overlay visualisation of authors' keywords in the field of smart textiles, with the time component.

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 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 environment, 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 be 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, and fabrics, 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 are 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, 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; these fibres are stretchable, conductive, with good pliability and high resistance-strain sensitivity [135]; washable smart textiles based on triboelectric nanogenerator arrays used as bedsheet for real-time and self-powered sleep behaviour monitoring [136]; self-powered smart gloves based on the triboelectric effect and electrostatic induction, that 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].

doi:10.20944/preprints202309.0314.v1

Self-powered sensors. Self-powered sensors constitute an important sub-class of self-powered products. Based on innovative self-powering technologies, they are harvesting 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 creating and for energy supplying [21]. Examples of smart textiles as self-powered sensing platforms include a textile thermoelectric generator for monitoring body temperature [139], and a smart bedsheet for monitoring human sleep [140], smart textile socks as a human-computer interface in a virtual reality space [141], a smart textile glove for human sign language recognition [142], a textile magnetoelastic generator for monitoring cardiovascular parameters [143], piezoelectric smart textile for sensing heart beats and speech [144], a textile biofuel cell that can generate electricity from swear enzymes to monitor the concentration of ions in sweat [145].

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 [10,146]. Solution immersion, layer-by-layer deposition, and sonochemical processes are established methods to deposit silver nanoparticles on various textile materials [146]. 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 a temperature- and pH-responsive microgels applied to cotton fabrics [147]; 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 the dip and dry coating with silver nanoparticles for applications in EMI shielding, lightweight batteries, and molecular electronic devices [148], use of PVDF nanofibres coated with nonpolar silver nanoparticles as electrodes for piezoelectric sensors [149], 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 [150].

Strain sensing. Mechanisms for detecting mechanical deformation in strain sensing are based on resistive, capacitive, piezoelectric, as well as electrical time-domain reflectometry and triboelectric effects [151]. 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) [20,151–154]. 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 [20,151]. Moreover, they can be self-powered, [152] or self-healing [153]. 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 [20,151,152].

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]. Second, numerous positive contributions of smart textiles to sustainability are highlighted in the following areas: environmental monitoring (temperature and humidity sensors, gas sensors); fresh water purification and harvesting (filtering, mist collection, collection by coalescence or mechanical squeezing); personal protection (warming, cooling, electromagnetic protection, EMI shielding, protection against UV radiation, toxic substances and microorganisms); power supply on the body with energy harvesting and storage (triboelectric nanogenerators, thermoelectric generators, photovoltaic textiles, textiles with perovskite solar cells, dry batteries, flexible electrodes, and wearable all-in-one power sources that integrate energy harvesting and storage capability into one textile [155].

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 [156]. Materials that convert electrical, chemical, or thermal energy into a shape change can be used to form artificial muscles. Conductive CNT fibres have been used to create artificial muscles [157]. 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 [158,159]. Other examples include woven hydraulic artificial muscles [160], aerogel fibres [161], printed hydrogel artificial muscles [162], 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 [163]. 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 [164–170]. 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 in 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 [171], filling hollow silicon fibres, including conductive yarn, with a mixture of silicone rubber and curing agent [140], coating triboelectric yarn containing conductive CNTs with PVDF fibres deposited by a tailored electrospinning process [172], increase the washability of smart textiles. It can thus be said that 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 [173]; they couple the triboelectric effect and electrostatic induction to convert mechanical energy into electricity [41]. Proper choice of materials and structures enhances performance [173]. Many designs and combinations of materials have been developed and fabricated. In general, triboelectric nanogenerators consist of substrates, electrode layers, and triboelectric layers [174]. 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(Ppheylene-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 [40,174]. 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 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 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 [175]. 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 [120,141,175–182]. 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), virtual reality and game controllers [141,176,179,180,183].

Self-cleaning. The term self-cleaning in smart textiles refers to coatings that work with two mechanisms [184]. 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. 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 coatings have been synthesised, such as PDMS, hexadecyltrimethoxysilane (HDTMS), noctyltriethoxysilane (OTES), octadecyltrimethoxysilane (ODTMS), trichloro(octadecyl)silane (OTS), aminosilicone emulsions and polyvinylsilsesquioxane (PVSQ) [185]. 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. Photocatalytic activity is demonstrated by coatings with nanoparticles of TiO_2, ZrO_2 nanocomposite, TiO_2/SiO_2 composite, ZnO, etc., applied to textiles using sol-gel technology [185]. Fluorocarbon resin coated phase change conductive fibres show excellent hydrophobic and self-cleaning properties [186].

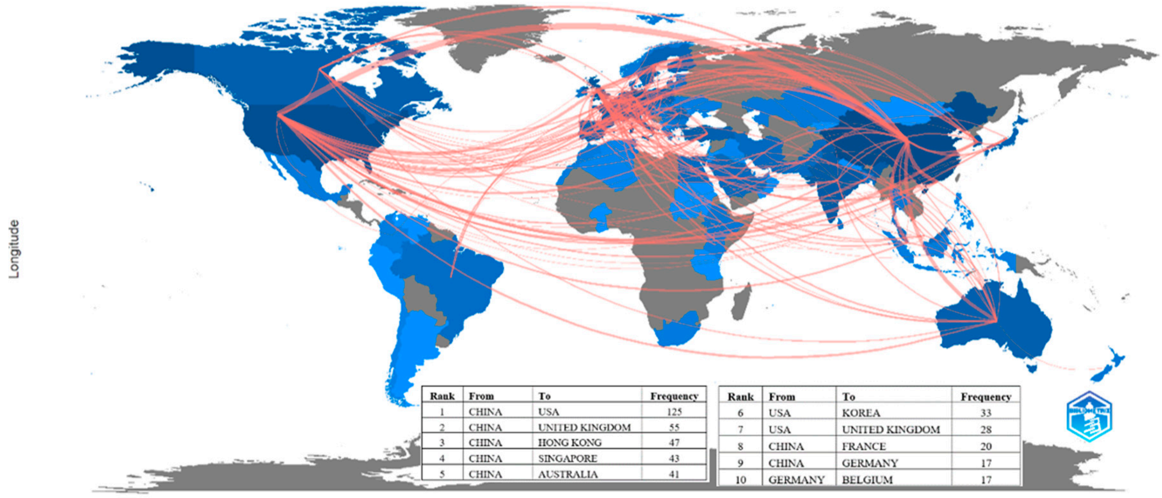
Fabrication. The term fabrication refers to the production or invention of individual components that make up larger assemblies or end products. In the case of smart textiles, the term is often used in the context of smart textiles that contain miniature parts, such as elements for wearable electronic textiles [187], sensors [188,189], textile-based triboelectric nanogenerators [39], miniaturized energy storage systems composed of micro-flexible supercapacitors [190], miniaturized platforms for autonomous and interconnected textiles applied in personalized healthcare [13], twisted coiled polymer actuators for artificial muscles [191], or embedding optical fibre technology in textile fabrics [192].

Soft robotics. Soft robots aim to be as flexible as living organisms [193]. Soft robotics is inspired by the movement of living organisms and features excellent adaptability and accuracy in performing tasks [194]. 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 [193], 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 [193,194]. 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) [194,195]. Reversible deformation (e.g., elongation, contraction, bending or rotation) is based on changes in the volume, distance or order of the material [193,194]. 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 [193–195].

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 [64]. 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.

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.



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.

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

doi:10.20944/preprints202309.0314.v1

extraction of the document sample from the Scopus database, for the bibliometric analyses using VOSviewer and Bibliometrix/Biblioshiny 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 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.

There are also some limitations to the present study that should be mentioned. 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, e.g., Web of Science, Google Scholar or patent databases such as Espacenet, may have disclosed additional insights not revealed by this study. Second, we may have missed some articles that did not use searched keywords in the title, abstract or keyword fields. Furthermore, we did not include grey literature, and we did not include articles published in languages other than English.

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 [196].

Petrovich [62] discussed the objectivity of science maps. The creation of a 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 [62]. These decisions in the science map workflow should be transparent in order to warrant the reproducibility of science maps [197].

Several authors [64,65,198] also recommended to use 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 5,810 documents on smart textiles were published in 1,739 different journals and conference proceedings from 1989 to 2022, with an average growth rate of 22%. There has been an 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 (6,556) 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 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 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).

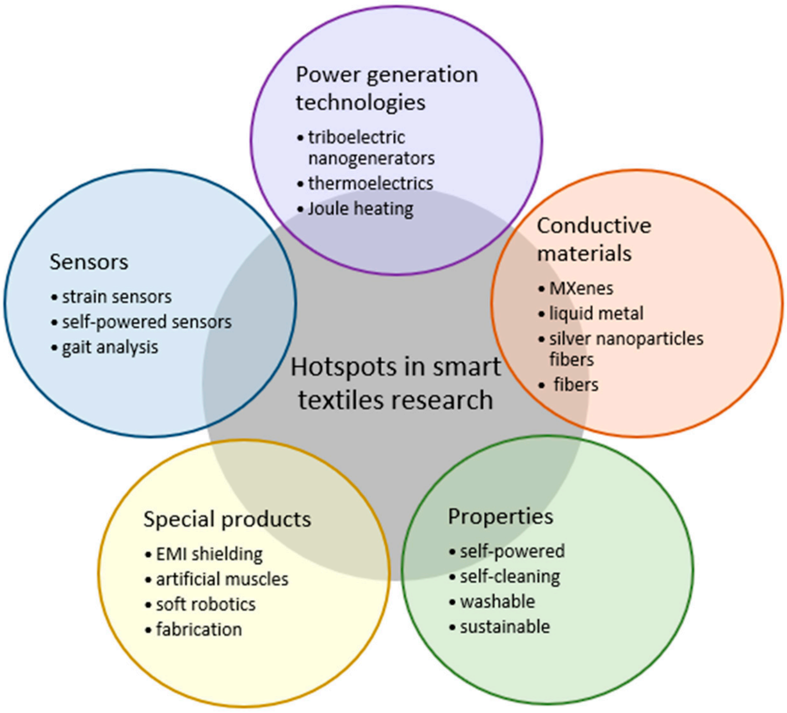


Figure 14. Newest research priorities in the domain of smart textiles.

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.

Author Contributions: Conceptualization, I.S., M.K. and B.B.P.; methodology, I.S. and B.B.P..; software, I.S.; validation, I.S., M.K. and B.B.P.; formal analysis, I.S., M.K. and B.B.P.; investigation, I.S., M.K. and B.B.P.; resources, I.S., M.K. and B.B.P.; data curation, I.S.; writing—original draft preparation, I.S., M.K. and B.B.P.; writing—review and editing, I.S., M.K. and B.B.P.; visualization, I.S., M.K. and B.B.P.; supervision, B.B.P.; project administration, I.S.; funding acquisition, B.B.P. and M.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Slovenian Research Agency, project Grant No. P2-0213 Textiles and ecology.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created in this study. Data sharing is not applicable to this review article.

Acknowledgments: The authors are very grateful to MDPI - Applied Sciences for the opportunity to publish this article with waiver of the processing fee.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Rijavec, T. Standardisation of smart textiles. *Glas. Hemičara Tehnol. Ekol. Repub. Srp.* **2010**, *4*, 35–38.
2. Liu, Z.; Jin, P.; Yin, Y.; Yin, F. Mapping the knowledge domains of smart textile: visualization analysis-based studies. *J. Text. Inst.* **2022**, *113*, 2651–2659, doi:10.1080/00405000.2021.2005278.
3. Takagi, T. A Concept of intelligent materials. *J. Intell. Mater. Syst. Struct.* **1990**, *1*, 149–156, doi:10.1177/1045389X9000100201.
4. Simon, C.; McCabe, M.; Baggerman, C.; Potter, E. *Smart Fabrics Technology Development: Final Report*; NASA, 2010.
5. Júnior, H.L.O.; Neves, R.M.; Monticeli, F.M.; Dall Agnol, L. Smart fabric textiles: recent advances and challenges. *Textiles* **2022**, *2*, 582–605, doi:10.3390/textiles2040034.

6. Tadesse, M.G.; Loghin, C.; Dulgheriu, I.; Loghin, E. Comfort evaluation of wearable functional textiles. *Materials* **2021**, *14*, 6466, doi:10.3390/ma14216466.
7. Meena, J.S.; Choi, S.B.; Jung, S.-B.; Kim, J.-W. Recent progress of $Ti_3C_2T_x$-Based MXenes for fabrication of multifunctional smart textiles. *Appl. Mater. Today* **2022**, *29*, 101612, doi:10.1016/j.apmt.2022.101612.
8. Schwarz, A.; Van Langenhove, L.; Guermonprez, P.; Deguillemont, D. A roadmap on smart textiles. *Text. Prog.* **2010**, *42*, 99–180, doi:10.1080/00405160903465220.
9. Syduzzaman, M.; Patwary, S.; Farhana, K.; Ahmed, S. Smart textiles and nano-technology: a general overview. *J. Text. Sci. Eng.* **2015**, *5*, doi:10.4172/2165-8064.1000181.
10. Shah, M.A.; Pirzada, B.M.; Price, G.; Shibiru, A.L.; Qurashi, A. Applications of nanotechnology in smart textile industry: a critical review. *J. Adv. Res.* **2022**, *38*, 55–75, doi:10.1016/j.jare.2022.01.008.
11. ISO/TR 23383:2020. Textiles and textile products — Smart (Intelligent) textiles— Definitions, categorisation, applications and standardization needs.
12. Gupta, D. Functional clothing— definition and classification. *IJFTR* **2011**, *36*.
13. Libanori, A.; Chen, G.; Zhao, X.; Zhou, Y.; Chen, J. Smart textiles for personalized healthcare. *Nat. Electron.* **2022**, *5*, 142–156, doi:10.1038/s41928-022-00723-z.
14. Deng, P.; Wang, Y.; Yang, R.; He, Z.; Tan, Y.; Chen, Z.; Liu, J.; Li, T. Self-powered smart textile based on dynamic schottky diode for human-machine interactions. *Adv. Sci.* **2023**, *10*, 2207298, doi:10.1002/advs.202207298.
15. Dong, K.; Hu, Y.; Yang, J.; Kim, S.-W.; Hu, W.; Wang, Z.L. Smart textile triboelectric nanogenerators: current status and perspectives. *MRS Bull.* **2021**, *46*, 512–521, doi:10.1557/s43577-021-00123-2.
16. Smart textiles market size, share, trends, global report 2023-2028 Available online: https://www.imarcgroup.com/smart-textiles-market (accessed on 31 July 2023).
17. Cherenack, K.; van Pieterson, L. Smart textiles: challenges and opportunities. *J. Appl. Phys.* **2012**, *112*, 091301, doi:10.1063/1.4742728.
18. Gehrke, I.; Tenner, V.; Lutz, V.; Schmelzeisen, D.; Gries, T. *Smart Textiles Production: Overview of Materials, Sensor and Production Technologies for Industrial Smart Textiles*; MDPI - Multidisciplinary Digital Publishing Institute, 2019; ISBN 978-3-03897-497-0.
19. Hu, J. *Active Coatings for Smart Textiles*; Woodhead Publishing, 2016; ISBN 978-0-08-100265-0.
20. Zhang, Y.; Xiao, Q.; Wang, Q.; Zhang, Y.; Wang, P.; Li, Y. A Review of wearable carbon-based sensors for strain detection: fabrication methods, properties, and mechanisms. *Text. Res. J.* **2023**, *93*, 2918–2940, doi:10.1177/00405175221148263.
21. Zhou, Y.; Xiao, X.; Chen, G.; Zhao, X.; Chen, J. Self-powered sensing technologies for human metaverse interfacing. *Joule* **2022**, *6*, 1381–1389, doi:10.1016/j.joule.2022.06.011.
22. Fouda, A.; Hamza, M.F.; Shaheen, Th.I.; Wei, Y. Editorial: Nanotechnology and smart textiles: sustainable developments of applications. *Front. Bioeng. Biotechnol.* **2022**, *10*, doi:10.3389/fbioe.2022.1002887.
23. Popescu, M.; Ungureanu, C. Green nanomaterials for smart textiles dedicated to environmental and biomedical applications. *Materials* **2023**, *16*, 4075, doi:10.3390/ma16114075.
24. Massaroni, C.; Saccomandi, P.; Schena, E. Medical smart textiles based on fiber optic technology: an overview. *J. Funct. Biomater.* **2015**, *6*, 204–221, doi:10.3390/jfb6020204.
25. Mokhtari, F.; Cheng, Z.; Raad, R.; Xi, J.; Foroughi, J. Piezofibers to smart textiles: a review on recent advances and future outlook for wearable technology. *J. Mater. Chem. A* **2020**, *8*, 9496–9522, doi:10.1039/D0TA00227E.
26. Persson, N.-K.; Martinez, J.G.; Zhong, Y.; Maziz, A.; Jager, E.W.H. Actuating textiles: next generation of smart textiles. *Adv. Mater. Technol.* **2018**, *3*, 1700397, doi:10.1002/admt.201700397.
27. Kongahage, D.; Foroughi, J. Actuator materials: review on recent advances and future outlook for smart textiles. *Fibers* **2019**, *7*, 21, doi:10.3390/fib7030021.
28. Mondal, S. Phase change materials for smart textiles – an overview. *Appl. Therm. Eng.* **2008**, *28*, 1536–1550, doi:10.1016/j.applthermaleng.2007.08.009.
29. Tabassum, M.; Zia, Q.; Zhou, Y.; Wang, Y.; Reece, M.J.; Su, L. A Review of recent developments in smart textiles based on perovskite materials. *Textiles* **2022**, *2*, 447–463, doi:10.3390/textiles2030025.
30. Cochrane, C.; Hertleer, C.; Schwarz-Pfeiffer, A. 2 - smart textiles in health: an overview. In *Smart Textiles and their Applications*; Koncar, V., Ed.; Woodhead Publishing Series in Textiles; Woodhead Publishing: Oxford, 2016; pp. 9–32 ISBN 978-0-08-100574-3.
31. Langenhove, L. van *Advances in Smart Medical Textiles: Treatments and Health Monitoring*; Woodhead Publishing, 2015; ISBN 978-1-78242-400-0.
32. Kubicek, J.; Fiedorova, K.; Vilimek, D.; Cerny, M.; Penhaker, M.; Janura, M.; Rosicky, J. Recent trends, construction, and applications of smart textiles and clothing for monitoring of health activity: a comprehensive multidisciplinary review. *IEEE Rev. Biomed. Eng.* **2022**, *15*, 36–60, doi:10.1109/RBME.2020.3043623.

33. Angelucci, A.; Cavicchioli, M.; Cintorrino, I.A.; Lauricella, G.; Rossi, C.; Strati, S.; Aliverti, A. Smart textiles and sensorized garments for physiological monitoring: a review of available solutions and techniques. *Sensors* **2021**, *21*, 814, doi:10.3390/s21030814.
34. Nigusse, A.B.; Mengistie, D.A.; Malengier, B.; Tseghai, G.B.; Langenhove, L.V. Wearable smart textiles for long-term electrocardiography monitoring—a review. *Sensors* **2021**, *21*, 4174, doi:10.3390/s21124174.
35. Tat, T.; Chen, G.; Zhao, X.; Zhou, Y.; Xu, J.; Chen, J. Smart textiles for healthcare and sustainability. *ACS Nano* **2022**, *16*, 13301–13313, doi:10.1021/acsnano.2c06287.
36. Ivanoska-Dacikj, A.; Stachewicz, U. Smart textiles and wearable technologies – opportunities offered in the fight against pandemics in relation to current COVID-19 state. *Rev. Adv. Mater. Sci.* **2020**, *59*, 487–505, doi:10.1515/rams-2020-0048.
37. Ivanoska-Dacikj, A.; Oguz-Gouillart, Y.; Hossain, G.; Kaplan, M.; Sivri, Ç.; Ros-Lis, J.V.; Mikucioniene, D.; Munir, M.U.; Kizildag, N.; Unal, S.; et al. Advanced and smart textiles during and after the COVID-19 pandemic: issues, challenges, and innovations. *Healthcare* **2023**, *11*, 1115, doi:10.3390/healthcare11081115.
38. Shabani, A.; Hylli, M.; Kazani, I. Investigating properties of electrically conductive textiles: a review. *Tekstilec* **2022**, *65*, 194–217, doi:10.14502/tekstilec.65.2022045.
39. Chen, G.; Li, Y.; Bick, M.; Chen, J. Smart textiles for electricity generation. *Chem. Rev.* **2020**, *120*, 3668–3720, doi:10.1021/acs.chemrev.9b00821.
40. Dolez, P.I. Energy harvesting materials and structures for smart textile applications: recent progress and path forward. *Sensors* **2021**, *21*, 6297, doi:10.3390/s21186297.
41. Hu, Y.; Zheng, Z. Progress in textile-based triboelectric nanogenerators for smart fabrics. *Nano Energy* **2019**, *56*, 16–24, doi:10.1016/j.nanoen.2018.11.025.
42. Dong, K.; Peng, X.; Cheng, R.; Wang, Z.L. Smart textile triboelectric nanogenerators: prospective strategies for improving electricity output performance. *Nanoenergy Adv.* **2022**, *2*, 133–164, doi:10.3390/nanoenergyadv2010006.
43. Weng, W.; Chen, P.; He, S.; Sun, X.; Peng, H. Smart electronic textiles. *Angew. Chem. Int. Ed.* **2016**, *55*, 6140–6169, doi:10.1002/anie.201507333.
44. Veske, P.; Ilén, E. Review of the end-of-life solutions in electronics-based smart textiles. *J. Text. Inst.* **2021**, *112*, 1500–1513, doi:10.1080/00405000.2020.1825176.
45. Stoppa, M.; Chiolerio, A. Wearable electronics and smart textiles: a critical review. *Sensors* **2014**, *14*, 11957–11992, doi:10.3390/s140711957.
46. Ghahremani Honarvar, M.; Latifi, M. Overview of wearable electronics and smart textiles. *J. Text. Inst.* **2017**, *108*, 631–652, doi:10.1080/00405000.2016.1177870.
47. Singha, K.; Kumar, J.; Pandit, P. Recent advancements in wearable & smart textiles: an overview. *Mater. Today Proc.* **2019**, *16*, 1518–1523, doi:10.1016/j.matpr.2019.05.334.
48. Vagott, J.; Parachuru, R. An overview of recent developments in the field of wearable smart textiles. *J. Text. Sci. Eng.* **2018**, *08*, doi:10.4172/2165-8064.1000368.
49. Fang, Y.; Chen, G.; Bick, M.; Chen, J. Smart textiles for personalized thermoregulation. *Chem. Soc. Rev.* **2021**, *50*, 9357–9374, doi:10.1039/D1CS00003A.
50. Chapman, R. *Smart Textiles for Protection*; Elsevier, 2012; ISBN 978-0-85709-762-0.
51. Degenstein, L.M.; Sameoto, D.; Hogan, J.D.; Asad, A.; Dolez, P.I. Smart textiles for visible and IR camouflage application: state-of-the-art and microfabrication path forward. *Micromachines* **2021**, *12*, 773, doi:10.3390/mi12070773.
52. Ramlow, H.; Andrade, K.L.; Immich, A.P.S. Smart textiles: an overview of recent progress on chromic textiles. *J. Text. Inst.* **2021**, *112*, 152–171, doi:10.1080/00405000.2020.1785071.
53. Li, S.; Jiang, S.; Tian, M.; Su, Y.; Li, J. Mapping the research status and dynamic frontiers of functional clothing: a review via bibliometric and knowledge visualization. *Int. J. Cloth. Sci. Technol.* **2022**, *34*, 697–715, doi:10.1108/IJCST-10-2021-0151.
54. de-la-Fuente-Robles, Y.-M.; Ricoy-Cano, A.-J.; Albín-Rodríguez, A.-P.; López-Ruiz, J.L.; Espinilla-Estévez, M. Past, present and future of research on wearable technologies for healthcare: a bibliometric analysis using Scopus. *Sensors* **2022**, *22*, 8599, doi:10.3390/s22228599.
55. Tian, M.; Li, J. Knowledge mapping of protective clothing research—a bibliometric analysis based on visualization methodology. *Text. Res. J.* **2019**, *89*, 3203–3220, doi:10.1177/0040517518809044.
56. Halepoto, H.; Gong, T.; Memon, H. A Bibliometric analysis of antibacterial textiles. *Sustainability* **2022**, *14*, 11424, doi:10.3390/su141811424.
57. Bataglini, W.V.; Forno, A.J.D.; Steffens, F.; Kipper, L.M. 3D printing technology: an overview of the textile industry. *Proc. Int. Conf. Ind. Eng. Oper. Manag. Sao Paulo Braz. April 5 - 8 2021* **2021**.
58. Falagas, M.E.; Pitsouni, E.I.; Malietzis, G.A.; Pappas, G. Comparison of PubMed, Scopus, Web of Science, and Google Scholar: strengths and weaknesses. *FASEB J.* **2008**, *22*, 338–342, doi:10.1096/fj.07-9492LSF.
59. Ravšelj, D.; Umek, L.; Todorovski, L.; Aristovnik, A. A review of digital era governance research in the first two decades: a bibliometric study. *Future Internet* **2022**, *14*, 126, doi:10.3390/fi14050126.

60. Aria, M.; Cuccurullo, C. Bibliometrix: an R-Tool for comprehensive science mapping analysis. *J. Informetr.* **2017**, *11*, 959–975, doi:10.1016/j.joi.2017.08.007.
61. van Eck, N.J.; Waltman, L. *VOSviewer Manual: Manual for VOSviewer Version 1 .6.19*; Universoteit Leiden, 2023;
62. Petrovich, E. Science mapping and science maps. *Knowl. Organ.* **2021**, *48*, 535–562, doi:10.5771/0943-7444-7-8-535.
63. Tijssen, R.J.W. A Scientometric cognitive study of neural network research: expert mental maps versus bibliometric maps. *Scientometrics* **1993**, *28*, 111–136, doi:10.1007/BF02016288.
64. Paschalidou, V. Bibliometric analysis on business processes: M.Sc. Thesis, Πανεπιστήμιο Μακεδονίας, 2022.
65. Donthu, N.; Kumar, S.; Mukherjee, D.; Pandey, N.; Lim, W.M. How to conduct a bibliometric analysis: an overview and guidelines. *J. Bus. Res.* **2021**, *133*, 285–296, doi:10.1016/j.jbusres.2021.04.070.
66. Gutiérrez-Salcedo, M.; Martínez, M.Á.; Moral-Munoz, J.A.; Herrera-Viedma, E.; Cobo, M.J. Some bibliometric procedures for analyzing and evaluating research fields. *Appl. Intell.* **2018**, *48*, 1275–1287, doi:10.1007/s10489-017-1105-y.
67. Noyons, E.C.M.; Moed, H.F.; Van Raan, A.F.J. Integrating research performance analysis and science mapping. *Scientometrics* **1999**, *46*, 591–604, doi:10.1007/BF02459614.
68. Raan, A.F.J. van *Handbook of Quantitative Studies of Science and Technology*; Elsevier, 2013; ISBN 978-1-4832-9016-4.
69. Narin, F.; Hamilton, K.S. Bibliometric performance measures. *Scientometrics* **1996**, *36*, 293–310, doi:10.1007/BF02129596.
70. Cobo, M.J.; López-Herrera, A.G.; Herrera-Viedma, E.; Herrera, F. An approach for detecting, quantifying, and visualizing the evolution of a research field: a practical application to the fuzzy sets theory field. *J. Informetr.* **2011**, *5*, 146–166, doi:10.1016/j.joi.2010.10.002.
71. Ramos-Rodríguez, A.-R.; Ruíz-Navarro, J. Changes in the intellectual structure of strategic management research: a bibliometric study of the Strategic Management Journal, 1980–2000. *Strateg. Manag. J.* **2004**, *25*, 981–1004, doi:10.1002/smj.397.
72. Baker, H.K.; Kumar, S.; Pandey, N. Forty years of the Journal of Futures Markets: a bibliometric overview. *J. Futur. Mark.* **2021**, *41*, 1027–1054, doi:10.1002/fut.22211.
73. Small, H. Update on science mapping: creating large document spaces. *Scientometrics* **1997**, *38*, 275–293, doi:10.1007/BF02457414.
74. Börner, K.; Chen, C.; Boyack, K.W. Visualizing knowledge domains. *Annu. Rev. Inf. Sci. Technol.* **2003**, *37*, 179–255, doi:10.1002/aris.1440370106.
75. Morris, S.A.; Van der Veer Martens, B. Mapping research specialties. *Annu. Rev. Inf. Sci. Technol.* **2008**, *42*, 213–295, doi:10.1002/aris.2008.1440420113.
76. Sajovic, I.; Boh Podgornik, B. Bibliometric analysis of visualizations in computer graphics: a study. *SAGE Open* **2022**, *12*, 21582440211071104, doi:10.1177/21582440211071105.
77. Cobo, M. j.; López-Herrera, A. g.; Herrera-Viedma, E.; Herrera, F. Science mapping software tools: review, analysis, and cooperative study among tools. *J. Am. Soc. Inf. Sci. Technol.* **2011**, *62*, 1382–1402, doi:10.1002/asi.21525.
78. Li, J.; Goerlandt, F.; Reniers, G. An Overview of scientometric mapping for the safety science community: methods, tools, and framework. *Saf. Sci.* **2021**, *134*, 105093, doi:10.1016/j.ssci.2020.105093.
79. Cobo, M. j.; López-Herrera, A. g.; Herrera-Viedma, E.; Herrera, F. SciMAT: a new science mapping analysis software tool. *J. Am. Soc. Inf. Sci. Technol.* **2012**, *63*, 1609–1630, doi:10.1002/asi.22688.
80. Agnusdei, G.P.; Elia, V.; Gnoni, M.G. Is digital twin technology supporting safety management? a bibliometric and systematic review. *Appl. Sci.* **2021**, *11*, 2767, doi:10.3390/app11062767.
81. Bujas, T.; Vladimir, N.; Koričan, M.; Vukić, M.; Ćatipović, I.; Fan, A. Extended bibliometric review of technical challenges in mariculture production and research hotspot Analysis. *Appl. Sci.* **2023**, *13*, 6699, doi:10.3390/app13116699.
82. Santana, M.; Cobo, M.J. What is the future of work? a science mapping analysis. *Eur. Manag. J.* **2020**, *38*, 846–862, doi:10.1016/j.emj.2020.04.010.
83. Herrera-Viedma, E.; López-Robles, J.-R.; Guallar, J.; Cobo, M.-J. Global trends in coronavirus research at the time of Covid-19: a general bibliometric approach and content analysis using SciMAT. *Prof. Inf.* **2020**, *29*, doi:10.3145/epi.2020.may.22.
84. Kerr, M.J. Interactive garment design using three-dimensional surface modelling techniques. Ph.D. Thesis, 1989.
85. Hinds, B.K.; McCartney, J. Interactive garment design. *Vis. Comput.* **1990**, *6*, 53–61, doi:10.1007/BF01901066.
86. Garner, J. Intelligent fabrics for keeping cool. *Afr. Text.* **1992**, 31–32.
87. Stylios, G.; Sotomi, O.J.; Zhu, R.; Fan, J.; Xu, Y.M.; Deacon, R. Sewability Integrated Environment (SIE) for intelligent garment manufacture: 4th international conference on advanced factory automation 1994. *4th Int. Conf. Adv. Fact. Autom. Fact. 2000* **1994**, 543–551, doi:10.1049/cp:19940913.

88. Anon Intelligent fabrics exact their price. *Bekleidung/Wear* **1994**, *8*, 25–26.
89. Kambe, H.; Yamasaki, N.; Lee, M.W. Super TEX-SIM: interactive textile design and simulation. *J. Vis. Comput. Animat.* **1994**, *5*, 265–279, doi:10.1002/vis.4340050406.
90. Stylios, G.; Sotomi, O.J.; Zhu, R.; Descon, R. Intelligent garment manufacture. *Text. Asia* **1995**, *26*, 30–33.
91. Stylios, G.; Sotomi, O.J.; Zhu, R.; Xu, Y.M.; Deacon, R. The mechatronic principles for intelligent sewing environments. *Mechatronics* **1995**, *5*, 309–319, doi:10.1016/0957-4158(95)00021-V.
92. Mann, S. Smart clothing: the shift to wearable computing. *Commun. ACM* **1996**, *39*, 23–24, doi:10.1145/232014.232021.
93. Stylios, G.; Sotomi, J.O. Thinking sewing machines for intelligent garment manufacture. *Int. J. Cloth. Sci. Technol.* **1996**, *8*, 44–55, doi:10.1108/09556229610109609.
94. Gladman Sydney, A.; Matsumoto, E.A.; Nuzzo, R.G.; Mahadevan, L.; Lewis, J.A. Biomimetic 4D printing. *Nat. Mater.* **2016**, *15*, 413–418, doi:10.1038/nmat4544.
95. Pantelopoulos, A.; Bourbakis, N.G. A Survey on wearable sensor-based systems for health monitoring and prognosis. *IEEE Trans. Syst. Man Cybern. Part C Appl. Rev.* **2010**, *40*, 1–12, doi:10.1109/TSMCC.2009.2032660.
96. Leng, J.; Lan, X.; Liu, Y.; Du, S. Shape-memory polymers and their composites: stimulus methods and applications. *Prog. Mater. Sci.* **2011**, *56*, 1077–1135, doi:10.1016/j.pmatsci.2011.03.001.
97. Chen, J.; Huang, Y.; Zhang, N.; Zou, H.; Liu, R.; Tao, C.; Fan, X.; Wang, Z.L. Micro-cable structured textile for simultaneously harvesting solar and mechanical energy. *Nat. Energy* **2016**, *1*, doi:10.1038/nenergy.2016.138.
98. Boulos, M.N.K.; Wheeler, S.; Tavares, C.; Jones, R. How smartphones are changing the face of mobile and participatory healthcare: an overview, with example from ECAALYX. *Biomed. Eng. Online* **2011**, *10*, doi:10.1186/1475-925X-10-24.
99. Xue, J.; Xie, J.; Liu, W.; Xia, Y. Electrospun nanofibers: new concepts, materials, and applications. *Acc. Chem. Res.* **2017**, *50*, 1976–1987, doi:10.1021/acs.accounts.7b00218.
100. Majumder, S.; Mondal, T.; Deen, M.J. Wearable sensors for remote health monitoring. *Sens. Switz.* **2017**, *17*, doi:10.3390/s17010130.
101. Chan, M.; Estève, D.; Fourniols, J.-Y.; Escriba, C.; Campo, E. Smart wearable systems: current status and future challenges. *Artif. Intell. Med.* **2012**, *56*, 137–156, doi:10.1016/j.artmed.2012.09.003.
102. Professor Stephen Beeby, University of Southampton. Available online: https://www.southampton.ac.uk/people/5wyhkv/professor-stephen-beeby (accessed on 31 July 2023).
103. Dr Russel Torah. Available online: https://www.arm.ecs.soton.ac.uk/people/dr-russel-torah/ (accessed on 31 July 2023).
104. Paosangthong, W.; Wagih, M.; Torah, R.; Beeby, S. Textile-based triboelectric nanogenerator with alternating positive and negative freestanding woven structure for harvesting sliding energy in all directions. *Nano Energy* **2022**, *92*, 106739, doi:10.1016/j.nanoen.2021.106739.
105. Li, M.; Torah, R.; Nunes-Matos, H.; Wei, Y.; Beeby, S.; Tudor, J.; Yang, K. Integration and testing of a three-axis accelerometer in a woven e-textile sleeve for wearable movement monitoring. *Sensors* **2020**, *20*, 5033, doi:10.3390/s20185033.
106. Komolafe, A.; Torah, R.; Wei, Y.; Nunes-Matos, H.; Li, M.; Hardy, D.; Dias, T.; Tudor, M.; Beeby, S. Integrating flexible filament circuits for e-textile applications. *Adv. Mater. Technol.* **2019**, *4*, 1900176, doi:10.1002/admt.201900176.
107. Yang, K.; Meadmore, K.; Freeman, C.; Grabham, N.; Hughes, A.-M.; Wei, Y.; Torah, R.; Glanc-Gostkiewicz, M.; Beeby, S.; Tudor, J. Development of user-friendly wearable electronic textiles for healthcare applications. *Sensors* **2018**, *18*, 2410, doi:10.3390/s18082410.
108. Yang, K.; Torah, R.; Wei, Y.; Beeby, S.; Tudor, J. Waterproof and durable screen printed silver conductive tracks on textiles. *Text. Res. J.* **2013**, *83*, 2023–2031, doi:10.1177/0040517513490063.
109. Paul, G.; Torah, R.; Beeby, S.; Tudor, J. Novel active electrodes for ECG monitoring on woven textiles fabricated by screen and stencil printing. *Sens. Actuators Phys.* **2015**, *221*, 60–66, doi:10.1016/j.sna.2014.10.030.
110. ZL Wang's Homepage. Available online: https://nanoscience.gatech.edu/ (accessed on 31 July 2023).
111. Zhong Lin Wang (0000-0002-5530-0380). Available online: https://orcid.org/0000-0002-5530-0380 (accessed on 31 July 2023).
112. Lv, T.; Cheng, R.; Wei, C.; Su, E.; Jiang, T.; Sheng, F.; Peng, X.; Dong, K.; Wang, Z.L. All-fabric direct-current triboelectric nanogenerators based on the tribovoltaic effect as power textiles. *Adv. Energy Mater.* **2023**, *13*, 2301178, doi:10.1002/aenm.202301178.
113. He, L.; Zhang, C.; Zhang, B.; Gao, Y.; Yuan, W.; Li, X.; Zhou, L.; Zhao, Z.; Wang, Z.L.; Wang, J. A high-output silk-based triboelectric nanogenerator with durability and humidity resistance. *Nano Energy* **2023**, *108*, 108244, doi:10.1016/j.nanoen.2023.108244.
114. Xiong, Y.; Luo, L.; Yang, J.; Han, J.; Liu, Y.; Jiao, H.; Wu, S.; Cheng, L.; Feng, Z.; Sun, J.; et al. Scalable spinning, winding, and knitting graphene textile TENG for energy harvesting and human motion recognition. *Nano Energy* **2023**, *107*, 108137, doi:10.1016/j.nanoen.2022.108137.

115. Ning, C.; Wei, C.; Sheng, F.; Cheng, R.; Li, Y.; Zheng, G.; Dong, K.; Wang, Z.L. Scalable one-step wet-spinning of triboelectric fibers for large-area power and sensing textiles. *Nano Res.* **2023**, *16*, 7518–7526, doi:10.1007/s12274-022-5273-7.
116. Wu, R.; Liu, S.; Lin, Z.; Zhu, S.; Ma, L.; Wang, Z.L. Industrial fabrication of 3D braided stretchable hierarchical interlocked fancy-yarn triboelectric nanogenerator for self-powered smart fitness system. *Adv. Energy Mater.* **2022**, *12*, 2201288, doi:10.1002/aenm.202201288.
117. Hu, S.; Han, J.; Shi, Z.; Chen, K.; Xu, N.; Wang, Y.; Zheng, R.; Tao, Y.; Sun, Q.; Wang, Z.L.; et al. Biodegradable, super-strong, and conductive cellulose macrofibers for fabric-based triboelectric nanogenerator. *Nano-Micro Lett.* **2022**, *14*, 115, doi:10.1007/s40820-022-00858-w.
118. Xing, F.; Ou, Z.; Gao, X.; Chen, B.; Wang, Z.L. Harvesting electrical energy from high temperature environment by aerogel nano-covered triboelectric yarns. *Adv. Funct. Mater.* **2022**, *32*, 2205275, doi:10.1002/adfm.202205275.
119. Sheng, F.; Zhang, B.; Cheng, R.; Wei, C.; Shen, S.; Ning, C.; Yang, J.; Wang, Y.; Wang, Z.L.; Dong, K. Wearable energy harvesting-storage hybrid textiles as on-body self-charging power systems. *Nano Res. Energy* **2023**, *2*, e9120079, doi:10.26599/NRE.2023.9120079.
120. Wei, C.; Cheng, R.; Ning, C.; Wei, X.; Peng, X.; Lv, T.; Sheng, F.; Dong, K.; Wang, Z.L. A self-powered body motion sensing network integrated with multiple triboelectric fabrics for biometric gait recognition and auxiliary rehabilitation training. *Adv. Funct. Mater. in press*, 2303562, doi:10.1002/adfm.202303562.
121. Dong, K.; Peng, X.; Cheng, R.; Ning, C.; Jiang, Y.; Zhang, Y.; Wang, Z.L. Advances in high-performance autonomous energy and self-powered sensing textiles with novel 3D fabric structures. *Adv. Mater.* **2022**, *34*, 2109355, doi:10.1002/adma.202109355.
122. Si, S.; Sun, C.; Wu, Y.; Li, J.; Wang, H.; Lin, Y.; Yang, J.; Wang, Z.L. 3D interlocked all-textile structured triboelectric pressure sensor for accurately measuring epidermal pulse waves in amphibious environments. *Nano Res.* **2023**, doi:10.1007/s12274-023-6025-z.
123. Ning, C.; Cheng, R.; Jiang, Y.; Sheng, F.; Yi, J.; Shen, S.; Zhang, Y.; Peng, X.; Dong, K.; Wang, Z.L. Helical fiber strain sensors based on triboelectric nanogenerators for self-powered human respiratory monitoring. *ACS Nano* **2022**, *16*, 2811–2821, doi:10.1021/acsnano.1c09792.
124. Jiang, Y.; An, J.; Liang, F.; Zuo, G.; Yi, J.; Ning, C.; Zhang, H.; Dong, K.; Wang, Z.L. Knitted self-powered sensing textiles for machine learning-assisted sitting posture monitoring and correction. *Nano Res.* **2022**, *15*, 8389–8397, doi:10.1007/s12274-022-4409-0.
125. Pang, Y.; Xu, X.; Chen, S.; Fang, Y.; Shi, X.; Deng, Y.; Wang, Z.-L.; Cao, C. Skin-inspired textile-based tactile sensors enable multifunctional sensing of wearables and soft robots. *Nano Energy* **2022**, *96*, 107137, doi:10.1016/j.nanoen.2022.107137.
126. Shen, S.; Yi, J.; Cheng, R.; Ma, L.; Sheng, F.; Li, H.; Zhang, Y.; Ning, C.; Wang, H.; Dong, K.; et al. Electromagnetic shielding triboelectric yarns for human–machine interacting. *Adv. Electron. Mater.* **2022**, *8*, 2101130, doi:10.1002/aelm.202101130.
127. Bie, B.; Xu, W.; Lv, Y. Liquid metal-based textiles for smart clothes. *Sci. China Technol. Sci.* **2023**, *66*, 1511–1529, doi:10.1007/s11431-022-2266-3.
128. Dong, C.; Leber, A.; Das Gupta, T.; Chandran, R.; Volpi, M.; Qu, Y.; Nguyen-Dang, T.; Bartolomei, N.; Yan, W.; Sorin, F. High-efficiency super-elastic liquid metal based triboelectric fibers and textiles. *Nat. Commun.* **2020**, *11*, 3537, doi:10.1038/s41467-020-17345-8.
129. Zheng, L.; Zhu, M.; Wu, B.; Li, Z.; Sun, S.; Wu, P. Conductance-stable liquid metal sheath-core microfibers for stretchy smart fabrics and self-powered Sensing. *Sci. Adv.* **2021**, *7*, eabg4041, doi:10.1126/sciadv.abg4041.
130. Votzke, C.; Daalkhaijav, U.; Mengüç, Y.; Johnston, M.L. 3D-printed liquid metal interconnects for stretchable electronics. *IEEE Sens. J.* **2019**, *19*, 3832–3840, doi:10.1109/JSEN.2019.2894405.
131. Ahmed, A.; Sharma, S.; Adak, B.; Hossain, M.M.; LaChance, A.M.; Mukhopadhyay, S.; Sun, L. Two-dimensional MXenes: new frontier of wearable and flexible electronics. *InfoMat* **2022**, *4*, e12295, doi:10.1002/inf2.12295.
132. Liu, S.; Ma, K.; Yang, B.; Li, H.; Tao, X. Textile electronics for VR/AR applications. *Adv. Funct. Mater.* **2021**, *31*, 2007254, doi:10.1002/adfm.202007254.
133. Wang, L.; Fu, X.; He, J.; Shi, X.; Chen, T.; Chen, P.; Wang, B.; Peng, H. Application challenges in fiber and textile electronics. *Adv. Mater.* **2020**, *32*, 1901971, doi:10.1002/adma.201901971.
134. Newby, S.; Mirihanage, W.; Fernando, A. Recent advancements in thermoelectric generators for smart textile application. *Mater. Today Commun.* **2022**, *33*, 104585, doi:10.1016/j.mtcomm.2022.104585.
135. Wu, Y.; Dai, X.; Sun, Z.; Zhu, S.; Xiong, L.; Liang, Q.; Wong, M.-C.; Huang, L.-B.; Qin, Q.; Hao, J. Highly integrated, scalable manufacturing and stretchable conductive core/shell fibers for strain sensing and self-powered smart textiles. *Nano Energy* **2022**, *98*, 107240, doi:10.1016/j.nanoen.2022.107240.
136. Lin, Z.; Yang, J.; Li, X.; Wu, Y.; Wei, W.; Liu, J.; Chen, J.; Yang, J. Large-scale and washable smart textiles based on triboelectric nanogenerator arrays for self-powered sleeping monitoring. *Adv. Funct. Mater.* **2018**, *28*, 1704112, doi:10.1002/adfm.201704112.

137. Shen, S.; Xiao, X.; Yin, J.; Xiao, X.; Chen, J. Self-powered smart gloves based on triboelectric nanogenerators. *Small Methods* **2022**, *6*, 2200830, doi:10.1002/smtd.202200830.
138. Verma, S.; Dhangar, M.; Paul, S.; Chaturvedi, K.; Khan, M.A.; Srivastava, A.K. Recent advances for fabricating smart electromagnetic interference shielding textile: a comprehensive review. *Electron. Mater. Lett.* **2022**, *18*, 331–344, doi:10.1007/s13391-022-00344-w.
139. Sun, T.; Zhou, B.; Zheng, Q.; Wang, L.; Jiang, W.; Snyder, G.J. Stretchable fabric generates electric power from woven thermoelectric fibers. *Nat. Commun.* **2020**, *11*, 572, doi:10.1038/s41467-020-14399-6.
140. Zhou, Z.; Padgett, S.; Cai, Z.; Conta, G.; Wu, Y.; He, Q.; Zhang, S.; Sun, C.; Liu, J.; Fan, E.; et al. Single-layered ultra-soft washable smart textiles for all-around ballistocardiograph, respiration, and posture monitoring during sleep. *Biosens. Bioelectron.* **2020**, *155*, 112064, doi:10.1016/j.bios.2020.112064.
141. Zhang, Z.; He, T.; Zhu, M.; Sun, Z.; Shi, Q.; Zhu, J.; Dong, B.; Yuce, M.R.; Lee, C. Deep learning-enabled triboelectric smart socks for IoT-based gait analysis and VR applications. *Npj Flex. Electron.* **2020**, *4*, 1–12, doi:10.1038/s41528-020-00092-7.
142. Zhou, Z.; Chen, K.; Li, X.; Zhang, S.; Wu, Y.; Zhou, Y.; Meng, K.; Sun, C.; He, Q.; Fan, W.; et al. Sign-to-speech translation using machine-learning-assisted stretchable sensor arrays. *Nat. Electron.* **2020**, *3*, 571–578, doi:10.1038/s41928-020-0428-6.
143. Zhao, X.; Zhou, Y.; Xu, J.; Chen, G.; Fang, Y.; Tat, T.; Xiao, X.; Song, Y.; Li, S.; Chen, J. Soft fibers with magnetoelasticity for wearable electronics. *Nat. Commun.* **2021**, *12*, 6755, doi:10.1038/s41467-021-27066-1.
144. Yan, W.; Noel, G.; Loke, G.; Meiklejohn, E.; Khudiyev, T.; Marion, J.; Rui, G.; Lin, J.; Cherston, J.; Sahasrabudhe, A.; et al. Single fibre enables acoustic fabrics via nanometre-scale vibrations. *Nature* **2022**, *603*, 616–623, doi:10.1038/s41586-022-04476-9.
145. Yin, L.; Kim, K.N.; Lv, J.; Tehrani, F.; Lin, M.; Lin, Z.; Moon, J.-M.; Ma, J.; Yu, J.; Xu, S.; et al. A self-sustainable wearable multi-modular e-textile bioenergy microgrid system. *Nat. Commun.* **2021**, *12*, 1542, doi:10.1038/s41467-021-21701-7.
146. Syafiuddin, A. Toward a comprehensive understanding of textiles functionalized with silver nanoparticles. *J. Chin. Chem. Soc.* **2019**, *66*, 793–814, doi:10.1002/jccs.201800474.
147. Štular, D.; Jerman, I.; Naglič, I.; Simončič, B.; Tomšič, B. Embedment of silver into temperature- and PH-responsive microgel for the development of smart textiles with simultaneous moisture management and controlled antimicrobial activities. *Carbohydr. Polym.* **2017**, *159*, 161–170, doi:10.1016/j.carbpol.2016.12.030.
148. Ahmad, S.; Subhani, K.; Rasheed, A.; Ashraf, M.; Afzal, A.; Ramzan, B.; Sarwar, Z. Development of conductive fabrics by using silver nanoparticles for electronic applications. *J. Electron. Mater.* **2020**, *49*, 1330–1337, doi:10.1007/s11664-019-07819-x.
149. Ramasundaram, S.; Rahaman, A.; Kim, B. Direct preparation of β-crystalline poly(vinylidene fluoride) nanofibers by electrospinning and the use of non-polar silver nanoparticles coated poly(vinylidene fluoride) nanofibers as electrodes for piezoelectric sensor. *Polymer* **2019**, *183*, 121910, doi:10.1016/j.polymer.2019.121910.
150. Bayan, S.; Pal, S.; Ray, S.K. Interface engineered silver nanoparticles decorated G-C3N4 nanosheets for textile based triboelectric nanogenerators as wearable power sources. *Nano Energy* **2022**, *94*, 106928, doi:10.1016/j.nanoen.2022.106928.
151. Liu, X.; Miao, J.; Fan, Q.; Zhang, W.; Zuo, X.; Tian, M.; Zhu, S.; Zhang, X.; Qu, L. Recent progress on smart fiber and textile based wearable strain sensors: materials, fabrications and applications. *Adv. Fiber Mater.* **2022**, *4*, 361–389, doi:10.1007/s42765-021-00126-3.
152. Xu, F.; Jin, X.; Lan, C.; Guo, Z.H.; Zhou, R.; Sun, H.; Shao, Y.; Meng, J.; Liu, Y.; Pu, X. 3D arch-structured and machine-knitted triboelectric fabrics as self-powered strain sensors of smart textiles. *Nano Energy* **2023**, *109*, 108312, doi:10.1016/j.nanoen.2023.108312.
153. Shuai, L.; Guo, Z.H.; Zhang, P.; Wan, J.; Pu, X.; Wang, Z.L. Stretchable, self-healing, conductive hydrogel fibers for strain sensing and triboelectric energy-harvesting smart textiles. *Nano Energy* **2020**, *78*, 105389, doi:10.1016/j.nanoen.2020.105389.
154. Kazani, I.; Hylli, M.; Berberi, P. Electrical resistivity of conductive leather and influence of air temperature and humidity. *Tekstilec* **2021**, *64*, 298–304, doi:10.14502/Tekstilec2021.64.298-304.
155. Zhang, Y.; Xia, X.; Ma, K.; Xia, G.; Wu, M.; Cheung, Y.H.; Yu, H.; Zou, B.; Zhang, X.; Farha, O.K.; et al. Functional textiles with smart properties: their fabrications and sustainable applications. *Adv. Funct. Mater.* **2023**, *n/a*, 2301607, doi:10.1002/adfm.202301607.
156. Zhu, C.; Wu, J.; Yan, J.; Liu, X. Advanced fiber materials for wearable electronics. *Adv. Fiber Mater.* **2023**, *5*, 12–35, doi:10.1007/s42765-022-00212-0.
157. Lima, M.D.; Li, N.; Jung de Andrade, M.; Fang, S.; Oh, J.; Spinks, G.M.; Kozlov, M.E.; Haines, C.S.; Suh, D.; Foroughi, J.; et al. Electrically, chemically, and photonically powered torsional and tensile actuation of hybrid carbon nanotube yarn muscles. *Science* **2012**, *338*, 928–932, doi:10.1126/science.1226762.
158. Mu, J.; Jung de Andrade, M.; Fang, S.; Wang, X.; Gao, E.; Li, N.; Kim, S.H.; Wang, H.; Hou, C.; Zhang, Q.; et al. Sheath-run artificial muscles. *Science* **2019**, *365*, 150–155, doi:10.1126/science.aaw2403.

159. Sheng, N.; Peng, Y.; Sun, F.; Hu, J. High-performance fasciated yarn artificial muscles prepared by hierarchical structuring and sheath–core coupling for versatile textile actuators. *Adv. Fiber Mater.* **2023**, *5*, 1534–1547, doi:10.1007/s42765-023-00301-8.
160. Phan, P.T.; Welch, D.; Spiggle, J.; Thai, M.T.; Hoang, T.T.; Davies, J.; Nguyen, C.C.; Zhu, K.; Phan, H.-P.; Lovell, N.H.; et al. Fabrication, nonlinear modeling, and control of woven hydraulic artificial muscles for wearable applications. *Sens. Actuators Phys.* **2023**, *360*, 114555, doi:10.1016/j.sna.2023.114555.
161. Sheng, Z.; Liu, Z.; Hou, Y.; Jiang, H.; Li, Y.; Li, G.; Zhang, X. The rising aerogel fibers: status, challenges, and opportunities. *Adv. Sci.* **2023**, *10*, 2205762, doi:10.1002/advs.202205762.
162. Alterby, M.; Johnson, E.; Jonason, A.; Svensson, D. *3D Printing Hydrogel Artificial Muscles and Microrobotics: Student Thesis*; 2023;
163. Aziz, S.; Zhang, X.; Naficy, S.; Salahuddin, B.; Jager, E.W.H.; Zhu, Z. Plant-like tropisms in artificial muscles. *Adv. Mater.* **2023**, *n/a*, 2212046, doi:10.1002/adma.202212046.
164. Faruk, M.O.; Ahmed, A.; Jalil, M.A.; Islam, M.T.; Shamim, A.M.; Adak, B.; Hossain, M.M.; Mukhopadhyay, S. Functional textiles and composite based wearable thermal devices for joule heating: progress and perspectives. *Appl. Mater. Today* **2021**, *23*, 101025, doi:10.1016/j.apmt.2021.101025.
165. Zhang, X.; Wang, X.; Lei, Z.; Wang, L.; Tian, M.; Zhu, S.; Xiao, H.; Tang, X.; Qu, L. Flexible MXene-decorated fabric with interwoven conductive networks for integrated Joule heating, electromagnetic interference shielding, and strain sensing performances. *ACS Appl. Mater. Interfaces* **2020**, *12*, 14459–14467, doi:10.1021/acsami.0c01182.
166. Ahmed, A.; Jalil, M.A.; Hossain, M.M.; Moniruzzaman, M.; Adak, B.; Islam, M.T.; Parvez, M.S.; Mukhopadhyay, S. A PEDOT:PSS and graphene-clad smart textile-based wearable electronic Joule heater with high thermal stability. *J. Mater. Chem. C* **2020**, *8*, 16204–16215, doi:10.1039/D0TC03368E.
167. Guo, Z.; Wang, Y.; Huang, J.; Zhang, S.; Zhang, R.; Ye, D.; Cai, G.; Yang, H.; Gu, S.; Xu, W. Multi-functional and water-resistant conductive silver nanoparticle-decorated cotton textiles with excellent Joule heating performances and human motion monitoring. *Cellulose* **2021**, *28*, 7483–7495, doi:10.1007/s10570-021-03955-y.
168. Sanivada, U.K.; Esteves, D.; Arruda, L.M.; Silva, C.A.; Moreira, I.P.; Fangueiro, R. Joule-heating effect of thin films with carbon-based nanomaterials. *Materials* **2022**, *15*, 4323, doi:10.3390/ma15124323.
169. Jalil, M.A.; Ahmed, A.; Hossain, M.M.; Adak, B.; Islam, M.T.; Moniruzzaman, M.; Parvez, M.S.; Shkir, Mohd.; Mukhopadhyay, S. Synthesis of PEDOT:PSS solution-processed electronic textiles for enhanced Joule heating. *ACS Omega* **2022**, *7*, 12716–12723, doi:10.1021/acsomega.1c07148.
170. Shi, J.; Li, X.; Sun, B.; Huang, X.-L.; Ning, X.; Long, Y.-Z.; Zheng, J. Flexible MXene decorative nonwovens with patterned structures for integrated Joule heating and strain sensing. *Sens. Actuators Phys.* **2023**, *358*, 114426, doi:10.1016/j.sna.2023.114426.
171. Owyeung, R.E.; Panzer, M.J.; Sonkusale, S.R. Colorimetric gas sensing washable threads for smart textiles. *Sci. Rep.* **2019**, *9*, 5607, doi:10.1038/s41598-019-42054-8.
172. Busolo, T.; Szewczyk, P.K.; Nair, M.; Stachewicz, U.; Kar-Narayan, S. Triboelectric yarns with electrospun functional polymer coatings for highly durable and washable smart textile applications. *ACS Appl. Mater. Interfaces* **2021**, *13*, 16876–16886, doi:10.1021/acsami.1c00983.
173. Munirathinam, P.; Anna Mathew, A.; Shanmugasundaram, V.; Vivekananthan, V.; Purusothaman, Y.; Kim, S.-J.; Chandrasekhar, A. A comprehensive review on triboelectric nanogenerators based on real-time applications in energy harvesting and self-powered sensing. *Mater. Sci. Eng. B* **2023**, *297*, 116762, doi:10.1016/j.mseb.2023.116762.
174. Li, J.; Cai, J.; Yu, J.; Li, Z.; Ding, B. The rising of fiber constructed piezo/triboelectric nanogenerators: from material selections, fabrication techniques to emerging applications. *Adv. Funct. Mater.* *n/a*, 2303249, doi:10.1002/adfm.202303249.
175. Biswas, N.; Chakrabarti, S.; Jones, L.D.; Ashili, S. Smart wearables addressing gait disorders: a review. *Mater. Today Commun.* **2023**, *35*, 106250, doi:10.1016/j.mtcomm.2023.106250.
176. Drăgulinescu, A.; Drăgulinescu, A.-M.; Zincă, G.; Bucur, D.; Feieș, V.; Neagu, D.-M. Smart socks and in-shoe systems: state-of-the-art for two popular technologies for foot motion analysis, sports, and medical applications. *Sensors* **2020**, *20*, 4316, doi:10.3390/s20154316.
177. Amitrano, F.; Coccia, A.; Ricciardi, C.; Donisi, L.; Cesarelli, G.; Capodaglio, E.M.; D'Addio, G. Design and validation of an e-textile-based wearable sock for remote gait and postural assessment. *Sensors* **2020**, *20*, 6691, doi:10.3390/s20226691.
178. Mileti, I.; Pasinetti, S.; Taborri, J.; Patanè, F.; Lancini, M.; Rossi, S. Realization and Validation of a Piezoresistive Textile-Based Insole for Gait-Related Measurements. In Proceedings of the 2023 IEEE International Instrumentation and Measurement Technology Conference (I2MTC); May 2023; pp. 1–6.
179. Zahn, E.F.; Fischer, H.F.; Gleiß, C.E.; Avramidis, E.; Joost, G. Textile Game Controller: Smart Knee Pads for Therapeutic Exercising. In Proceedings of the Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems; Association for Computing Machinery: New York, NY, USA, April 19 2023; pp. 1–5.

180. Zhao, M.; Xu, H.; Zhong, W.; Ming, X.; Li, M.; Hu, X.; Jia, K.; Wang, D. Robust and breathable all-textile gait analysis platform based on lenet convolutional neural networks and embroidery technique. *Sens. Actuators Phys.* **2023**, *360*, 114549, doi:10.1016/j.sna.2023.114549.
181. Sanchez-Botero, L.; Agrawala, A.; Kramer-Bottiglio, R. Stretchable, breathable, and washable fabric sensor for human motion monitoring. *Adv. Mater. Technol. n/a*, 2300378, doi:10.1002/admt.202300378.
182. Pazar, A.; Khalilbayli, F.; Ozlem, K.; Yilmaz, A.F.; Atalay, A.T.; Atalay, O.; İnce, G. Gait Phase Recognition Using Textile-Based Sensor. In Proceedings of the 2022 7th International Conference on Computer Science and Engineering (UBMK); September 2022; pp. 1–6.
183. Bonanno, M.; De Nunzio, A.M.; Quartarone, A.; Militi, A.; Petralito, F.; Calabrò, R.S. Gait analysis in neurorehabilitation: from research to clinical practice. *Bioengineering* **2023**, *10*, 785, doi:10.3390/bioengineering10070785.
184. Dang, T.; Zhao, M. The application of smart fibers and smart textiles. *J. Phys. Conf. Ser.* **2021**, *1790*, 012084, doi:10.1088/1742-6596/1790/1/012084.
185. Pakdel, E.; Wang, J.; Kashi, S.; Sun, L.; Wang, X. Advances in photocatalytic self-cleaning, superhydrophobic and electromagnetic interference shielding textile treatments. *Adv. Colloid Interface Sci.* **2020**, *277*, 102116, doi:10.1016/j.cis.2020.102116.
186. Niu, Z.; Qi, S.; Shuaib, S.S.A.; Yuan, W. Flexible, stimuli-responsive and self-cleaning phase change fiber for thermal energy storage and smart textiles. *Compos. Part B Eng.* **2022**, *228*, 109431, doi:10.1016/j.compositesb.2021.109431.
187. Naeem, M.A.; Javed, K.; Fraz, A.; Anwar, F. Recent Trends in wearable electronic textiles (e-textiles): a mini review. *J. Des. Text.* **2023**, *2*, 62–72, doi:10.32350/jdt.21.05.
188. Vu, C.C.; Kim, J. Highly elastic capacitive pressure sensor based on smart textiles for full-range human motion monitoring. *Sens. Actuators Phys.* **2020**, *314*, 112029, doi:10.1016/j.sna.2020.112029.
189. Seesaard, T.; Wongchoosuk, C. Fabric-based piezoresistive Ti_3AlC_2/PEDOT:PSS force sensor for wearable e-textile applications. *Org. Electron.* **2023**, *122*, 106894, doi:10.1016/j.orgel.2023.106894.
190. Samartzis, N.; Athanasiou, M.; Sygellou, L.; Yannopoulos, S.N. Modified Laser-Assisted Method for Direct Graphene Deposition on Sensitive Flexible Substrates: Fabrication of Interdigitated Micro-Flexible Supercapacitors. Available at SSRN: https://ssrn.com/abstract=4522623 or http://dx.doi.org/10.2139/ssrn.4522623.
191. Mersch, J.; Witham, N.S.; Solzbacher, F.; Gerlach, G. Continuous textile manufacturing method for twisted coiled polymer artificial muscles. *Text. Res. J.* **2023**, 00405175231181095, doi:10.1177/00405175231181095.
192. Gong, Z.; Xiang, Z.; OuYang, X.; Zhang, J.; Lau, N.; Zhou, J.; Chan, C.C. Wearable fiber optic technology based on smart textile: a review. *Materials* **2019**, *12*, 3311, doi:10.3390/ma12203311.
193. Fu, C.; Xia, Z.; Hurren, C.; Nilghaz, A.; Wang, X. Textiles in soft robots: current progress and future trends. *Biosens. Bioelectron.* **2022**, *196*, 113690, doi:10.1016/j.bios.2021.113690.
194. Xiong, J.; Chen, J.; Lee, P.S. Functional fibers and fabrics for soft robotics, wearables, and human–robot interface. *Adv. Mater.* **2021**, *33*, 2002640, doi:10.1002/adma.202002640.
195. Yang, Y.; Wu, Y.; Li, C.; Yang, X.; Chen, W. Flexible actuators for soft robotics. *Adv. Intell. Syst.* **2020**, *2*, 1900077, doi:10.1002/aisy.201900077.
196. Wallin, J.A. Bibliometric methods: pitfalls and possibilities. *Basic Clin. Pharmacol. Toxicol.* **2005**, *97*, 261–275, doi:10.1111/j.1742-7843.2005.pto_139.x.
197. Rafols, I.; Porter, A.L.; Leydesdorff, L. Science overlay maps: a new tool for research policy and library management. *J. Am. Soc. Inf. Sci. Technol.* **2010**, *61*, 1871–1887, doi:10.1002/asi.21368.
198. Chang, Y.-W.; Huang, M.-H.; Lin, C.-W. Evolution of research subjects in library and information science based on keyword, bibliographical coupling, and co-citation analyses. *Scientometrics* **2015**, *105*, 2071–2087, doi:10.1007/s11192-015-1762-8.