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Conducting Polymers for Wearable Sensors: A Bibliometric Analysis Using VOSviewer

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Abstract

The objective of this study is to conduct a bibliometric analysis using VOSviewer on the research progress of the conducting polymer for wearable sensors topic. Data was extracted from the Dimensions database from 2014 to August 2023. 268 Dimensions articles were relevant to the keywords. The title and abstract from the metadata were employed to be analyzed for co-occurrence using VOSviewer. As a result, 9544 terms were obtained through the search method, but only 184 met the threshold of 10 minimum occurrences in all retrieved articles and were selected for further analysis. There was a consistent upward trend in publication numbers between 2014 to August 2023. Based on the network visualization of keyword co-occurrence, it evidenced six clusters that group all specific keywords based on the common themes. The most recent keywords (occurred between 2021 and 2022) included conductive hydrogel, polymer hydrogel, flexible sensor, MXene, strain sensor, and stretchable strain sensor. Based on this study, it is suggested to discover more about conducting and flexible hydrogel materials and the possibilities to enhance the electrical and mechanical properties of conducting polymers by introducing MXene. The materials are viewed for applications such as flexible strain sensors and other wearable sensors.

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INTRODUCTION

The discovery of polyacetylene conductivity has led to the subsequent identification of other stable conducting polymers, including polyaniline (PANI), polypyrrole (PPy), polyacetylene (PA), poly (phenylene vinylene) (PPV), polythiophene (PT), and poly 3,4-ethylene-dioxythiophene (PEDOT)(Kumar & Verma, 2024). Following the introduction of doping, the majority of conjugated polymers exhibit conductivities ranging from 10^{-3} to 10^{3} S/cm. This particular polymer has received significant interest due to its exceptional electrical conductivity, satisfactory mechanical strength, and advantageous processability. The conducting polymer's electrical and mechanical characteristics also make it suitable for various technological applications. (Himadri Reddy et al., 2023)

Wearable sensors refer to compact electronic devices that can be affixed to the human body in order to monitor various physiological, environmental, or contextual factors. The sensors have been specifically engineered to gather data about an individual's health, activity, or surroundings. The rising popularity of this material can be attributed to the advancements in technology and miniaturization (Mukhopadhyay, 2015). The main objectives of wearable sensors are to advance the development of diverse sensor types with sensing characteristics similar to human skin and to detect different external stimuli, such as pressure, strain, and temperature (Sun et al., 2022), healthcare monitoring (Seyedin et al., 2020), diseases diagnostics (An & Kwon, 2021), human-machines interactions (Cai et al., 2017), and smart

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robot devices (Kim et al., 2014).

To accomplish these goals, it is essential to have conducting materials for designing the wearable sensing equipment. Flexibility and stretchability are significant characteristics wearable sensors should exhibit. The inherent flexibility of these materials enables them to detect variations in mechanical force, such as bending, stretching, pressing, and compressing (Chen et al., 2022). The wearable sensor should also possess sensitivity, linearity, and response time. Sensitivity refers to a relative electrical signal change (resistance or capacitance) in response to an applied strain. The structure and properties of materials significantly influence their value (Liu et al., 2021). The linearity is a crucial parameter as it enables the sensors to handle various outputs. Nonlinearity makes the calibration process complex and difficult(Amjadi et al., 2016). Response time measures how rapidly the sensors reach the steady state responses. Responses delays are present in all polymers due to their viscoelastic nature of polymers (Gong et al., 2015). It is necessary to have highly responsive sensors to ensure the measurement's precision and efficiency. The significance of these advancements lies in their potential integration into wearable health technologies such as wearable fitness trackers, intelligent health watches, wearable ECT monitors, and wearable blood pressure monitors(Seesaard & Wongchoosuk, 2023).

Bibliometric analysis uses a large-scale data mining approach to a specifically chosen database, focusing on quantifying the number of citations within a defined timeframe based on the intended analysis theme. (Indriati & Nandiyanto, 2023). Bibliometrics also facilitates examining and representing connections among many components: research topics, researchers, affiliations, or journals (R Ball, 2020). The VosViewer presents three visualization maps: network visualization, density visualization, and overlay visualization. Network visualization provides insight by displaying clusters representing a specific field's thematic area. Density visualization proposes to get an understanding of the concentration of keywords within specific regions in the network. The higher density indicates how frequently particular terms co-occur in the analysis. Researchers can focus on highly populated regions to discern key themes and topics within the literature. Furthermore, overlay visualization is used to analyze the research trends and how research themes have evolved and help identify trends and shifts in focus. This approach empowers researchers to remain updated on the latest advancements, make well-informed decisions regarding the necessity of further investigations, and find a research gap or novelty regarding a particular subject.

Based on our search, there are still relatively few studies on bibliometric analysis of conducting polymer for wearable sensors. This bibliometric study might be beneficial for estimating the amount and current status of a conducting polymer for sensor applications. The research aims to undertake mapping analysis in bibliometrics using VOSviewer software. We extracted metadata from the Dimensions database and processed the data using VOSviewer software. This bibliometric study is expected to provide assistance and insights to other researchers in their related fields, select potentially relevant topics to be done in the near future, and serve as a valuable reference.

METHOD

This study performed a comprehensive search on the Dimensions database to retrieve publications on "conducting polymer for wearable sensors." The search scope was limited to articles published within a specific ten-year timeframe from 2014 to August 14, 2023. Dimensions is a research platform offering access to a wide range of scholarly publications, grants, clinical trials, and patents. Dimensions are highly preferred due to their ability to incorporate articles from diverse sources, effectively clarify researchers, and provide the functionality to conduct comprehensive full-text searches inside articles (Palmblad et al., 2023). Compared to Google Scholar, this database contains a more extensive array of research-related data.

Queries for conducting the Dimensions full data search involved the terms "conducting polymer for wearable sensors." The Dimensions comprehensive data search was carried out on August 14, 2023, at 2:30 p.m. Subsequently; the VOSviewer software program was employed to represent and identify subjects based on the visual co-occurrence. These maps were overlaid with additional data to reveal publication trends, such as the average publishing year. A total of 268 publications regarding conducting polymer for wearable sensors were acquired from the Dimensions database. We extract the article's metadata from the database in CSV and RIS files. In the analysis process using VosViewer, we selected the "create a map based on text data" option for the type of data input to generate a keyword co-occurrence. Afterward, we clicked on "read data from bibliographic database files" to choose a data source since we utilized the Dimension data. The "title and abstract fields" option was then picked for the choose field option. Full counting was chosen for the choice counting method input. The search process involved using the title and abstract, although copyright declarations and structured abstract labels were not taken into consideration. The counting method employed in this query was the entire counting approach. A 10-occurrence determines the minimum requirement for a term in a co-occurrence analysis as a default set by the VosViewer. As a result, 9544 terms were found using the search technique. Meanwhile, only 184 of these phrases fulfilled the criterion and were chosen for additional examination. We carefully chose the 184 terms, excluding the incorrect ones from the bibliometric analysis and selecting the irrelevant keywords.

The lists of excluded keywords are Vol, chemical, preparation, b l gray, s m, self, characterization, kpa, cph, overview, teng, chapter, s cm, recent advance, progress, effect, display, recent progress, concept, article, class, practical application, presence, review, electronic, advantage, sample, fabric, function, need, poly, variety, information, research, mechanism, point, way, type, study, series, possibility, order, attention, example, strategy, demand, field, range, work, recent year, state, time. Following the process of refining the most relevant term, a bibliometric keyword co-occurrence analysis was conducted, resulting in three different maps: network visualization, overlay visualization, and density visualization. The resulting image was utilized to examine keyword analysis, terminology and concepts, as well as the prospect of research novelty. Additionally, from extracted Dimension metadata, we analyzed the trend of publication numbers during the analysis timeframe. Finally, the compilation of the five most frequently referenced documents among the obtained search results was summarized.

RESULTS AND DISCUSSION

Annual Publications

Dimensions conducted a comprehensive data search and successfully extracted 268 publications from the database. These publications were sourced from all recorded articles between 2014 and August 2023 (**Figure 1**). Between 2014 and 2022, the number of publications exhibited a steady increase. As of now, a total of 35 published articles have been published in 2023, with the possibility of additional publications before the year concludes. According to this data, there has been a significant rise in research interest regarding the utilization of conducting polymers as wearable sensors. The majority of publications originate from the fields of engineering and chemical sciences. Other minor-recorded research categories were physical science, biological sciences, and health sciences.

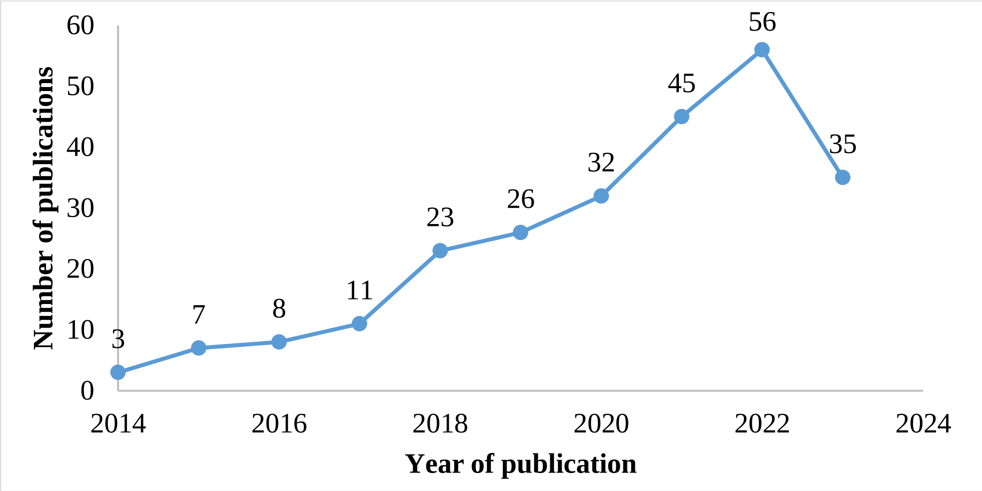

Figure 1. The number of articles in the Dimensions database matching the search query for each year of publication 2014- August 2023.

Highly Cited Documents

Table 1 presents the five most highly cited documents on conducting polymer for wearable sensors. The most cited document, "An Integrated Self-healable Electronic Skin System Fabricated Via Dynamic Reconstruction of a Nanostructured Conducting Network, " is an article from (Son et al., 2018), which received 671 citations. The article provides a report on the observation of self-reconstruction in conducting nanostructures upon contact with a dynamically crosslinked polymer network. The utilization of this material, in conjunction with the inherent self-bonding property of self-healing polymers, facilitated the subsequent integration of heterogeneous multi-component devices, including interconnects, sensors, and light-emitting devices, into a single multi-functional system. The development of autonomous self-healable and stretchable multi-component electronic skin paves the way for future robust electronics.

The second-most-cited article, with 470 citations, was from the Advanced Materials journal (Baeg et al., 2013) titled: "Toward Printed Integrated Circuits based on Unipolar or Ambipolar Polymer Semiconductors." This article reviewed the latest advancements in printed ICs based on polymeric semiconductors. The primary emphasis is placed on strategies for designing and synthesizing high-mobility polymers and developing appropriate printing equipment and techniques. The third-most-cited document is a review article by (S. Wang et al., 2018), which covers recent significant advancements in the field of skin-inspired electronics, with a particular emphasis on three significant aspects: stretchability, self-healing properties, and biodegradability. Skin-inspired electronics have found powerful utility for three major applications: prosthetic e-skin, wearable, and implantable electronics, enabling other unforeseen applications.

Subsequently, the paper (B. Wang & Facchetti, 2019) received 305 citations and was the fourth-most-cited document. The author provided a concise overview of the latest significant developments in using conducting nanomaterials to produce conducting elements and optoelectronics devices in stretchable and wearable e-skin and e-textile applications. The following most-cited paper by (Seyedin et al., 2020) discussed the behaviour of MXene composites within elastomeric composites and proposed strategies for developing MXene-based fibres and textiles with strain-sensing properties. These advancement have potential applications in health, sports and entertainment.

Table 1. List of top-5-highly-cited articles from Dimension's database articles matching the search query of publications between 2014 and 2023

Article Title	Year	Cites	Cites Per Year	Source Title
An integrated self-healable electronic skin system fabricated via dynamic reconstruction of a nanostructured conducting network	2018	671	134	Nature Technology (Nature)
Toward Printed Integrated Circuits based on Unipolar or Ambipolar Polymer Semiconductors	2013	470	47	Advanced Materials (Wiley)
Skin-Inspired Electronics: An Emerging Paradigm	2018	377	75	Accounts of Chemical Research (ACS)
Mechanically Flexible Conductors for Stretchable and Wearable E-Skin and E-Textile Devices	2019	305	76	Advanced Materials (Wiley)
MXene Composite and Coaxial Fibers with High Stretchability and Conductivity for Wearable Strain Sensing Textiles	2020	257	86	Advanced Functional Materials (Wiley)

Clusters of Keyword Analysis

VOSviewer has functionalities that enable the visualization of term co-occurrence, facilitating the identification of research clusters, examining the interconnections between these clusters, and identifying whether these clusters are linked to form a subdomain (Palmblad et al., 2023). The primary nodes within this network are identified by their connections with other keywords and by how frequently they appear across the 268 articles. A unique color is assigned to each cluster. The density visualization demonstrates a direct correlation between the circle size and the magnitude of the yellow color. Additionally, there is a positive correlation between the research frequency and the level of clustering observed in the keywords. (Kurniati et al., 2022).

Table 2 and Figure 2 show that the keywords have been classified into six clusters. This categorization was derived from analysis, resulting in 106 items, 4311 links, and 58982 link strength. Cluster 1, characterized by red color, includes 36 items. This cluster represents a collection of commonly utilized polymers for wearable sensors, for example, PEDOT PSS, polypyrrole, and polyvinyl alcohol. Cluster 2, denoted by a green circle, consisted of 22 items representing various uses of conducting polymer for battery technology, electrode development, energy harvesting, polymer electrolytes, supercapacitors, and wearable electronics. Furthermore, 21 items were discovered inside cluster 3 (dark blue), followed by 12 things grouped in cluster 4 (yellow). These two clusters focused on the properties of wearable sensors, such as their electrical properties (conductivity), stretchability, flexible substrate, and selectivity to detect various analytes.

Clusters 5 (shown in purple) and 6 (light blue) primarily discussed the inherent properties of polymers, including good biocompatibility and conductive characteristics. Both clusters also explored the potential applications of polymers in textile and wearable technology development, such as wearable actuators and sensors. Accordingly, the applications of the materials for healthcare aspects were captured from this group, for example, application in human skin. It also can be concluded that two significant signals that are frequently used in wearable devices are pressure and temperature. The details of items in each cluster are summarized in Table 2.

Terminology and Concept

'Sensor' was found to be the most frequently used keyword, as can be seen in Table 3. It has 502 occurrences and 104 links to other keywords. 'Polymer' is the second most encountered keyword with 316 occurrences and linked to 105 different keywords. The third most encountered keyword is 'application' with 280 occurrences and 105 links. The rest are 'electrode (164 occurrences, 103 links), 'property (148 occurrences, 102 links), "performance" (129 occurrences, 103 links), "film" (127 occurrences, 100 links), "sensitivity" (111 occurrences, 102 links), "electrical conductivity" (102 occurrences, 102 links), and "hydrogel" with 93 occurrences and 94 links.

The prevalence of 'polymer' and 'sensor' in the most encountered keywords might not be surprising because they were used as the primary keywords in the search part. The properties and performances of the synthesized materials have been extensively studied from all articles taken from Dimensions during the time frame. The utilization of material properties such as sensitivity, electrical conductivity, and volumetric capacitance have found applications in several fields. These include the development of wearable health monitoring films, thermoelectric power generation, piezoresistive sensors, and environmentally sensitive materials for glucose biosensing (Khadtare et al., 2019),(Jiang et al., 2022).

Furthermore, recent applications of these materials are as conductive hydrogels for wearable strain sensors, motion sensors, wearable electronics, and supercapacitors (Zhao et al., 2020),(Chu et al., 2019), nitrite sensors (Gao et al., 2020), as well as for applications as electrode materials for strain sensor, ion-selective electrodes (Kozma et al., 2023), on-skin sensors, humidity dosimeters, and stretchable supercapacitors (Li et al., 2021),(Diao et al., 2021), semitransparent organic solar cells (Fan et al., 2017). Table 3 shows the ten most frequently used keywords with the respective total link strengths.

Table 2. Summary of items recorded in each cluster

Cluster	Terms
Cluster 1 (36 items)	3,4-ethylene dioxythiophene, addition, conductive hydrogel, electronic skin, filler, flexible sensor, gauge factor, health monitoring, human body, human motion, humidity, hydrogel, ion, mechanical property, monitoring, motion, movement, network, pedot, pedot pss, polymer hydrogel, polypyrrole, polystyrene sulfonate, pressure sensor, pva, real time, resistance, response, room temperature, sensitivity, strain, strain sensor, stretchability, stretchable strain sensor, styrene sulfonate, wearable strain sensor
Cluster 2 (22 items)	Battery, carbon, carbon nanotube, cycle, electrode, energy, fabrication, flexibility, high performance, low cost, mxene, nanofiber, paper, performance, polymer electrolyte, potential application, stability, supercapacitor, surface, synthesis, wearable electronics
Cluster 3 (21 items)	Application, combination, composite, electrical conductivity, electrical property, electronic device, fiber, flexible device, graphene, inkjet printing, integration, metal, nanomaterial, polydimethylsiloxane, polymer composite, property, silver nanowire, soft robotic, stretchable conductor, substrate, transistor
Cluster 4 (12 items)	Biosensor, detection, film, flexible substrate, nanocomposite, pani, polyaniline, selectivity, sensing, sensor, solution, sweat
Cluster 5 (8 items)	Actuator, gel, human skin, polymer, technology, textile, wearable actuator, wearable sensor
Cluster 6 (7 items)	Biocompatibility, bioelectronic, conductive polymer, healthcare, pressure, temperature, wearable device

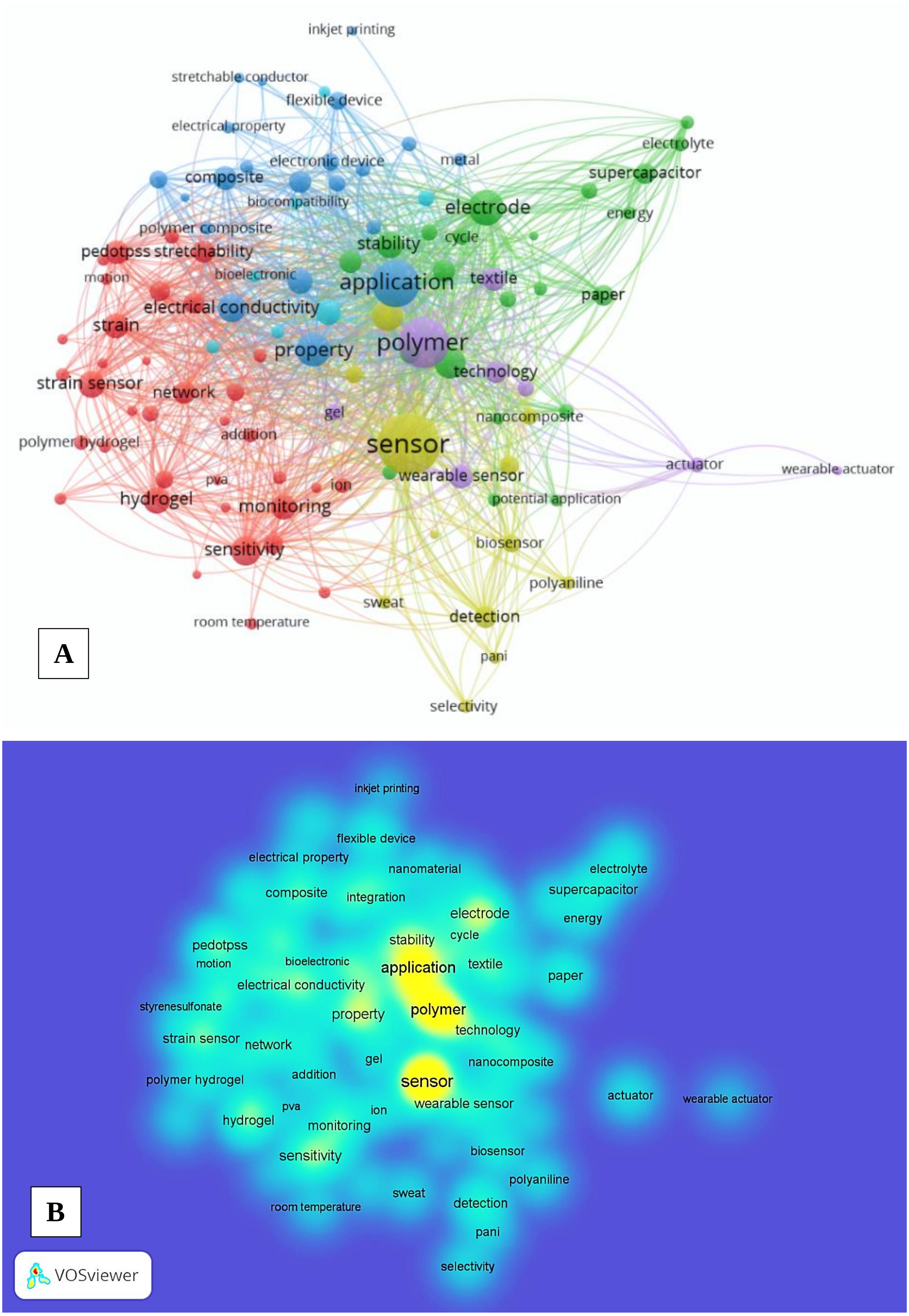

Figure 2. The network visualization of keyword co-occurrence (A). VOSviewer visualization of terms co-occurring in the titles and abstracts of conducting polymer for wearable sensors (B). The density visualization of co-occurrence

Table 3. Top 10 the most frequently used keywords

Keywords (cluster)	Link	Total Link Strenght	Total Occurrences
Sensor (4)	104	9349	502
Polymer (5)	105	6029	316
Application (3)	105	6071	280
Electrode (2)	103	3911	164
Property (3)	102	3439	148
Performance (2)	103	2831	129
Film (4)	100	3121	127
Sensitivity (1)	102	2460	111
Electrical conductivity (3)	102	2292	102
Hydrogel (1)	94	1901	93

Prospect of Research Novelty

This bibliometric analysis also conducted the relationship between terms that are categorized based on the time of the research. **Figure 3** depicts an overlay visualization map illustrating the trends in publications related to conducting polymer for wearable sensors. The yellow-color keywords are the recent trends (exist between 2021 and 2022) and the current focus of researchers. They include conductive hydrogel, polymer hydrogel, flexible sensor, MXene, strain sensor, and stretchable strain sensor. One of the primary objectives in this particular field is to create various sensors with human skin-like sensing capabilities that can perceive different external stimuli (Chu et al., 2019). Considerable attention has been directed towards the fabrication of soft and conductive materials. Many efforts have been devoted to fabricating diverse stretchable strain sensors based on flexible conductive materials, such as conducting polymer hydrogels, which exhibit remarkable biocompatibility, mechanical flexibility, and stable conductivity (Gao et al., 2020).

Flexible and wearable sensors have attracted significant attention due to their exceptional performance and a broad range of applications, such as personalized health monitoring, human-machine interfaces, and soft robotics. In the context of health monitoring, the flexible sensor stands out due to its exceptional stretchability and sensitivity. It can be applied to the skin to detect physiological signals in real-time, for instance, speaking, blinking, smiling, and arm and finger movement (Xu et al., 2019). This wearable system can detect vital indicators, including breathing frequency and heart rate (Lo Presti et al., 2019). Guo and co-workers developed a pressure wearable sensor using PANI-coated RGO layers on polyurethane sponges (PANIH/C-RGO@PU). This flexible sensor can accurately measure strain deformation with excellent reproducibility (over 1000 cycles) from 0,2% to 80% with fast response time (22 ms/20 ms). This technology shows potential for predicting individuals in the early stages of Parkinson's disease (Guo et al., 2018). Moreover, the signals from wearable sensors can be used to actuate intelligent devices, for instance, various smart gloves. This sensor was attached to the glove finger to monitor the flexion angle of a finger joint. As a finger joint was flexed, the electrical signal underwent alteration. The sensor data was wirelessly transmitted from the smart glove to the gripper robot to facilitate various operations (Amjadi et al., 2016). Hence, these domains hold immense potential for the future owing to the growing demand for cost-effective and sustainable polymer materials for medical devices. In addition, the advancement of robotics and artificial intelligence also necessitates the use of polymer-based flexible materials, ensuring the ongoing requirement for research and development in this domain.

An alternative method for improving polymer hydrogels' conductivity and tensile properties involves integrating a relatively novel inorganic material called MXene. MXene is a large family of 2D materials with notable electrical conductivity (10 to 10^4 S/cm), outstanding mechanical properties, and excellent specific capacitance (Kozma et al., 2023). MXene has good mechanical properties and excellent electrical conductivity due to the interlayer distance that changes dramatically when subjected to external stresses (Zhang et al., 2023). The multilayer MXene exhibits a high aspect ratio on the surface with many functional groups, such as –OH, –F, and –O, which can form hydrogen bonds or electrostatic interactions with polymer chains (Cao et al., 2023). These interactions are important to strengthen the sensor under a dynamic load. Due to its distinctive combination properties, MXene has been utilized in various fields, for instance, energy storage, sensing, catalyst, antennas, and neural interfaces. Another noteworthy application of MXene is for fillers in composite fibre that need electrical conductivity and elasticity simultaneously. This combination of conductivity and stretchability is the fundamental requirement for sensing physical deformations such as strains(Li et al., 2021). Based on the findings of this bibliometric analysis, it is recommended that researchers in a particular field further investigate the properties and applications of conducting and flexible hydrogel materials, particularly in combination with different types of MXene, in order to develop enhanced materials with superior characteristics. The novel materials possess the potential to function as a stretchable strain sensor as well as other sensors (pressure, temperature, and electrochemical sensors to detect various molecules, ions, and gases).

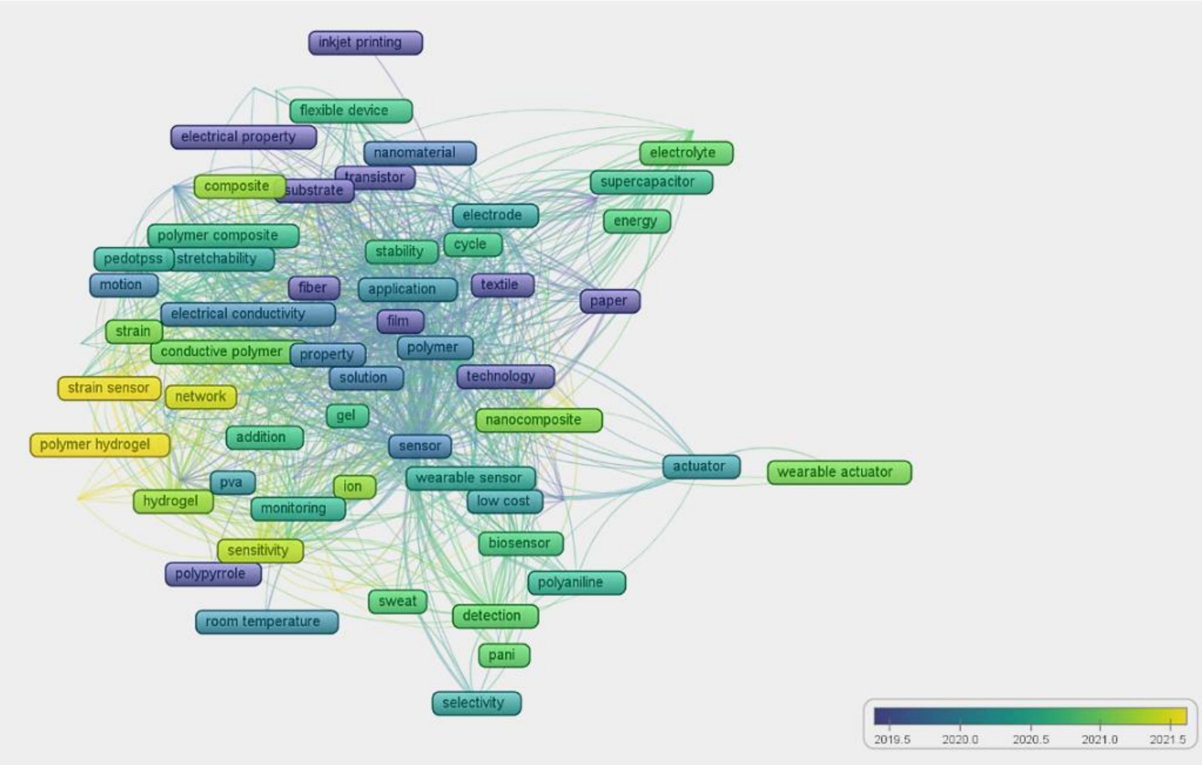

Figure 3 VOSviewer visualization of terms co-occurring trend analysis.

Table 4. The keywords with the most recent from the overlay visualization of bibliometric analysis using VOSviewer

Keyword	Average Year of Publications
Conductive hydrogel	2022,05
Polymer hydrogel	2022,17
Flexible sensor	2022,05
MXene	2021,72
Strain sensor	2021,51
Stretchable strain sensor	2021,54

LIMITATION OF STUDY

This study aims to integrate mapping visualization with VOSviewer software to conduct bibliometric research on conducting polymers in wearable sensors. It includes titles, abstracts, and keywords on the keyword "conducting polymer for wearable sensors". Based on the search results, 268 articles published between 2014 and 2023 were compiled. The trend of publications has continued to rise from 2014 until 2022 and has room for more improvement by the end of this year.

Based on the keyword co-occurrence, it has six different clusters that group all specific keywords based on the most common themes. The top ten most frequently used keywords are sensor, polymer, application, electrode, property, performance, film, sensitivity, electrical conductivity, and hydrogel. The most recent trends and the current focus of researchers include conductive hydrogel, polymer hydrogel, flexible sensor, MXene, strain sensor, and stretchable strain sensor. All keywords exist between 2021 and 2022.

Based on this study, it is suggested that more is discovered about conducting and flexible hydrogel materials and the possibilities to enhance the electrical and mechanical properties of the pristine polymer by introducing MXene-based materials. The new materials could be used as a flexible strain sensor and other wearable sensors, such as pressure, temperature, and electrochemical sensors, to detect various molecules, ions, and gases.

CONCLUSION

This study aims to integrate mapping visualization with VOSviewer software to conduct bibliometric research on conducting polymers in wearable sensors. It includes titles, abstracts, and keywords on the keyword "conducting polymer for wearable sensors". On the basis of the search results, 268 articles published between 2014 and 2023 were compiled. The publication trend continued to rise from 2014 until 2022 and has room for more improvement by the end of this year.

Based on the keyword co-occurrence, it has six different clusters which groups all specific keywords based on the most common themes. The top ten most frequently used keywords are, respectively: sensor, polymer, application, electrode, property, performance, film, sensitivity, electrical conductivity, and hydrogel. The most recent trends and the current focus of researchers include conductive hydrogel, polymer hydrogel, flexible sensor, MXene, strain sensor and stretchable strain sensor. All keywords exist between 2021 and 2022..

RECOMMENDATIONS

Based on this study, it is proposed the need for further research on cost-effective and sustainable flexible conducting polymer materials for applications in health monitoring, robotics and artificial intelegence. Additionally, more is discovered about conducting and flexible hydrogel materials and the possibilities to enhance the electrical and mechanical properties of the bare polymer by the introduction of MXene-based materials. The new materials could be used as a flexible strain sensor and other wearable sensors such as pressure temperature, as well as electrochemical sensor to detect various molecules, ion, and gas.

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