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Research article

Research trends and hot topics of wearable sensors in wound care over past 18 years: A bibliometric analysis☆

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ABSTRACT

Objective: This study determined the development trends, analyzed collaboration networks, and identified research hotspots in the field of wearable sensors for wound care from 2007 to 2024 using a rigorous bibliometric analysis approach.
Methods: Bibliometric and scientometric analyses were performed utilizing data sourced from the Web of Science Core Collection database. This study examined publication trends, contributions from various countries and institutions, author productivity, keyword prevalence, and citation patterns to discern research hotspots and potential future avenues in the application of wearable sensors for wound care.
Results: This study included 1177 articles, which demonstrated a marked increase in publications since 2016 and underscores the burgeoning interest in wearable sensors for wound care. China and the United States have emerged as prominent contributors to the research field, exhibiting numerous international collaborations. An analysis of keywords and citation bursts highlighted wound healing, hydrogels, and sensors as the key research foci with recent trends shifting towards the integration of wearable technology with advanced materials and artificial intelligence for advanced wound management. The research landscape is characterized by a diverse network of international collaborations and an emphasis on interdisciplinary approaches that integrate materials science, sensor technology, and clinical applications.
Conclusion: The utilization of wearable sensors in wound care constitutes a rapidly progressing area of research, garnering significant interest and promising avenues for future advances. The

☆ **Subject areas:** Wearable Sensor. Wound Care. Bibliometrics. Telecare. Wise Information Medical Technology.

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integration of wearable sensors with advanced materials and AI technologies presents a frontier of opportunity for innovating wound care methodologies, enhancing patient outcomes, and optimizing the allocation of healthcare resources.

1. Introduction

A wound refers to the disruption of normal skin or tissue integrity resulting from various external insults, including surgical procedures, trauma, heat, electricity, chemicals, low temperatures, and internal conditions, such as local blood flow disturbances [1]. The wound management market is projected to expand from 11.27 billion USD in 2023 to 13.59 billion USD by 2028, according to Mordor Intelligence, with a compounded annual growth rate of 3.81 % over the forecast period (2023–2028). This anticipated growth underscores the significant clinical challenges and economic pressures posed to the global healthcare system [2].

Wounds are typically categorized into acute and chronic types. The standard healing process of acute wounds encompasses predictable phases, including inflammation, proliferation, repair, and remodeling [3]. Chronic wounds, defined as wounds that fail to heal within 1 month, exhibit exceptional complexity at the cellular level, encompassing intricate regulatory axes and signaling cascades [4]. A myriad of factors contribute to delayed wound healing, including chronic diseases, vascular impairment, diabetes mellitus, malnutrition, and high-risk conditions, such as infection [5]. Furthermore, the prevalence of acute and chronic wounds is escalating, paralleling the rise in risk factors, such as population aging and obesity [6]. Among the multitude of factors influencing wound healing, infection stands out as the most prevalent obstacle to the healing process [7]. Wound infections pose significant consequences for patients, including prolonged hospital stays, heightened psychological stress, pain, and in severe cases, sepsis, which can be life-threatening [8]. Wound infections are characterized by the proliferation of bacteria within living tissues, leading to tissue destruction and impaired wound healing [9]. Consequently, prompting diagnosis and continuous monitoring of wound status is paramount to ensuring that patients receive optimal care.

Current diagnostic methods predominantly rely on clinical assessment and microbiological analyses, which exhibit limitations, like inaccuracy, necessitating the removal of wound dressings and reliance on medical expertise [6]. Microbiological analysis has limitations, including lengthy analysis time, invasiveness associated with testing live tissues and an inability to detect bacteria in deep tissues using swab cultures [8]. The advances in wearable sensor technology presents groundbreaking opportunities for wound management, benefiting clinical practices and trials via personalized, continuous, and remote monitoring of physiologic functions in real-world settings and controlled laboratory environments [10]. The emergence of wearable healthcare devices has facilitated the

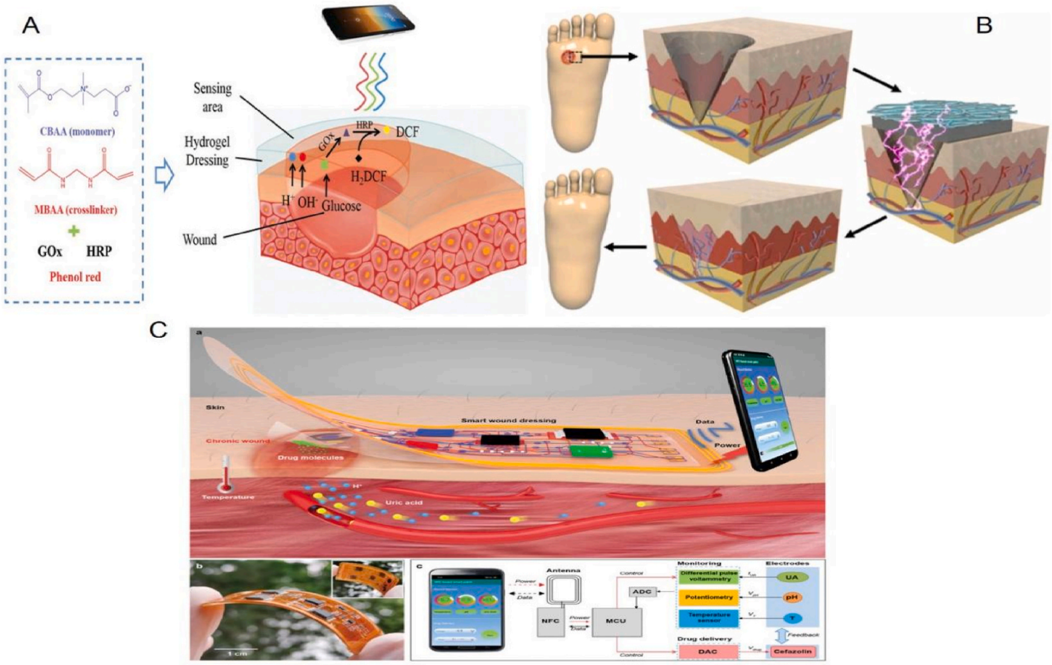

Fig. 1. Three common applications of wearable devices in wound care. (A): Multifunctional amphiphilic ion hydrogel monitoring the pH and glucose of diabetic wounds. The graph of hydrogel: Reproduced with permission, Copyright 2020 [16], John Wiley & Sons. (B): PTENG dressing provides electrical stimulation to promote wound healing. The graph of PTENG dressing: Reproduced with permission, Copyright 2022 [17], Elsevier. (C): Battery-free and wireless smart wound dressing for infection monitoring and electro-controlled on-demand drug delivery. The graph of drug delivery Smart Wound Dressing: Reproduced with permission, Copyright 2021 [15], John Wiley & Sons.

development of intelligent wound dressings, incorporating sensors that offer numerous benefits to patients and healthcare professionals. By detecting biochemical signals pertinent to wound healing, these dressings pave new avenues for expedited and precise diagnosis and treatment of infected wounds [11]. For example, smart wound dressings possess the capability to perceive the individual wound microenvironment of patients and automatically administer drugs, enabling tailored treatment strategies [12]. Wearable sensor technology in wound management can be categorized into three primary types (Fig. 1): monitoring sensors [13]; therapeutic sensors [14]; and those that integrate both treatment and monitoring functions [15].

In comparison to traditional dressings, wearable smart dressings equipped with sensors can significantly reduce the need for wound inspections. By continuously monitoring various biomarkers within the wound environment and dynamically releasing therapeutic molecules based on factors, such as pH, temperature, enzymes, and toxins, these dressings enhance patient comfort and compliance while diminishing the risk of wound infection [18,19]. Smart sensing dressings possess the potential to modulate the immune response within the wound microenvironment and manage skin scars. By facilitating re-epithelialization and vascularization, directing macrophage polarization, and reducing inflammatory responses, smart sensing dressings enhance wound healing, thereby mitigating the psychological, emotional, and social distress experienced by patients [20]. In the future, wearable smart sensors will occupy a

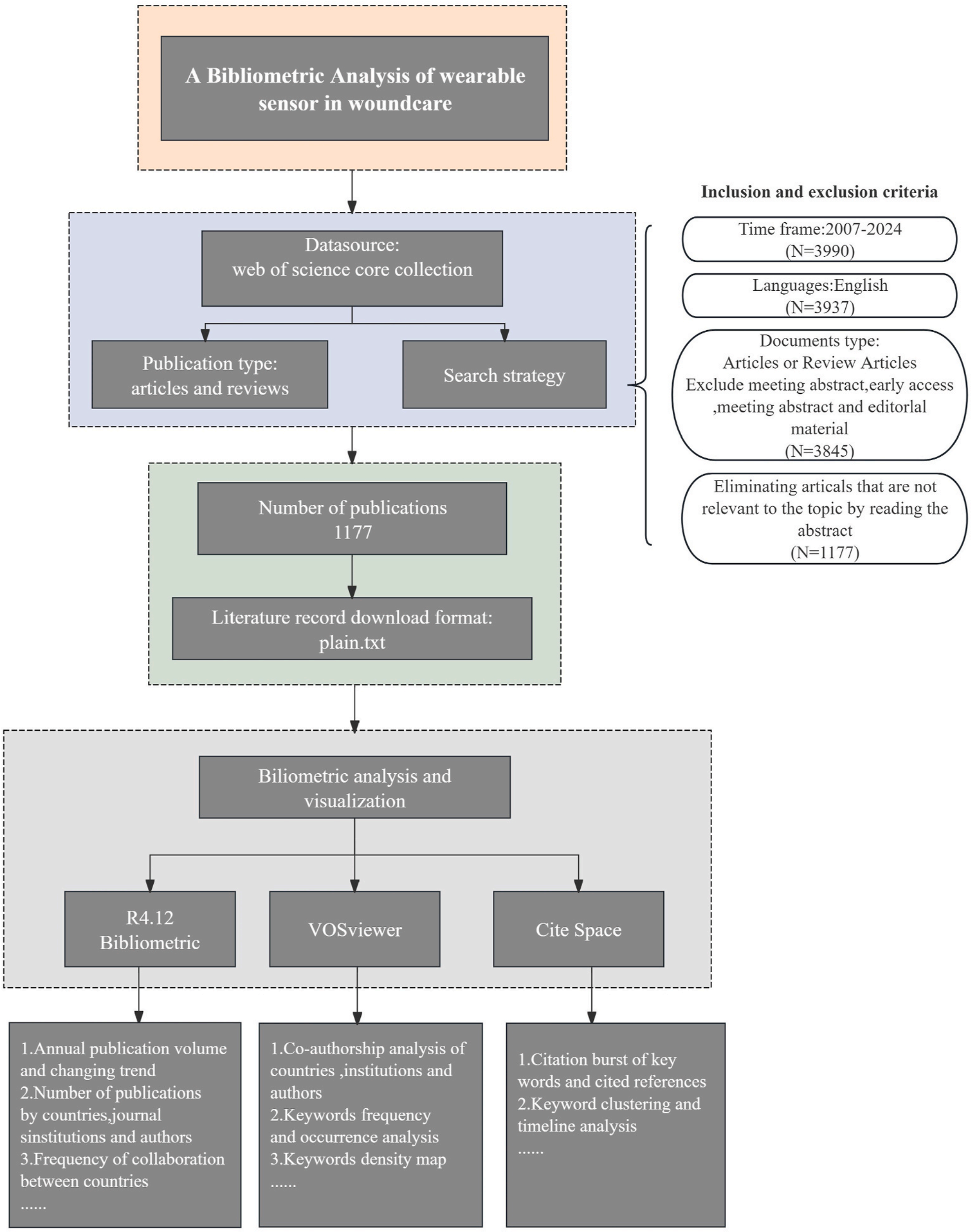

Fig. 2. Workflow of literature screening and data analysis.

pivotal position in wound care, encompassing the assessment of wound infection status, monitoring the healing process, and facilitating treatment. The implementation of wearable smart sensors is intricately intertwined with various disciplines, such as life sciences, material sciences, engineering, and others [21].

In recent years, the utilization of wearable smart sensors in wound management has garnered substantial attention, accompanied by a steadily increasing volume of literature. Bibliometric analysis, a quantitative method for mining literature and information using mathematical and statistical approaches, enables the identification of research trends and hotspots by analyzing keyword clustering relationships. It also facilitates the quantification of research impact and tracks the dissemination and influence of research over time [22]. This study systematically reviewed the literature on wearable sensor technology in wound care, evaluating current status, emerging trends, and anticipated future directions of research. The objective of this review was to offer researchers and healthcare professionals valuable insights and references for utilizing wearable sensors in wound management.

2. Bibliometric analysis methods

2.1. Data source and search strategy

This study used the Core Collection of the Web of Science database to guarantee the comprehensiveness and scholarly quality of the selected literature. The search query was TS= ("wearable*" AND "wound*") OR TS= ("sensor*" AND "wound*") OR TS= ("Electronic Skin" AND "wound*") OR TS= ("smart*" AND "wound*"), with the search date up to July 31, 2024. For further analysis, only peer-reviewed articles written in English were considered with complete records extracted and references cited from relevant publications. These articles were saved in plain text format for subsequent research purposes. Two researchers independently collected and screened the literature for relevance to the topic based on abstract content. Discrepancies were resolved by a third-party adjudicator. From 2007 to July 31, 2024, a total of 3845 articles were retrieved with 1177 ultimately selected for analysis after the screening process. The detailed screening methodology is illustrated in Fig. 2.

2.2. Scientometric analysis

R version 4.2.3 [23], VOSviewer [24], and CiteSpace [25] were used as tools for conducting bibliometric analysis. The number of publications and the frequency of international collaborations were quantified using the bibliometric R package. VOSviewer was used to calculate keyword frequencies and visually represent collaborations across countries, institutions, and authors. CiteSpace was leveraged to identify highly cited publications and key terms within distinct timeframes. Publication quantity was analyzed using the exponential growth function in Excel [26]. The detailed methodology is illustrated in Fig. 2.

3. Results

3.1. Literature development trends

The present study involved 1177 articles on wearable sensors utilized in wound management. Fig. 3A illustrates the comprehensive

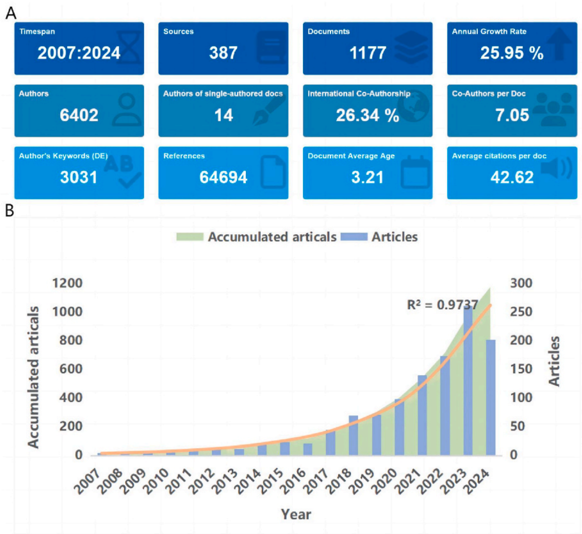

Fig. 3. Overall Statistics of Publication. (A). Additional statistics on wearable sensor publications from R bibliometrix. (B). Annual and cumulative output of global wearable sensor research publications from 2007 to 2024.

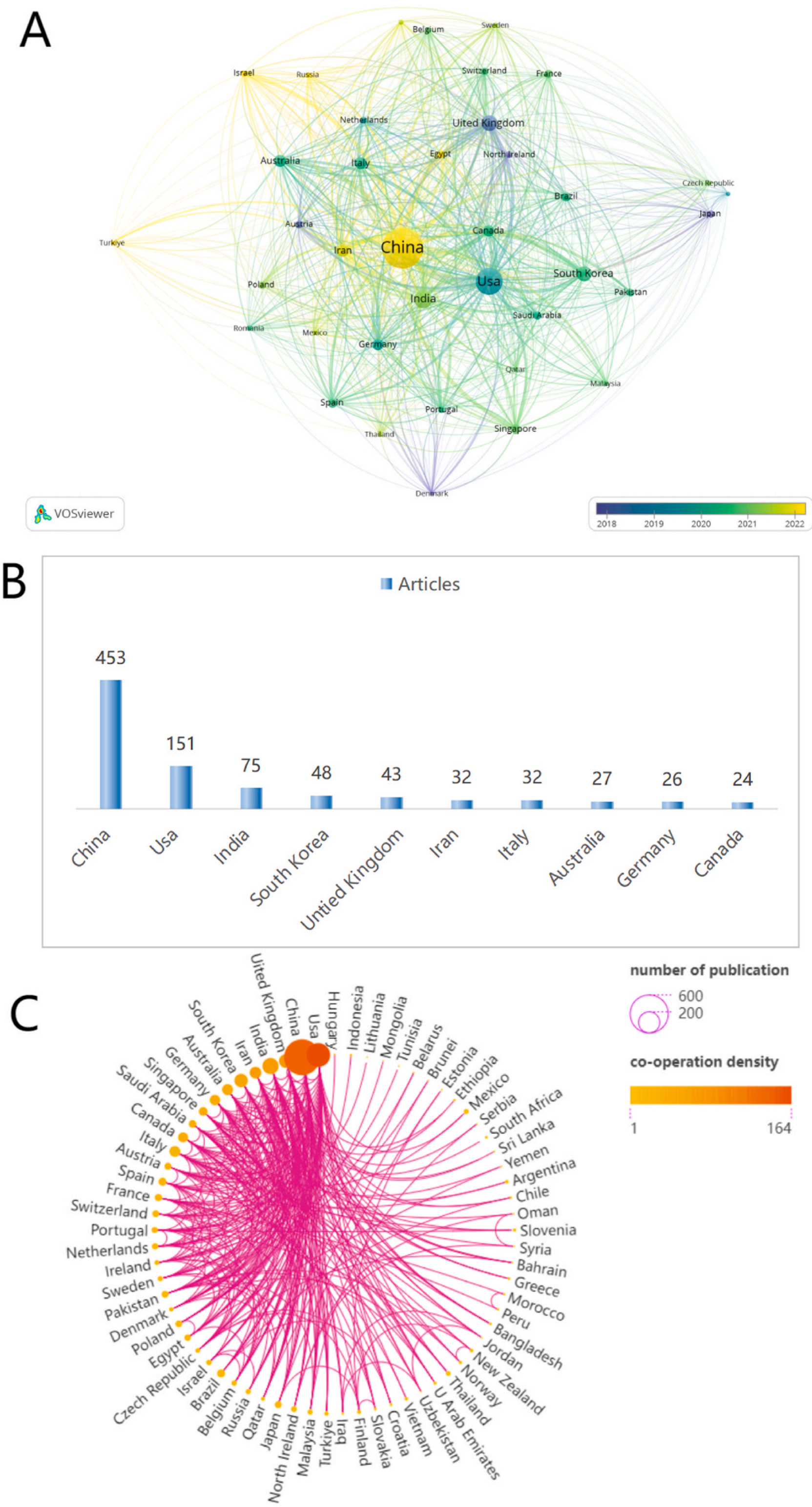

Fig. 4. Overview of Publication country/region. (A) Country/region network visualization, revealing 703 links spanning 38 countries/regions worldwide. (B) The top 10 contributing countries/regions in the wearable sensor. (C) Country presentation of the number of publications collaboration map and the cross-map.

overview of the literature in this domain spanning the past 15 years, while Fig. 3B depicts the correlation between the annual publication count and cumulative tally. Between the first publication in 2007 and the third publication in 2012, the field exhibited a sluggish growth rate. Nonetheless, over the subsequent 12 years, the publication counts surged, culminating in 1177 articles by July 31, 2024. An exponential growth model was used to evaluate the correlation between cumulative publications and publication years, yielding an R^2 value of 0.973, thereby attesting to the substantial growth and advances in wearable sensors in wound management.

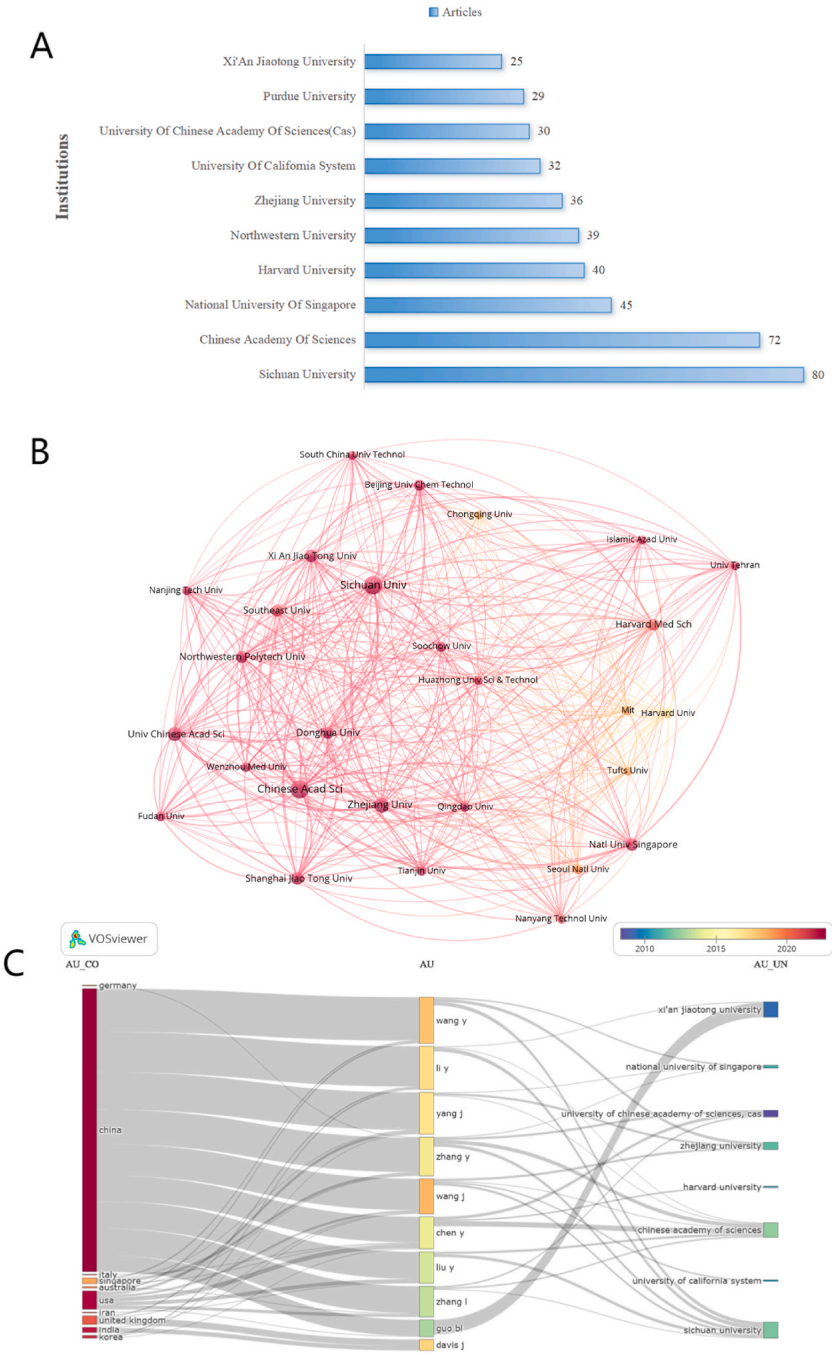

Fig. 5. Overview of Publication Institutions. (A) Top ten organizations in terms of number of articles issued. (B) Clustering of issuing organizations. (C)Interconnections of the top 10 high-productivity countries/regions, institutions, and authors.

3.2. Countries and institutions analysis

3.2.1. Country frequencies and Co-occurrences

Authors from 76 countries contributed to the published articles, with 38 authors engaging in collaborative efforts. The publications originating from these 38 countries were analyzed, as depicted in Fig. 4. The diameter of the circles within the time-overlapping network signifies the total number of publications, whereas the interior color signifies the average year of publication for each country [24]. Fig. 4A shows that the UK embarked on research in this field at an early stage, whereas China, despite initiating research relatively later, boasts the highest number of publications. To evaluate the respective contributions of different countries and regions, an analysis of the top 10 nations was performed based on the publication count. China dominates the research landscape in wearable devices for wound management, with 453 publications, followed closely 151, 75, and 48 by the USA, India, and South Korea, respectively. The remaining countries/regions have <45 publications each, as depicted in Fig. 4B. Fig. 4C illustrates the collaborations between various countries and regions. Notably, the most prevalent collaboration occurred between the USA and China (frequency = 44), followed by the USA and South Korea (frequency = 20).

3.2.2. Institutions analysis

To investigate the contributions of diverse institutions to wearable devices in wound care, publication output was analyzed from various institutions (Fig. 5). Globally, approximately 19 institutions conducted research, with China and the USA being the most prominent contributors, accounting for 5 and 4 of the top 10 institutions, respectively. Sichuan University led with 80 publications, followed by the Chinese Academy of Sciences (Fig. 5A). Among these institutions, 28 had published at least 10 papers. A co-authorship analysis of the publications was performed. Early research efforts were primarily led by institutions, such as MIT and Harvard Medical School (Fig. 5B). Conversely, several Chinese research institutions have increasingly engaged in the application research of wearable

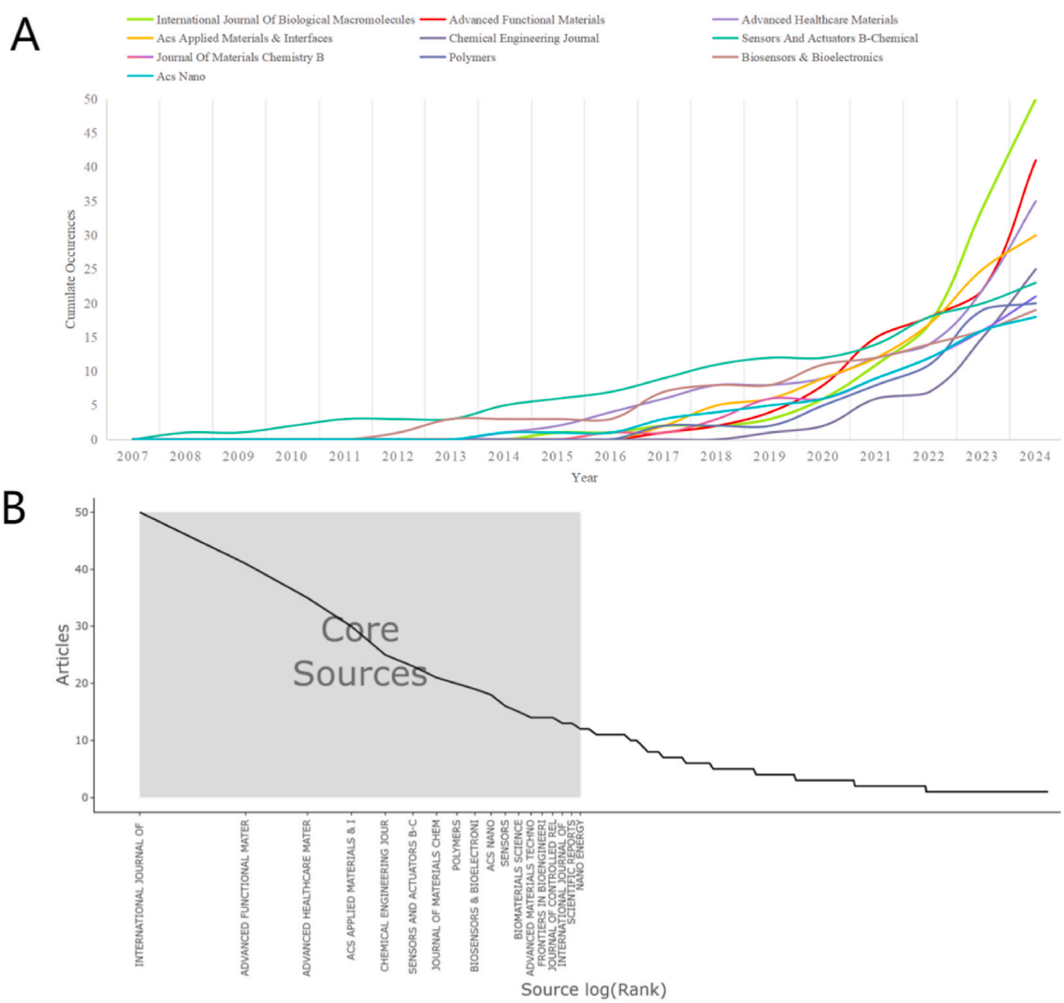

Fig. 6. Overview of Publication Journals. (A) Journal output trends within the top 10 from 2007 to 2024. (B) Delineation of core and non-core journals according to Bradford's law.

sensors for wound care after 2020. Fig. 5C demonstrates the clear cross-connections among the top 10 countries, institutions, and authors with China and the USA emerging as the primary research hubs.

3.3. Journals/cited journals analysis

3.3.1. Publication quantity and journal impact

A total of 387 journals contributed to the publication of these papers. The top 10 journals ranked by the number of published papers, are shown in Fig. 6A, with most journals having rapid growth since 2016. Among the top 10 journals, the International Journal of Biological Macromolecules leads with 50 publications, followed by Advanced Functional Materials and Advanced Healthcare Materials with 41 and 35 publications, respectively. Table 1 presents the top 10 journals, ranked by publication count with the 2023 impact factor (IF). The top 10 journals are all situated in the first quartile (Q1) of the Journal Citation Reports (JCR) with a distribution of publishers across various countries: 3 from the Netherlands; 2 from Switzerland; 2 from the USA, 2 from Germany; and 1 from the UK. The 387 journals have been categorized into 3 zones according to Bradford's law with 18 core source journals comprising the first zone, as depicted in Fig. 6B and Table 1.

3.3.2. Most cited publications and citation bursts

We assessed the most cited articles based on the citation frequency and compiled a list of the top 10 publications in Table 2, each publication having received >550 citations. The most frequently cited article [27], "A tissue-scale gradient of hydrogen peroxide mediates rapid wound detection in zebrafish," was published in 2009 and discusses the function of H_2O_2 in initiating wound responses in zebrafish larvae. The article reveals a consistent increase in H_2O_2 concentration at the wound site beginning 3 min post-injury and peaking at 20 min. The second most cited article, "Wearable and flexible electronics for continuous molecular monitoring," was published in 2019 and reviews the latest developments in non-invasive molecular monitoring utilizing wearable and flexible sensors in diverse biological fluids, including sweat, tears, saliva, interstitial fluid, blood, wound exudate, and exhaled breath [28]. Furthermore, the article delves into the primary challenges and opportunities confronted by wearable and flexible chemical sensors. In the context of wound care, these advanced dressings, capable of automatically or semi-automatically sensing and delivering therapeutic agents, have the potential to substantially enhance patient comfort and mitigate wound-related complications.

A citation burst represents a notable surge in the citations received by a publication, spanning a minimum of 2 y. The line depicts an observation period spanning from 2007 to 2024, wherein the red line signifies the duration of the citation burst [37]. As depicted in Fig. 7A, the top 10 most cited references are presented, with the article titled "Sensors and Imaging for Wound Healing: A Review" in *Biosensors and Bioelectronics* exhibiting the highest citation burst strength of 22.4 during the specified period. Furthermore, there are currently seven articles undergoing citation bursts. An article by Peter Kassal et al. [38], entitled "Smart Bandage with Wireless Connectivity for Uric Acid Biosensing as an Indicator of Wound Status" published in *Electrochemistry Communications* introduced a novel smart bandage capable of determining uric acid (UA) status. This bandage facilitates on-demand wireless data transfer of UA status to various devices, including computers, tablets, and smartphones, utilizing radio frequency identification (RFID) or near-field communication (NFC) technology. In the noteworthy work of Farooqui et al., entitled "Low-cost Inkjet-printed Smart Bandage for Wireless Monitoring of Chronic Wounds," a continuous wireless monitoring system is introduced [39]. This system enables early detection of wound status, including irregular bleeding, pH level variations, and external pressure at the wound site. Concurrently, Tamayol et al. [40] developed pH-responsive hydrogel fibers designed for long-term monitoring of epidermal wound conditions. Furthermore, Gao et al. [41] presented a mechanically flexible and fully integrated sensor array for multiplexed *in situ* perspiration analysis. This array simultaneously and selectively measures sweat metabolites, electrolytes, and skin temperature, leveraging the rich physiologic information present in human sweat. Fig. 8 provides a summary of the development sequence of wearable sensors and smart dressings for wound care based on the top 10 cited references. These research studies offer robust support for the clinical application of wearable sensors in wound care. As discussed in "Smart Bandages: The Future of Wound Care" by Derakhshandeh et al. [42], the emergence of smart bandages is anticipated to revolutionize clinical practice.

Smart bandages offer dual functionality, not only facilitating the detection of wound status but also treating wounds by delivering therapeutic drugs. For example, Zhao and colleagues [43] developed a series of injectable hydrogels for cutaneous wound healing,

Table 1
Top 10 journals in the field of wearable sensors in wound care.

Sources	Articles	PY_start	H_index	G_index	JCR	IF	Country
International Journal of Biological Macromolecules	50	2015	15	33	Q1	7.7	Netherlands
Advanced Functional Materials	41	2017	19	41	Q1	18.5	Germany
Advanced Healthcare Materials	35	2014	16	35	Q1	10	Germany
ACS Applied Materials & Interfaces	30	2017	18	30	Q1	8.3	USA
Chemical Engineering Journal	25	2019	11	25	Q1	13.3	Netherlands
Sensors And Actuators B-Chemical	23	2008	13	23	Q1	8	Switzerland
Journal of Materials Chemistry B	21	2016	13	21	Q1	6.1	England
Polymers	20	2017	10	20	Q1	4.7	Switzerland
Biosensors & Bioelectronics	19	2012	12	19	Q1	10.7	Netherlands
ACS Nano	18	2014	13	18	Q1	15.8	USA

Abbreviation: PY-start: The year for the first publication. USA: The United States of America. IF: Impact Factor.

Table 2
The top 10 cited articles in the field of wearable sensors in wound care.

Rank	First author	Year	Journal	IF	Total citations	TC Per Year	JCR	Title
1	Niethammer P	2009	Nature	50.5	1183	73.94	Q1	A tissue-scale gradient of hydrogen peroxide mediates rapid wound detection in zebrafish [27]
2	Yang YR	2019	Chem Soc Rev	40.4	846	141.00	Q1	Wearable and flexible electronics for continuous molecular monitoring [28]
3	Xue JJ	2017	Accounts Chem Res	16.4	787	98.38	Q1	Electrospun Nanofibers: New Concepts, Materials, and Applications [29]
4	Jayakumar R	2010	Biotechnol Adv	12.1	769	51.27	Q1	Novel chitin and chitosan nanofibers in biomedical applications [30]
5	Koetting MC	2015	Mat Sci Eng R	31.6	762	76.20	Q1	Stimulus-responsive hydrogels: Theory, modern advances, and applications [31]
6	Han L	2017	Acs Nano	15.8	750	93.75	Q1	Mussel-Inspired Adhesive and Tough Hydrogel Based on Nanoclay Confined Dopamine Polymerization [32]
7	Nussbaum SR	2018	Value Health	4.9	697	99.57	Q1	An Economic Evaluation of the Impact, Cost, and Medicare Policy Implications of Chronic Nonhealing Wounds [33]
8	Liang YQ	2021	Acs Nano	15.8	652	163.00	Q1	Dual-Dynamic-Bond Cross-Linked Antibacterial Adhesive Hydrogel Sealants with On-Demand Removability for Post-Wound-Closure and Infected Wound Healing [34]
9	Metcalfe AD	2007	J R Soc Interface	3.7	564	31.33	Q1	Tissue engineering of replacement skin: the crossroads of biomaterials, wound healing, embryonic development, stem cells and regeneration [35]
10	Toyota M	2018	Science	44.7	561	80.14	Q1	Glutamate triggers long-distance, calcium-based plant defense signaling [36]

Abbreviation: TC Per Year: Total Citation Per Year, JCR: Journal Citation Reports.

exhibiting excellent properties, such as self-healing, electroactivity, adhesiveness, conductivity, high swelling ratio, antibacterial activity, antioxidant capability, and biocompatibility. Furthermore, these hydrogels upregulate the expression of growth factors, such as VEGF, EGF, and TGF-β, leading to enhanced granulation tissue thickness and collagen deposition. Concurrently, Han et al. [32] presented a PDA-clay-PAM hydrogel, which is both adhesive and robust. This hydrogel adheres seamlessly to human skin without eliciting inflammatory responses, is effortlessly removable without causing harm, promotes cell adhesion and proliferation *in vitro*, and accelerates wound healing *in vivo*.

By utilizing these bandages, we can non-invasively diagnose wound parameters, address a wide range of chronic wound symptoms, and mitigate wound infections through closed-loop therapy systems. This approach offers patients enhanced care standards and expedites wound healing mechanisms with the potential to mitigate long-term hospitalization, reduce frequent medical visits, and diminish the need for costly laboratory tests associated with chronic wound management. Ultimately, the clinical application of wearable sensors in wound care was strengthened.

3.4. Author and keyword analysis

3.4.1. Author analysis

A total of 6402 authors have contributed to research on wearable sensors in wound care. Table 3 indicates that X Wang is the most prolific author, with 16 publications and an H-index of 11, followed by Y Wang, who also has 16 publications and an H-index of 8. Fig. 6C demonstrates clear cross-connections among the top 10 authors, institutions, and countries with the most significant research efforts primarily emanating from China and the USA.

The researcher collaboration network is illustrated in Fig. 7B. The size of each circle corresponds to the number of publications, while the color represents the distinct cluster. A total of 223 authors have published ≥3 articles, which are grouped into 59 clusters. Of these 59 clusters, 17 comprised ≥5 authors, 24 contained <5 authors, and 18 had only 1 author. The clusters exhibited relative dispersion, suggesting an imperative for fostering a stronger collaboration among research teams and laboratories specializing in wearable sensors for wound management. Furthermore, a nascent research network is emerging among Chinese researchers. Nonetheless, inadequate collaboration among various research groups underscores the importance of fostering national and institutional collaboration as a pivotal future development direction.

3.4.2. Keyword frequencies and Co-occurrence

Keyword analysis facilitates comprehension of research avenues within a given topic. Among the 5090 keywords analyzed, 226 surpassed the threshold of appearing ≥7 times after merging similar keywords. The frequently occurring keywords include “wound healing," “hydrogel," “sensor," and “antibacterial" (Fig. 9A). Early keywords are depicted in blue, whereas recent keywords are highlighted in red (Fig. 9B). Earlier research primarily concentrated on “pressure ulcers," “expression," and “care," whereas recent studies have shifted focus towards themes, such as “hydrogel," “antibacterial," “biomaterial," and “adhesion."

3.4.3. Keyword clustering analysis and citation bursts

Clustering analysis aids in gaining a deeper understanding of various research areas of this topic. As depicted in Fig. 10A, 226

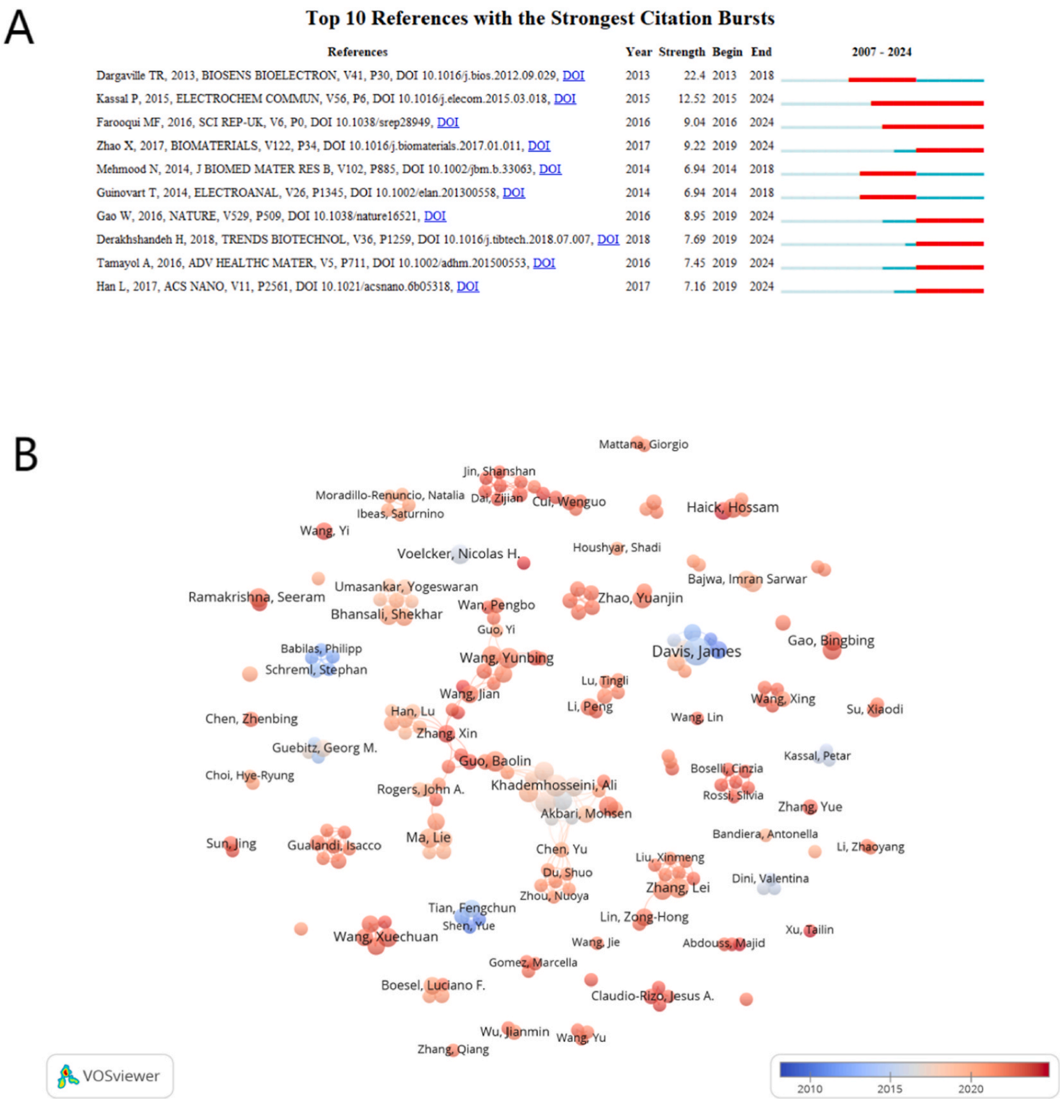

Fig. 7. Research hotspots on wearable sensors in wound care. (A) Top 10 references with the strongest citation bursts. (B) Connection map of authors with a minimum number of publications of 3.

keywords were categorized into five distinct clusters, exhibiting reliable outcomes as evidenced by a modularity score (Q score) of 0.376 and a silhouette score (S score) of 0.733. The overlap among these clusters suggests a degree of content similarity. The two most prominent clusters were Cluster #0 (smart bandage) and Cluster #1 (wound dressing), each containing >50 keywords. Cluster 0 centers around the monitoring capabilities of smart bandages, particularly emphasizing keywords, such as “pH," “sensor," and “management." Cluster 1 primarily explores the antimicrobial performance of wearable sensors, with key themes, such as “antibacterial," “hydrogel," and “adhesion." Cluster 2 underscores the applications of wearable sensors in wound healing, especially featuring keywords, such as “drug delivery," “tissue engineering," and “*in vitro*." Cluster 3 encapsulates the performance aspects of wearable sensors, addressing topics, such as “inflammation," “oxidative stress," and “angiogenesis." Cluster 4 concerns the utilization of “microneedle" and “patch" technologies in the context of wearable sensors for wound healing.

The keyword timeline visualization elucidates the evolution of research, transitioning from physical therapy for wound management, leveraging wearable technology, to intelligent monitoring bandages, advancing towards wireless therapy and multifunctional sensors (Fig. 10B). Burst detection pinpoints keywords experiencing rapid frequency increases within a brief timeframe, thereby unveiling emerging research hotspots and frontiers. Fig. 10C displays the 19 keywords exhibiting the strongest burst strengths, wherein “growth" (2009–2021) maintains the highest level of consistent interest, while “pH-sensor" (2022–2024) is anticipated to garner widespread attention in upcoming research endeavors.

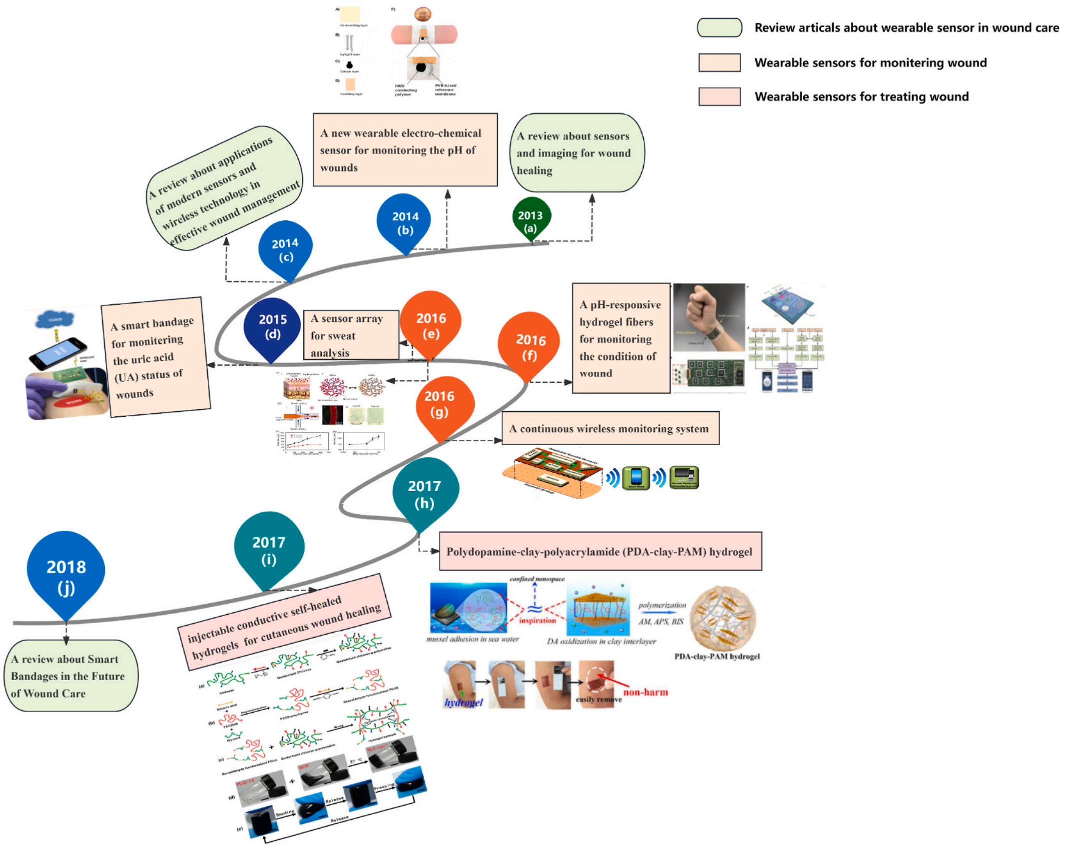

Fig. 8. A chronological account of the top 10 cited references in wound care.
(a) A review of sensors and imaging for wound healing [30]. (b) A wearable electrochemical sensor for monitoring the pH of wounds, reproduced with permission [31], Copyright 2014, John Wiley and Sons. (c) A review of applications of sensors and wireless technology in wound management [33]. (d) A smart bandage-based uric acid (UA) biosensing system with non-contact wireless, reproduced with permission [38], Copyright 2015, Elsevier. (e) A mechanically flexible and fully integrated sensor array for multiplexed *in situ* perspiration analysis, reproduced with permission [41], Copyright 2016, Springer Nature. (f) A pH-responsive hydrogel for monitoring the condition of wounds, reproduced with permission [40], Copyright 2016, John Wiley and Sons. (g) A Smart Bandage for Wireless Monitoring of Chronic Wounds, reproduced with permission [39], Copyright 2016, Springer Nature. (h) An adhesive and tough polydopamine-clay-polyacrylamide (PDA-clay-PAM) hydrogel, reproduced with permission [32], Copyright 2017, American Chemical Society (ACS). (i) An injectable hydrogel with hemostasis and adhesiveness for cutaneous wound healing, reproduced with permission [43], Copyright 2017, Elsevier. (j) A review of Smart Bandages in Wound Care [42].

Table 3
Top 10 authors in the field of wearable sensors in wound care.

Authors	Articles	H_index	G_index	TC	PY_start	Institution
Wang J	16	11	16	901	2014	Sichuan University
Wang Y	16	8	16	322	2018	Zhejiang University
Davis J	13	11	13	427	2008	Ulster University
Li Y	13	6	13	308	2021	Sichuan University
Yang J	13	8	13	552	2020	National University of Singapore
Zhang Y	12	7	11	128	2021	Chinese Academy of Sciences, Cas
Chen Y	9	6	9	350	2016	Chinese Academy of Sciences
Liu Y	9	5	9	381	2020	Chinese Academy of Sciences
Zhang L	9	8	9	608	2018	Sichuan University
Guo BL	8	6	8	1826	2020	Xi'An Jiaotong University

4. Discussion and future prospects

4.1. General information

The growth trajectory of wearable sensors in wound care applications from 2007 to 2024 was scrutinized using bibliometric

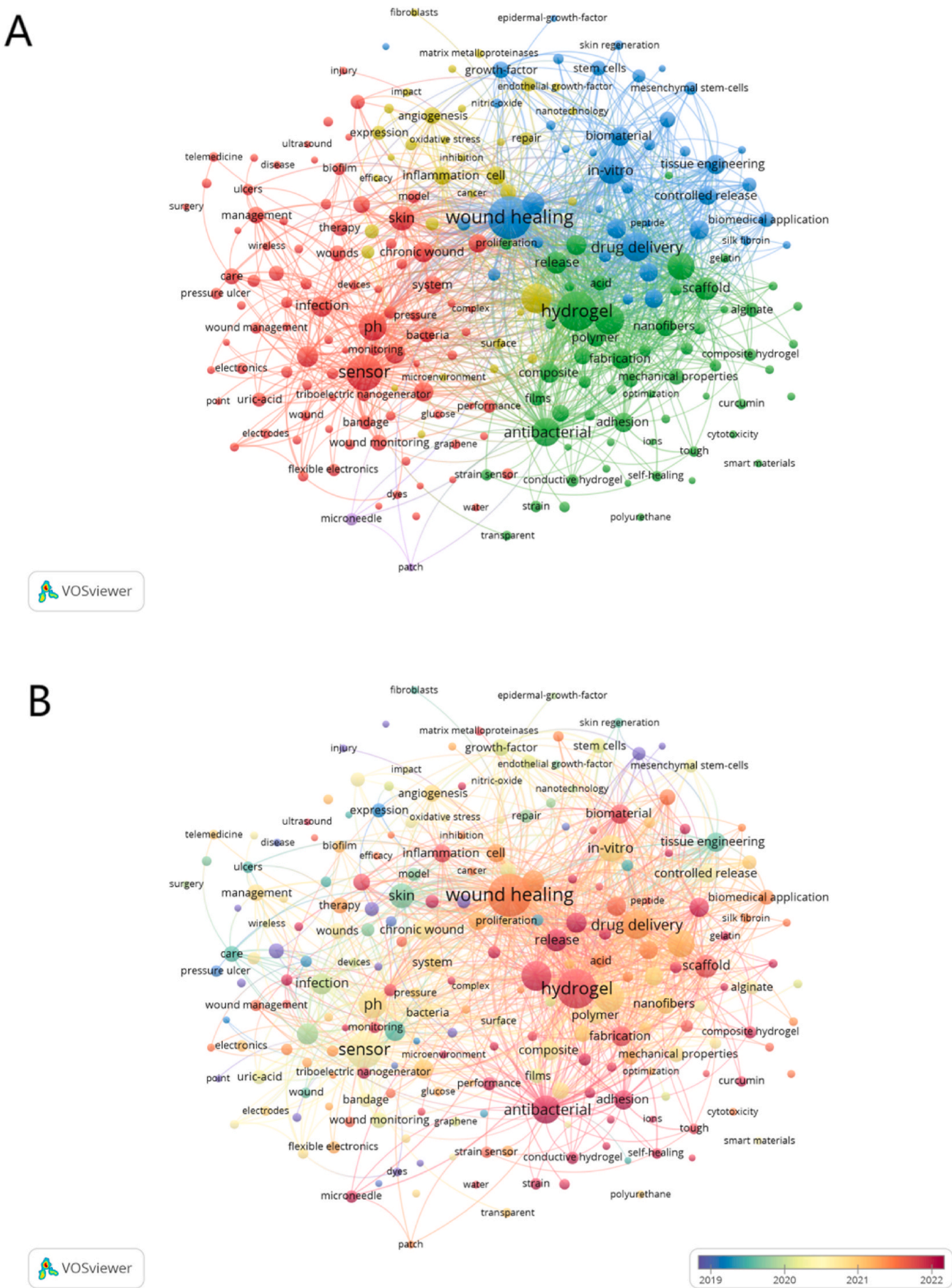

Fig. 9. Research hotspots on wearable sensors in wound care. (A) and (B) Co-occurrence analysis of all keywords with at least 7 occurrences, revealing 7101 links spanning across 226 keywords.

analysis. The evolution of research in wearable sensors for wound care can be bifurcated into two distinct phases, demarcated by the annual publication count exceeding 10 papers. Before 2012, the annual publication count remained below 10, suggesting a sluggish pace of research growth in the initial stages. Commencing in 2012, research on wearable sensors for wound care has accelerated, with an annual output exceeding 10 publications. By the end of 2023, the annual publication volume soared to 262, marking a significant escalation in the development of wearable sensors for wound care. As of July 31, 2024, a total of 202 papers have been documented,

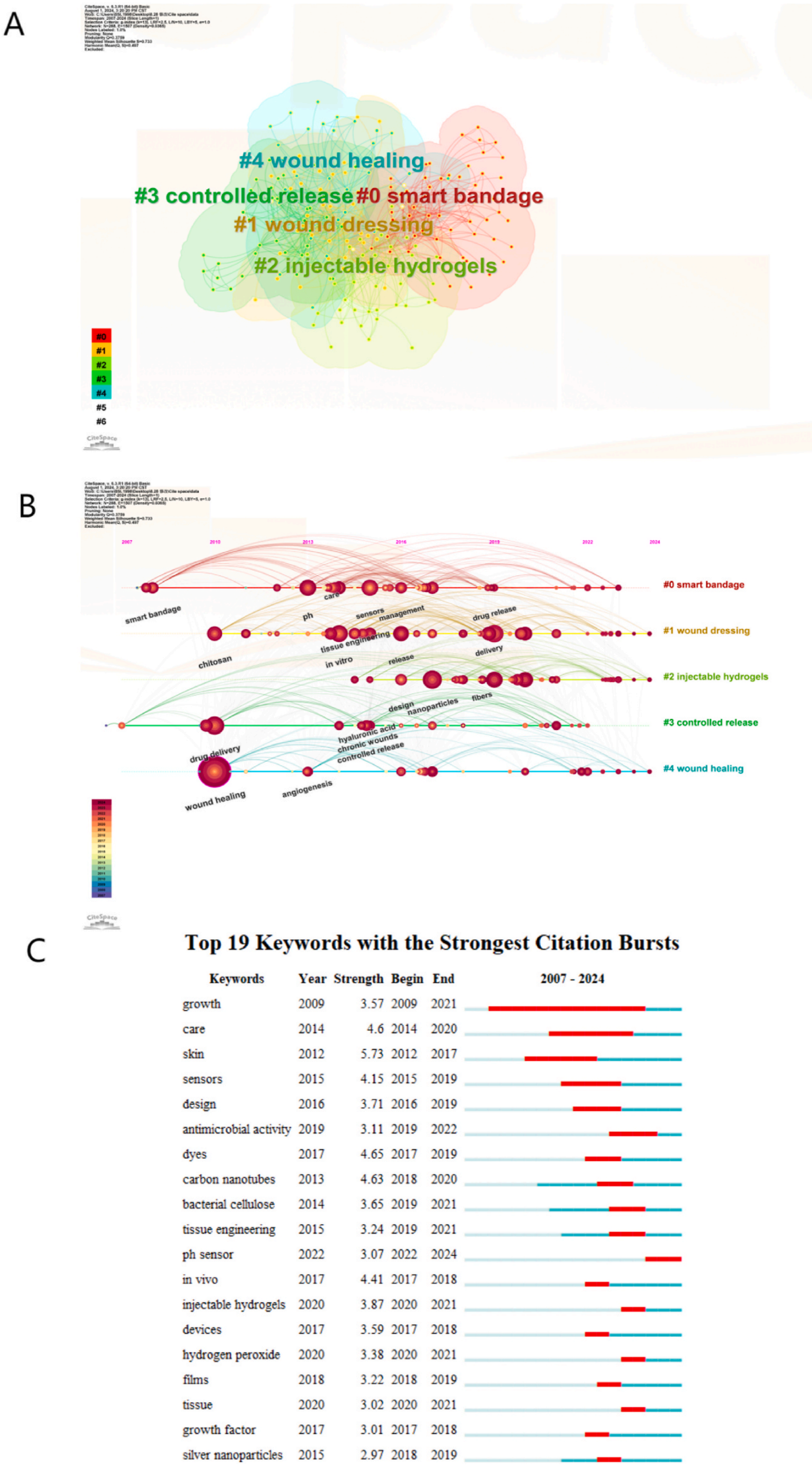

Fig. 10. Keywords analysis. (A) Cluster information for keywords reveals the plausibility and reasonability of the cluster structure, as indicated by the Q score and S score. (B) Keyword timeline visualization map for wearable sensor in wound care. (C) Top 19 keywords with the strongest citation bursts.

portending heightened interest in future research endeavors. This heightened interest could stem from the escalating prevalence of chronic comorbidities in aging populations and rising obesity rates, which contribute to delayed wound healing and elevated wound management expenses [44]. Advancement of wearable technology has heightened awareness of its potential to enhance patient management in wound care. Subsequently, research institutions have bolstered their support for wearable sensor research, leading to a sustained increase in funding and thereby facilitating rapid advances in this field.

Additionally, China and the USA lead the top 10 countries in scientific publications, with China-centric global partnerships accounting for 6 of the top 10 most common collaborative countries. These findings validate the significant role of China in advancing wearable sensor research for wound care, potentially influenced by the high demand for chronic wound management in China.

Journals are categorized into 4 quartiles (Q1-Q4) according to the IF scores in the JCR. Among the top 10 journals, all of which belong to the Q1 quartile, *Advanced Functional Materials* stands out with the highest IF (18.5), closely followed by *ACS Nano* (IF, 15.8). Despite the substantial contributions from China to research in this field, Asian publishers are notably underrepresented among the top 10 journals, emphasizing the necessity to establish and foster internationally prominent journals in Asia.

4.2. Analysis of research contents

Cluster analysis groups similar keywords into distinct themes, facilitating researchers' comprehension of topic diverse research directions and content. Fig. 10A illustrates the five clusters of the study: smart bandage (#0); wound dressing (#1); injectable hydrogels (#2); controlled release (#3); and wound healing (#4). Smart bandages, wound dressings, and injectable hydrogels have attracted widespread attention, suggesting that wearable sensors and smart bandages for wound care are a prevalent research direction. Future studies are likely to emphasize the effects on wound healing and chronic wound management, particularly in developing controlled release functionalities. Furthermore, integrating wearable sensors into practical wound management applications represents a pivotal area for future research.

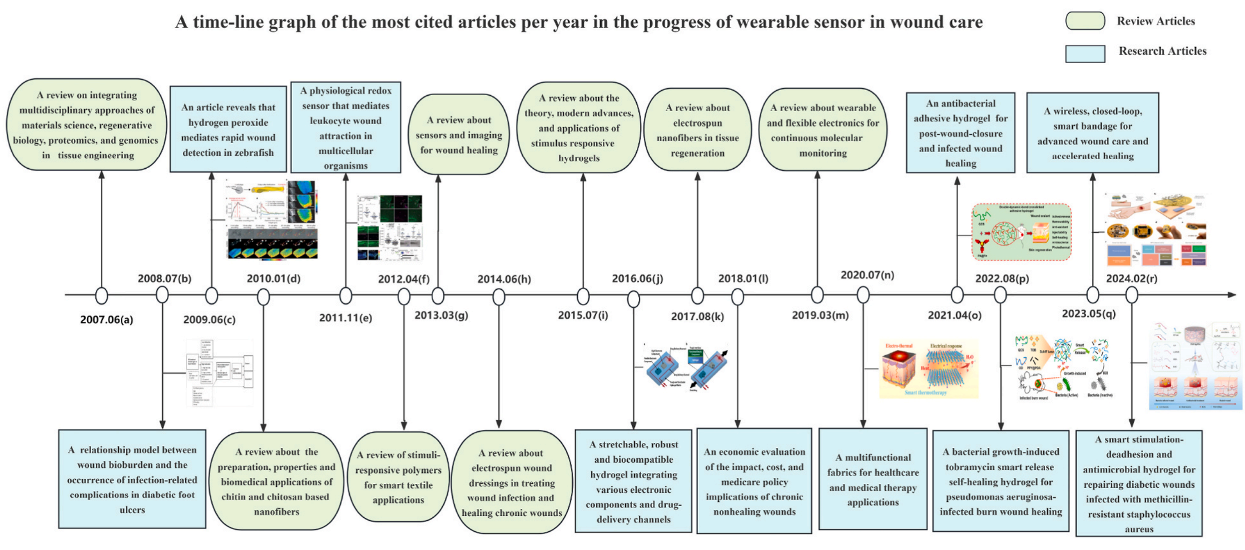

Fig. 11. A chronological account of the most cited articles per year in wound care.
(a) A review of multidisciplinary application in tissue engineering [34]. (b) A model between wound bioburden and the occurrence of infection-related complications in diabetic foot ulcers, reproduced with permission, Copyright 2008 [35], SAGE Publications. (c) An article reveals that hydrogen peroxide mediates rapid wound detection in zebrafish, reproduced with permission, Copyright 2009 [27], Springer Nature. (d) A review of the preparation, properties, and biomedical applications of chitin and chitosan-based nanofibers [36]. (e) A physiological redox sensor that mediates leukocyte wound attraction in multicellular organisms, reproduced with permission, Copyright 2011 [45], Springer Nature. (f) A review of stimuli-responsive polymers for smart textile applications [46]. (g) A review of sensors and imaging for wound healing [30]. (h) A review of electrospun wound dressings in treating wound infection and healing chronic wounds [47]. (i) A review of the theory, modern advances, and applications of stimulus-responsive hydrogels [44]. (j) A stretchable, robust, and biocompatible hydrogel, reproduced with permission, Copyright 2016, John Wiley and Sons [48]. (k) A review of electrospun nanofibers in tissue regeneration [29]. (l) An economic evaluation of the impact, cost, and medicare policy implications of chronic nonhealing wounds [49]. (m) A review of wearable and flexible electronics for continuous molecular monitoring [28]. (n) A multifunctional fabric for healthcare and medical therapy applications, reproduced with permission, Copyright 2020 [50], American Chemical Society. (o) An antibacterial adhesive hydrogel for post-wound-closure and infected wound healing, reproduced with permission, Copyright 2021 [51], American Chemical Society. (p) A bacterial growth-induced tobramycin smart hydrogel, reproduced with permission, Copyright 2022 [52], American Chemical Society. (q) A wireless, closed-loop, smart bandage for advanced wound care and accelerated healing, reproduced with permission, Copyright 2023 [53], Springer Nature. (r) A smart stimulation-deadhesion and antimicrobial hydrogel for repairing diabetic wounds, reproduced with permission, Copyright 2024 [54], John Wiley and Sons.

4.3. Research hot spot analysis

Citation metrics serve as a quantitative indicator of publication academic influence. Publications with high citation counts frequently embody pivotal themes within a research domain, facilitating the identification of research hotspots through analysis of these metrics. From 2007 to 2021, the top 10 most cited articles centered on the fabrication of wearable sensors (Table 2), while the leading 10 cited references predominantly concerned the utilization of wearable sensors in wound care (Fig. 8). Additionally, Fig. 11 outlines the evolutionary trajectory of wearable sensors and smart dressings in wound management, as evidenced by the annually most cited articles. Research has significantly evolved, progressing from early work on monitoring sensors embedded in bandages to recent advances in smart bandages for UA measurement, conductive hydrogels for expedited wound healing, and multifunctional hydrogels. Consequently, future research should focus on integrating hydrogels with wearable sensors and drug delivery materials and developing wearable sensors capable of monitoring, treatment, and remote transmission, thereby offering a novel platform for wound care.

4.4. Frontier analysis

Keyword analysis encapsulates the essence of research, enabling researchers to swiftly grasp the current research frontier. The keywords (wound healing, hydrogel, and sensor) frequently emerge, highlighting key areas of research interest. Furthermore, the rapid advances in artificial intelligence technology have revolutionized wearable sensors for wound care [55].

4.4.1. Hydrogel and sensor in wound care

Hydrogels are hydrophilic polymers composed of natural or synthetic materials, characterized by a three-dimensional network structure. Hydrogels rapidly absorb and retain a significant volume of water without dissolving [56]. The high water content, biocompatibility, and structural similarity of hydrogels to human macromolecular components enable hydrogels to create a moist wound environment, facilitate exudate removal, prevent infection, and support tissue regeneration [57]. Furthermore, hydrogels have the potential to mitigate scar formation and stimulate the migration of epithelial cells towards the wound site [58]. Consequently, hydrogels are widely regarded as the optimal material for wet wound dressings. In recent years, research on hydrogels has increasingly focused on transitioning from single-function physical barriers to multifunctional systems. Researchers are actively pursuing the development of multifunctional dressings and hydrogels, endowed with antibacterial, adhesive hemostatic, material delivery, self-healing, stimulus-responsive, and conductive properties, aimed at enhancing wound care outcomes [59–62]. For instance, Xiong et al. [63] developed a bacteria-responsive DNA hydrogel capable of smartphone-based wound infection detection, potentially facilitating optimized management of surgical and chronic wounds.

A sensor is a device that is sensitive to specific substances, transforming the concentrations into electronic or other measurable signals for detection. Sensors can be categorized as physical, chemical, and biological sensors, depending on the intended measurement purposes [64]. A biosensor is a detection tool that incorporates biologically sensitive materials (e.g., enzymes, antibodies, antigens, and other bioactive substances) as recognition elements [65]. The biosensor generates signals that are sensitive to specific biological substances. As biosensors have become widely applied in disease diagnosis, food contamination detection, and environmental monitoring, research focused on enhancing biosensor functionalities has garnered increasing attention [66–68]. In 2021, Gao

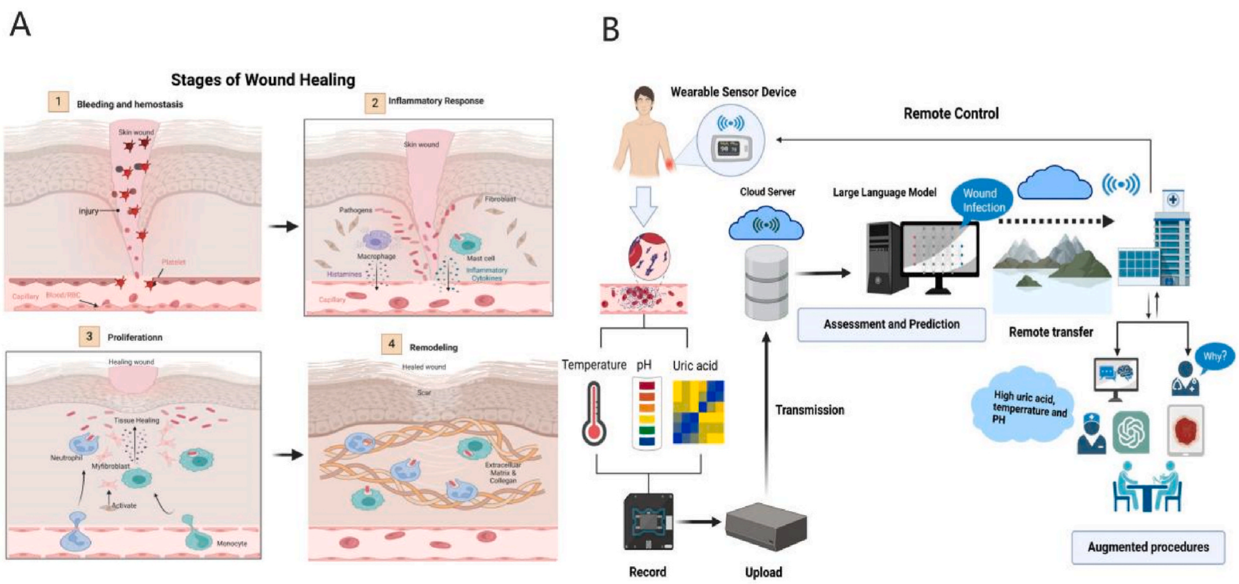

Fig. 12. Wearable sensor in wound care. (A) The graph of wound healing in 4 phases. (B) Schematic diagram of the application process of wearable sensors in wound care.

et al. [69] developed a flexible multiplexed immune sensor for point-of-care, *in situ* wound monitoring, capable of detecting the wound microenvironment, inflammation, and infection status. Consequently, the development of biosensors that incorporate pH conduction, wound care assistance, and wearable functionalities has emerged as a key research area.

4.4.2. Wearable sensors in wound healing

Wound healing constitutes a complex and dynamic self-repair process, typically encompassing four overlapping stages (hemostasis, inflammation, proliferation, and tissue remodeling; Fig. 12A) [70]. Notably, these stages are not discrete but occur concurrently [71]. Hemostasis initiates immediately post-injury, with blood vessels forming clots and secreting factors that pave the way for subsequent healing stages [72]. During the inflammatory phase, neutrophils and other inflammatory cells infiltrate the wound bed, engaging in phagocytosis to eliminate bacteria, pathogens, necrotic tissue, and damaged cells. This process leads to fluid accumulation and localized swelling. During the proliferative phase, granulation tissue formation occurs, which facilitates wound contraction and angiogenesis, driving the healing process forward [73]. The remodeling phase marks the ultimate stage, during which mature myofibrils transform into myofibroblasts, and type III collagen in granulation tissue undergoes a gradual substitution by type I collagen, subsequently emerging as the primary fibrous protein [74]. Finally, myofibroblasts engage with collagen bundles and growth factors, facilitating wound contraction and skin repair. Nonetheless, extensive deep skin injuries frequently necessitate external monitoring and intervention due to an inability to self-repair [44]. Therefore, for cases involving severe skin defects and wounds with limited healing potential, the application of intelligent dressings on the wound surface is indispensable for enabling real-time monitoring and on-demand therapeutic intervention.

Generally, hydrogel materials and wearable sensors designed to enhance wound care can be tailored for the four aforementioned stages, effectively reducing wound infection rates, accelerating healing times, and lowering management costs through timely monitoring of wound status and targeted drug delivery in one or more stages [75]. Analyzing high-frequency keywords in research highlights pivotal areas, including wound healing, hydrogels, and sensors, thereby broadening our comprehension of wearable sensors for wound care. Therefore, the integration of hydrogels and sensors for wound care management represents a promising research avenue aimed at further exploring wearable sensors in wound care and optimizing patient outcomes.

4.4.3. Wound care with artificial intelligence

Incorporating AI in wound management significantly boosts efficiency and treatment efficacy. By leveraging deep learning and machine learning algorithms, AI analyzes vast sensor data to extract key insights and accurately predict wound healing processes [76]. This advanced data analysis capability of AI allows for the prediction of healing processes, early detection of infections, and the recommendation of tailored treatment plans in wound care [77]. Furthermore, the sophisticated image recognition technology of AI enables in-depth wound image analysis, accurately assessing healing stages, and providing recommendations to aid physicians and patients in adjusting treatment strategies [78]. For example, Zheng et al. [79] have reported battery-free, AI-powered multiplexed sensor patches for real-time monitoring of wound progression and severity. These patches enable early detection of adverse events, facilitating prompt clinical intervention for wound management [79].

In the realm of remote control, the integration of AI with wireless technology for sensor data transmission has fundamentally transformed how medical professionals oversee and administer patient wounds [80]. This technology surpasses geographic constraints, enhancing the accessibility and immediacy of medical services, while also introducing unparalleled flexibility into treatment planning. Physicians can now adapt treatment plans in real-time, utilizing data gathered and transmitted by sensors worn by patients. This instantaneous flow of information not only enhances the precision of medical decisions but also facilitates instant patient feedback via wearable devices, thereby substantially boosting treatment compliance and engagement. Advances in natural language processing technology has spurred the development of large language models, harnessing the immense potential for processing and analyzing vast quantities of unstructured data gathered in wound care settings [81]. These models effectively extract valuable insight from medical records, patient feedback, and annotations, empowering physicians to gain deeper understanding of patient conditions and offer more tailored treatment recommendations [82]. For example, the models can scrutinize patient descriptions and feedback, aiding physicians in pinpointing changes in symptoms or potential complications during the wound healing process, thereby facilitating the refinement of treatment strategies or suggesting additional diagnostic tests.

With the ongoing advances in large language models and machine learning technologies, these tools are poised to assume a pivotal role in wound care in the future. These tools will offer data-driven insight to facilitate medical decision-making and will also enable advanced capabilities, including automated patient report generation, interpretation of complex medical images and data monitoring, and direct patient interaction for automated consultations and support. The recent advances in wearable sensor devices are poised to enhance their intelligence, personalization, and efficiency in wound care. This will significantly improve patient treatment experiences and outcomes, optimizing medical resource allocation, and boosting the overall efficiency of the healthcare system. Furthermore, the integration of hydrogels with smart materials and nanotechnology enables these materials to detect minute variations in the wound environment (e.g., pH level and temperature) and dynamically adjust functionalities, such as modulating drug release rates. This integration of hydrogels with smart materials is achieved through the precise control and real-time feedback mechanisms offered by AI technology. Future advances may lead to these tools assuming a pivotal role in wound care, offering data-driven insight, supporting medical decision-making, and enabling sophisticated functions, including patient report generation and complex medical image analysis (Fig. 12B).

4.5. Strengths and limitations

This study presents a comprehensive and systematic analysis of publications and development trends about wearable sensors in wound care, providing valuable guidance for clinicians and scholars alike. Nevertheless, this study is not without limitations, notably the exclusive reliance on data sourced from the Web of Science database. Future research endeavors should strive to incorporate a more extensive array of literature from diverse databases to ensure a broader and more comprehensive analysis.

5. Conclusion

The utilization of wearable sensors constitutes a pivotal new trajectory in wound care, addressing the pressing issues of heightened demand and costs within the wound management sector, while also facilitating the realization of remote care. The substantial annual surge in publications underscores the escalating significance of this research domain, in which China and the USA stand out as major contributors and collaborators. Pinpointing the leading researchers and institutions globally engaged in this research endeavor can assist clinicians and researchers in grasping the research hotspots in wearable sensors for wound care, thereby offering valuable insight for guiding future research trajectories.

Ethical approval

No ethical approval and patient consent were required for all analyses were based on literature research.

Data and code availability statement

The data in this study is not sensitive and is accessible in the public domain.

The data is therefore available and not of a confidential nature. All data reported in this paper will be shared by the corresponding author upon request. This paper does not report the original code. Any additional information required to re-analyze the data reported in this paper is available from the corresponding author upon request.

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CRediT authorship contribution statement

Shuilan Bao: Formal analysis, Data curation, Conceptualization. **Yiren Wang:** Supervision, Software, Methodology, Funding acquisition. **Li Yao:** Software, Methodology. **Shouying Chen:** Project administration, Funding acquisition. **Xiuting Wang:** Supervision, Investigation. **Yamei Luo:** Supervision, Resources. **Hongbin Lyu:** Validation, Supervision. **Yang Yu:** Supervision, Funding acquisition. **Ping Zhou:** Visualization, Supervision. **Yun Zhou:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e38762.

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