

Future direction of wound dressing research: Evidence From the bibliometric analysis

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Abstract

A bibliometric analysis based on the Science Citation Index Expanded database from 1991 to 2020 was performed to obtain insight into the future direction of wound dressing research. The study focused on the publication's performance in terms of yearly outputs and citations, mainstream journals, categories of the Web of Sciences, top countries, leading institutions, trends in research, and hotspots. A summary of the most commonly used keywords extracted from words in the paper title analysis, authors' keyword analysis, and *KeyWords Plus* analysis served as the foundation for determining current research priorities and future trends. The findings revealed that the annual output of the corresponding scholarly articles remained more or less the same during the first decade, followed by a rapid increase in the remaining period of the study. Tissue engineering would be the future of the existing wound dressing research. Biomaterials and electrospinning are gaining importance as raw materials and fabrication techniques for wound dressing. Advanced wound dressings with antimicrobial functionality and sustained drug release properties are becoming a popular research avenue in the wound dressing research field.

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Keywords

Wound dressing, medical textile, science citation index expanded, scientometrics, electrospinning, TC_{year} , CPP_{year}

Introduction

In human history, poultices of mud, milk, and plants were likely the first dressings used by ancient Sumerians to aid healing. Plasters of honey, plant fibers, and animal fats prepared by Egyptians followed.¹ Dressing materials available today are designed to provide particular wound healing benefits and have then slowly evolved from the early wound covers. The evolution of wound dressing materials has increased greatly in the last quarter-century of the 20th century+early 2000s.²

Some common features of wound dressings, such as their relatively low cost, ease of use, and effectiveness in cleaning, covering, and protecting the wound from the external environment, have made them widely acceptable in wound management. The primary functions of an ideal dressing are to: keep the wound bed moist, remove excess exudate, and avoid maceration, thus minimizing scar formation, protecting the wound from infection, and maintaining an adequate exchange of gases.^{3,4} Wound dressings should be able to flex and fit the lesion region, avoid excessive dehydration, absorb wound fluid without allowing bacteria to multiply, exhibit adequate mechanical properties, provide pressure for hemostasis, and adhere well to the wound bed to restrict bandage leakage. Furthermore, the wound and the surrounding tissues should also be supported by dressing, be able to protect the wound from further injury, promote re-epithelialization in the remedial stage, and be simple to apply and remove without causing further trauma to the wound.^{5,6} The development of an ideal wound dressing has been a task for researchers which can manage the wound effectively and efficiently as well as promote wound healing and tissue regeneration. Many research works are being carried out worldwide to develop an ideal wound dressing.

Bibliometrics is a valuable method for mapping the literature on a specific research topic. It has been utilized to track the research trend in specialized fields of study recently, such as pigment coloration research⁷ and bacterial nanocellulose.⁸ Bibliometrics is a research methodology based on quantitative analysis and statistics commonly used in library and information sciences. This research method can reveal the distribution patterns of articles published in the database within a given topic, field, institution, and country. The Science Citation Index Expanded (SCI-EXPANDED) from the Web of Science Core Collection of the Clarivate Analytics (previously known as Thomson Reuters) is the most valuable and widely used data repository for analyzing scientific achievements across all fields of research.

To the best of our knowledge, there is no bibliometric analysis of wound dressing research in the published literature. This study seeks to assess current research in the literature on wound dressing by bibliometric and visual analyses in order to show global trends and predicting future advancements that would be valuable for fundamental scientists and clinicians to acquire a comprehensive understanding of the area.

The research on wound dressing over the last three decades was examined to gain a better understanding of the global research situation in this field. Thus, the analysis synthetically covered quantitative descriptions of publications encompassing major journals, Web of Science categories, annual outputs, and top countries and leading institutions, together with the research trends and hotspots identified through the analyses of paper titles, author keywords, and *KeyWords Plus*.

Data and bibliometric methods

The data for this present study was obtained from the SCI-EXPANDED Web of Science in Clarivate Analytics (updated on 14 July 2021). The journal impact factors in 2020 were presented on 30 June 2021 in Journal Citation Reports (JCR). According to the definition of journal impact factor, it is better to collect the documents published in 2020 from the SCI-EXPANDED after 30 June 2021. Although SCI-EXPANDED is created primarily to find and search the literature by researchers, it does not present data in a readily available form for bibliometric investigations.⁹ As a result, data processing is always required for bibliometric studies, followed by data collection directly from SCI-EXPANDED. Recently, a big difference was found by using ‘front page’ including the paper title, abstract, and author keywords in paper¹⁰ as a filter in widely bibliometric studies.¹¹ *KeyWords Plus* can enhance and supplement title-word and author-keyword indexing by extracting additional search terms from the titles of publications that are mentioned by the authors in their bibliographies and footnotes in the ISI (now Clarivate Analytics) database.¹² It was pointed out that the documents that could only be searched using *KeyWords Plus* were unrelated to the topic being searched.¹³ Search keywords “wound dressing,” “wound dressings,” “wound dressed,” and “wound dress” was searched by the terms of Topic in the SCI-EXPANDED. It results in 6552 documents from 1991 to 2020. A total of 255 documents (3.4% of the 6552 documents) do not have search keywords on their ‘front page’. Only 6297 documents were defined as wound dressing publications. For analysis, these records were imported into a spreadsheet, and additional coding was done manually using Microsoft Excel 2016.¹⁴ Moreover, each journal’s journal impact factor (IF2020) was acquired from the JCR in 2020. However, some publications contained the search keywords in their abstract but the wound dressings were not the main research focus in the publications.

The corresponding author is marked as a reprint author in SCI-EXPANDED; however, we utilized the term corresponding author in this study.¹⁵ In the case of articles with multiple corresponding authors, only the last corresponding author, institute, and country was designated as the corresponding author information.¹⁶ In a single-author article where the corresponding authorship was not specified, the single author was considered both the first and corresponding author. Similarly, in an article with a single institution, the institution was designated as the institution of the first and the corresponding author.¹⁷

To have accurate analysis results, affiliations originating from England, Scotland, Northern Ireland, and Wales were categorized as being from the United Kingdom (UK).¹⁸

Table I. Citations and authors according to document type.

Document type	TP	TP*	%	AU	APP	TC_{2020}	CPP_{2020}
Article	5351	5351	84	30,210	5.6	134,168	25
Review	583	583	9.1	2538	4.4	43,189	74
Meeting abstract	243	240	3.8	1094	4.6	37	0.15
Proceedings paper	145	145	2.3	737	5.1	5941	41
Editorial material	45	44	0.70	107	2.4	335	7.4
Letter	33	32	0.52	80	2.5	74	2.2
Correction	19	18	0.30	80	4.4	8	0.42
Book chapter	13	13	0.20	55	4.2	1453	112
News item	11	3	0.17	19	6.3	0	0
Note	8	8	0.13	24	3.0	181	23
Reprint	2	2	0.031	9	4.5	17	8.5
Retracted publication	2	2	0.031	13	6.5	38	19
Retraction	2	2	0.031	14	7.0	1	0.50

TP: number of publications; TP*: number of publications with author information in SCI-EXPANDED; AU: number of authors; APP: number of authors per publication; TC_{2020} : the total number of citations from Web of Science Core Collection since publication year to the end of 2020; CPP_{2020} : number of citations (TC_{2020}) per publication (TP).

Four citation metrics were used to analyze the citations received by the publications:

C_0 : the total number of citations from the Web of Science Core Collection in publication year.¹⁹

C_{year} : the total number of citations (in a particular year) from the Web of Science Core Collection. C_{2020} means the number of citations in 2020.¹⁵

TC_{year} : the total number of citations from the Web of Science Core Collection since publication year to the end of the most recent year.²⁰ In this study, the most recent year is 2020 (TC_{2020}).

CPP_{year} : citations per publication ($CPP_{2020} = TC_{2020}/TP$),¹⁵ TP is total number of articles.

Results and discussion

Document type and language of publication

It has been claimed that there is a connection between document type and citations per publication.²¹ In 2015, the citations per publication were improved by using the citation indicator of CPP_{year} , which gives values more accurate.²² The number of authors per publication (APP) has recently been used in the discussion of the document types.²³ Table 1 illustrates the characteristics of 13 document types, including 5351 articles (84% of the 6397 documents) with the number of authors per publication (APP) of 5.6. The largest number of authors in the article is "Feasibility work to inform the design of a randomized clinical trial of wound dressings in elective and unplanned abdominal surgery",²⁴ published by 92 authors. The document type of the book chapters had the highest CPP_{2020} of 112, which can be attributed to three highly cited book chapters with a

TC_{2020} of 100 or more,¹⁹ by Reneker et al.,²⁵ Muzzarelli and Muzzarelli,²⁶ and Klemm et al.²⁷ with a TC_{2020} of 498, 405, and 332, respectively. High citations of book chapters may indicate that books on wound dressing research have attracted researchers in this field.

The CPP_{2020} of the reviews was 3.0 times the CPP_{2020} of the articles. A total of 583 reviews were published widely in 272 journals, mainly in the *Cochrane Database of Systematic Reviews* (46 reviews; 7.9% of 583 reviews). Four classic reviews with TC_{2020} of 1000 or more²⁸ were published by Lee and Mooney,²⁹ Bhardwaj and Kundu,³⁰ Boateng et al.,³¹ and Agarwal et al.³² with a TC_{2020} of 2,808, 2,437, 1,397, and 1,125, respectively. In addition, seven of the top 10 most frequently cited publications were review articles in wound dressing research. It is worth noting that documents in the Web of Science Core Collection can be split into two categories. For example, 145 documents were classified as document types of proceedings, papers, and articles; thus, the sum of the percentages is greater than 100%.³³

Only 5351 articles were chosen for further analysis out of all document categories since they contain the entire research, including the introduction, methods, findings, discussions, and conclusions. One of the most important considerations in bibliometric research as a big data analysis is the language of publishing.²⁰ A total of 14 languages were used in those 5351 articles. The most common language was English, which accounted for 97% of all articles, followed distantly by German (85 articles; 1.5% of 5351 articles), Korean (19; 0.36%), French (12; 0.22%), and Chinese (11; 0.21%). Some other languages were as follows: Japanese (5 articles), Spanish (4), Czech (3), Portuguese (3), Russian (3), Turkish (3), Polish (2), Welsh (1), and one in a bilingual journal in Serbo-Croatian. Those published in English had a much higher CPP_{2020} of 26 than non-English articles with CPP_{2020} of 4.0. Articles published in English had a higher APP of 5.7 than non-English articles with an APP of 3.9. It is apparent that English was the lingua franca for communicating wound dressing research with scientific society in the last three decades.

Characteristics of publication output

To analyze publications and their impact trends in a research field, Ho³⁴ suggested a connection between the total annual number of articles (TP) and their citations per publication ($CPP_{\text{year}} = TC_{\text{year}}/TP$) by years. Figure 1 depicts the year-by-year distribution of TP and their citations per publication (CPP_{2020}), represented as TC_{2020}/TP . In 2003, 57 articles had the highest CPP_{2020} of 89. A total of 13 articles (23% of 57 articles) published in 2003 were highly cited articles with a TC_{2020} of 100 or more, including one classic article with a TC_{2020} of 1000 or more by Khor and Lim.³⁵ Since 2003, CPP_{2020} has been on a decreasing trend, but TP has been increasing at a faster rate hitting 800 in the year 2020. That clearly indicates that wound dressing overall has attracted great attention among researchers. It can be expected that the CPP_{year} in the near future will continue to increase as many more articles are being published every year.

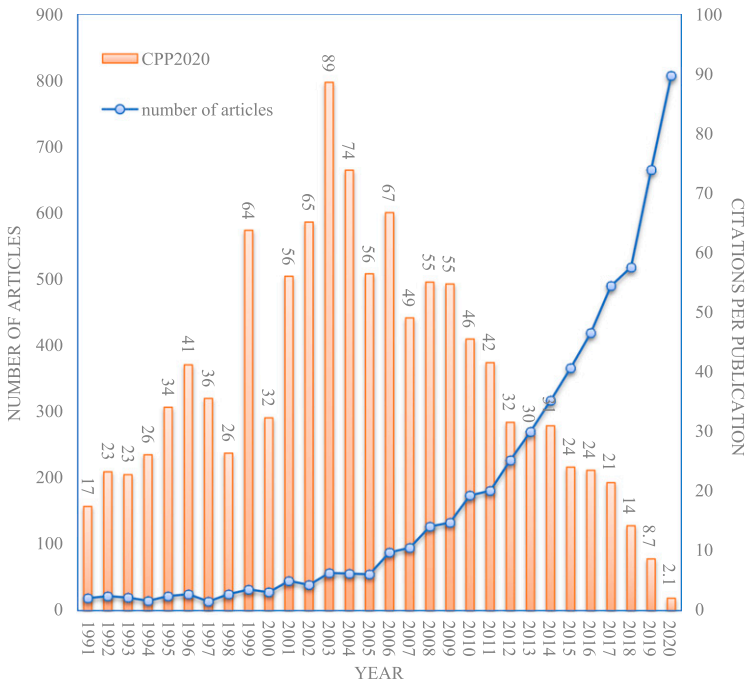


Figure 1. Number of articles and citations per publication by year.

Web of Science categories and journals

In the year 2020, a total of 9500 journals were indexed by JCR across 178 Web of Science categories in SCI-EXPANDED. A relationship between the number of papers in categories and publication years was suggested to identify development trends between research fields and their interactions.³⁶ Wound dressing-related articles (5351) considered for this bibliometric study were published in a wide range of 1070 journals under 129 Web of Science categories in SCI-EXPANDED. In 2020, a total of 191 articles were published in 97 journals with no journal impact factor. These journals were not classified in SCI-EXPANDED in 2020.

The top 10 Web of Science categories is shown in Table 2. Web of Science category of polymer science was the leading category with 1326 articles (25% of 5351 articles), followed by biomaterials materials science (951; 18%). Compared to the top 10 categories, wound dressing articles with the highest CPP_{2020} ($CPP_{2020}=48$) were published in the category of biomedical engineering. Category of organic chemistry published 243 articles (ranked 13th; 4.5% of 5351 articles) and also had a high CPP_{2020} of 54. The average of authors (APP) in the category of nanoscience and nanotechnology was 6.9, while dermatology was 5.2. Journals indexed in the Web of Science can be classified into two or more categories; for example, *International Journal of Biological Macromolecules* was classified in biochemistry and molecular biology, applied chemistry, and polymer

Table 2. The top 10 productive Web of Science category.

Web of science category	TP (%)	TC ₂₀₂₀	CPP ₂₀₂₀	AU	APP
Polymer science	1326 (25)	34,453	26	7126	5.4
Biomaterials materials science	951 (18)	36,822	39	5641	5.9
Surgery	649 (12)	13,380	21	3512	5.4
Biomedical engineering	615 (11)	29,496	48	3579	5.8
Dermatology	613 (11)	10,387	17	3185	5.2
Multidisciplinary materials science	556 (10)	14,337	26	3488	6.3
Applied chemistry	485 (9.1)	16,205	33	2774	5.7
Biochemistry and molecular biology	410 (7.7)	10,959	27	2348	5.7
Nanoscience and nanotechnology	392 (7.3)	13,531	35	2724	6.9
Multidisciplinary chemistry	389 (7.3)	11,456	29	2417	6.2

TP: number of publications; %: percentage of 5351 articles; TC₂₀₂₀: the total number of citations from Web of Science Core Collection since publication year to the end of 2020; CPP₂₀₂₀: number of citations (TC₂₀₂₀) per publication (TP); AU: the total number of authors; APP: number of authors per publication.

science, thus the sum of percentages could be higher than 100%.¹⁹ Figure 2 shows the development of the top nine categories with 400 articles or more. Before 2008, the category of surgery published the main part articles. Wound dressing articles were published mainly in the category of polymer science in the last decade. Multidisciplinary categories such as materials science, applied chemistry, biochemistry, and molecular biology are getting popular in recent years, ranked 2nd, 3rd, and 5th in 2020, respectively. A total of 649 articles (ranked 3rd) were published in the category of surgery, but only 35 articles were published in 2020 (ranked 14th in 2020), which indicates that the publishing trend in medical journals is decreasing. Although, it was generally expected that wound dressing research being a medical item, would be published more in medical category journals.

The top five most productive journals with 100 articles or more were: *International Journal of Biological Macromolecules* ($IF_{2020} = 6.953$) with 255 articles (4.8% of 5351 articles), *Carbohydrate Polymers* ($IF_{2020} = 9.381$) with 194 articles (3.6%), *Materials Science & Engineering C-Materials for Biological Applications* ($IF_{2020} = 7.328$) with 160 articles (3.0%), *Journal of Applied Polymer Science* ($IF_{2020} = 3.125$) with 152 articles (2.8%), and *Journal of Wound Care* ($IF_{2020} = 2.072$) with 125 articles (2.3%). According to the journal impact factor, *Lancet*, with one article placed first with the highest IF_{2020} of 79.321, followed by *JAMA-Journal of the American Medical Association* with three articles ($IF_{2020} = 56.272$), *Science* with one article ($IF_{2020} = 47.728$), and *Nature Materials* with one article ($IF_{2020} = 43.841$).

Publication performance: Countries and institutions

The 12 articles (0.22% of 5351 articles) were excluded from the analysis because they did not include authors' affiliation information in SCI-EXPANDED. Of the 5339 wound dressing articles from 97 different countries, 4330 articles (81% of the 5336 articles) were

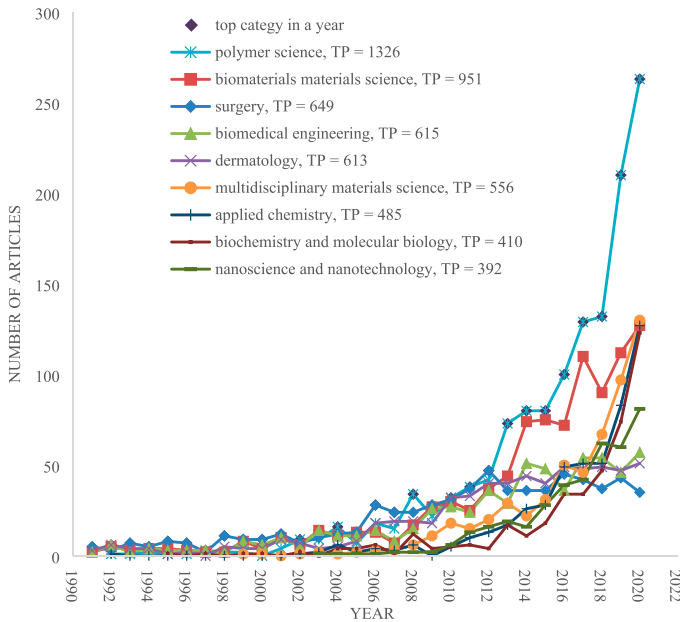


Figure 2. Developments of the top nine Web of Science categories with $TP > 400$.

single-country articles across 71 different countries, while 1009 (19%) articles were international collaborations from 93 different countries. The top 10 productive countries are listed in Table 3. Seven Asian countries, two European countries, and one American country made the top 10 list of publications. Outside the top 10, Australia, with 136 articles, ranked 13th, and Egypt, with 94 articles, ranked 18th, which was the top productive country in Africa. Wound dressing research activities are shifting from the USA to Asia, especially in China.

Six indicators were used for the comparison of publication performance: total number of articles (TP), single-country articles (IP), internationally collaborative articles (CP), first-author articles (FP), corresponding-author articles (RP), and single-author articles (SP)³⁷ as well as their CPP_{2020} . China dominated among the four publication indicators with a TP of 1070 articles (20% of 5339 articles), an IP of 836 articles (19% of 4330 single-country articles), an FP of 996 articles (19% of 5339 first-author articles), and an RP of 958 articles (18% of 5312 corresponding-author articles). USA ranked first in the two publication indicators with a CP of 297 articles (29% of 1009 internationally collaborative articles) and an SP with 31 articles (23% of 134 single-author articles). Compared to the top 10 countries, wound dressing articles from South Korea had the highest CPP_{2020} of TP , FP , and RP , respectively. South Korea is a plastic surgery nation.³⁸ Three of the top 10 wound dressing articles were published by Min et al.,³⁹ Khil et al.,⁴⁰ and Rho et al.⁴¹ from South Korea.

Figure 3 shows a comparison of development among the top six leading countries with 300 publications or more. The annual number of articles for a country before 2013 was less than 40, mainly published by the USA. China dominated wound dressing research

Table 3. Top 10 productive countries.

Country	TP	TPR (%)	TP CPP ₂₀₂₀	IPR (%)	CPR (%)	FPR (%)	FP CPP ₂₀₂₀	RPR (%)	RP CPP ₂₀₂₀	SPR (%)
China	1070	1 (20)	24	1 (19)	2 (23)	1 (19)	22	1 (18)	23	4 (4.5)
USA	758	2 (14)	32	2 (11)	1 (29)	2 (10)	33	2 (11)	32	1 (23)
India	422	3 (7.9)	27	3 (7.7)	5 (8.6)	3 (7.3)	27	3 (7.2)	28	6 (3.7)
UK	388	4 (7.3)	26	6 (5.2)	3 (16)	6 (5.3)	25	6 (5.4)	24	3 (11)
Germany	381	5 (7.1)	18	4 (6.3)	4 (11)	4 (5.9)	17	4 (6.0)	17	2 (12)
Iran	319	6 (6.0)	18	5 (5.8)	7 (6.6)	5 (5.7)	18	5 (5.5)	18	15 (1.5)
South Korea	289	7 (5.4)	41	7 (4.7)	6 (8.3)	7 (4.5)	44	7 (4.7)	43	6 (3.7)
Japan	194	8 (3.6)	30	10 (3.1)	11 (6.0)	9 (2.9)	24	8 (2.9)	24	10 (2.2)
Turkey	172	9 (3.2)	16	8 (3.2)	24 (3.2)	8 (3.0)	16	8 (2.9)	16	6 (3.7)
Taiwan	163	10 (3.1)	30	9 (3.1)	26 (2.8)	11 (2.8)	32	10 (2.8)	32	15 (1.5)

TP: total number of articles; TPR (%): rank of the total number of articles and percentage; IPR (%): rank of single country articles and percentage in all single country articles; CPR (%): rank of internationally collaborative articles and percentage in all internationally collaborative articles; FPR (%): rank of first-author articles and percentage in all first-author articles; RPR (%): rank of corresponding-author articles and percentage in all corresponding-author articles; SPR (%): rank of single-author articles and percentage in all single-author articles; CPP₂₀₂₀: number of citations (TC₂₀₂₀) per publication (TP).

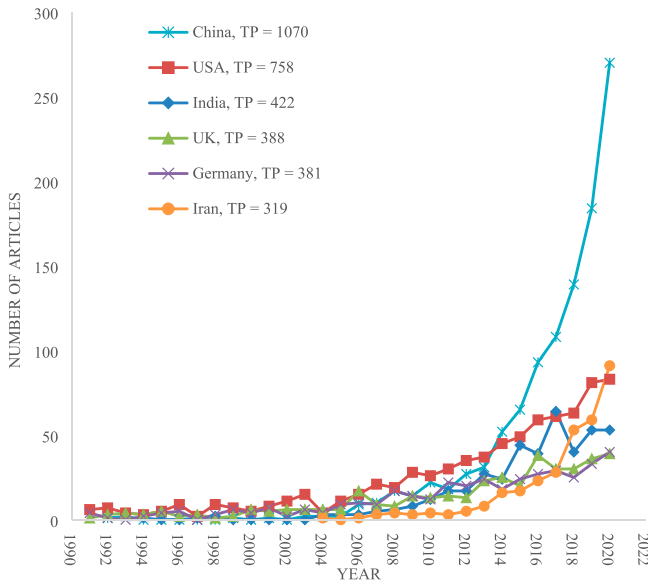


Figure 3. Comparison of development trends among the top six productive countries with $TP > 300$.

with a sharply increasing annual number of articles to reach 270 articles in 2020. Iran published the first article in 2004. A sharp increase in the publication by Iranians was found in recent years helping Iran to reach 2nd in 2020 with 91 articles.

In the case of performance of institutions, 1921 articles (36% of 5339 articles) came from a single institution, while 3417 articles (64%) were collaborative amongst institutions. The features of the top 10 productive institutions measured by the six publication metrics are shown in Table 4. The Sichuan University in China has taken the lead in three publication indicators with a TP of 81 articles (1.5% of 5339 articles), an IP of 30 articles (1.6% of 1921 single-institution articles), and an FP with 57 articles (1.1% of 5339 first-author articles). In two publication metrics, China's Donghua University came out on top with an IP of 30 articles (1.6% of 1921 single-institution articles) and RP of 53 articles (1.0% of 5312 corresponding author articles). Chulalongkorn University in Thailand was also ranked top in the corresponding author articles.

The Chinese Academy of Sciences in China ranked top with a CP of 70 articles (2.0% of 3417 inter-institutionally collaborative articles). The Amirkabir University of Technology in Iran was the only institute among the top 10 that produced single-author articles. Jiaxing College in China published nine articles, ranking 208th, with an SP of five articles (3.7% of 134 single-author articles). Compared to the top 10 leading institutes, wound dressing articles published by the National University of Singapore had the highest CPP_{2020} of 160, followed distantly by Chulalongkorn University in Thailand, while institutes in China and Iran had lower values of CPP_{2020} . A bias emerged as a result of the Chinese Academy of Sciences' multiple branches in various cities.⁴² At present, the

Table 4. Top 10 productive institutions.

Institute	TP	TPR (%)	IPR (%)	CPR (%)	FPR (%)	RPR (%)	SPR (%)	CPP ₂₀₂₀
Sichuan university, China	81	1 (1.5)	1 (1.6)	3 (1.5)	1 (1.1)	3 (0.94)	N/A	24
Chinese academy of sciences, China	79	2 (1.5)	20 (0.47)	1 (2.0)	4 (0.82)	5 (0.60)	N/A	28
Chulalongkorn university, Thailand	74	3 (1.4)	3 (1.1)	2 (1.5)	3 (0.88)	1 (1.0)	N/A	36
Donghua university, China	72	4 (1.3)	1 (1.6)	7 (1.2)	2 (1.0)	1 (1.0)	N/A	24
Islamic azad university, Iran	64	5 (1.2)	4 (0.78)	4 (1.4)	5 (0.77)	4 (0.62)	N/A	11
Amirkabir university of technol, Iran	58	6 (1.1)	10 (0.62)	5 (1.3)	6 (0.64)	6 (0.55)	9 (0.75)	21
Shanghai Jiao Tong university, China	50	7 (0.94)	40 (0.31)	6 (1.3)	11 (0.45)	17 (0.40)	N/A	23
Tehran university of medical sciences, Iran	45	8 (0.84)	111 (0.16)	7 (1.2)	22 (0.37)	27 (0.32)	N/A	25
University of Tehran, Iran	42	9 (0.79)	77 (0.21)	9 (1.1)	14 (0.43)	21 (0.38)	N/A	19
National university of Singapore, Singapore	41	10 (0.77)	13 (0.57)	14 (0.88)	14 (0.43)	9 (0.49)	N/A	160

TP: total number of articles; TPR (%): rank of the total number of articles and percentage; IPR (%): rank of single-institute articles and percentage in all single-institute articles; CPR (%): rank of inter-institutionally collaborative articles and percentage in all inter-institutionally collaborative articles; FPR (%): rank of first-author articles and percentage in all first-author articles; RPR (%): rank of corresponding-author articles and percentage in all corresponding-author articles; SPR (%): rank of single-author articles and percentage in all single-author articles; CPP₂₀₂₀: number of citations (TC₂₀₂₀) per publication (TP); N/A: not available.

publications of the institute with branches were considered under one institution, and if the publications were divided into branches, different rankings would have resulted.

The most frequently cited articles and the most impact articles in 2020

After publication, highly cited publications may or may not have a high impact or visibility.⁴³ The number of citations received in the recent year of 2020 (C_{2020}) may offer readers extra information about the influence of a highly referenced work today.¹⁵ When 5351 wound dressing articles were sorted by TC_{2020} , a different ranking was generated compared to the ranking obtained from the C_{2020} sorting. A total of 1282 articles (24% of 5351 articles) did not receive any citation in the most recent year ($C_{2020} = 0$) and 531 (9.9%) articles had no citations from their publishing year until the end of 2020 ($TC_{2020} = 0$). Moreover, 46% of the top 100 C_{2020} publications were also among the top 100 TC_{2020} articles. The 5351 wound dressing articles have been searched with search keywords in their title, abstract, and author keywords. A total of 1787 articles (33% of 5351 articles); 4661 articles (88% of 5325 articles with abstract); and 1642 articles (38% of 4303 articles with author keywords) contained search keywords in their title, abstract, and author keywords, respectively. The title of an article is a label that supplies reasonable details of the article subjects.⁴⁴ Author keywords were given by the authors to offer more information about the main research focused on articles. Articles that contain search keywords in their abstract might relate less to the search topic directly.

The top three most frequently cited articles included two classic articles entitled “Cytotoxicity and genotoxicity of silver nanoparticles in human cells”,⁴⁵ and “Implantable applications of chitin and chitosan”,³⁵ and a highly cited article entitled “Electrospinning of silk fibroin nanofibers and its effect on the adhesion and spreading of normal human keratinocytes and fibroblasts in vitro”,³⁹ contained search keywords in their abstract only. These articles do not directly relate to wound dressing research. Four of the top 20 articles on TC_{2020} contained search keywords in all their title, abstract, and author keywords. Typical examples include articles by Khil et al.⁴⁰ ranked 6th with TC_{2020} of 614, Balakrishnan et al.⁴⁶ ranked 11st with TC_{2020} of 571, Mi et al.⁴⁷ ranked 13rd with TC_{2020} of 504, and Kokabi et al.⁴⁸ ranked 20th with TC_{2020} of 390.

Figure 4 shows the citation records of the top seven most often cited publications ($TC_{2020} > 500$) with search keywords in the title or author keywords. Article by Mi et al.⁴⁷ ranked 13th on TC_{2020} with 504 but ranked 91st on C_{2020} with 31. Similarly, an article by Khil et al.⁴⁰ ranked 6th on TC_{2020} with 614 but ranked 66th on C_{2020} with 39. Article entitled “Antibacterial anti-oxidant electroactive injectable hydrogel as self-healing wound dressing with hemostasis and adhesiveness for cutaneous wound healing” by Zhao et al.⁴⁹ from Xi’an Jiao Tong University in China and University of Michigan in the USA had a sharp citation increasing trend after its publication year. This sharp increase in the citation of that article may indicate the importance of self-

healing characteristics of wound dressing. Moreover, the multifunctional dressing which can be injected and also offers hemostasis and antimicrobial properties attracted a great deal of attention. Table 5 shows the top 10 articles with the most citations containing search keywords in their title or author keywords. The USA published three of the top

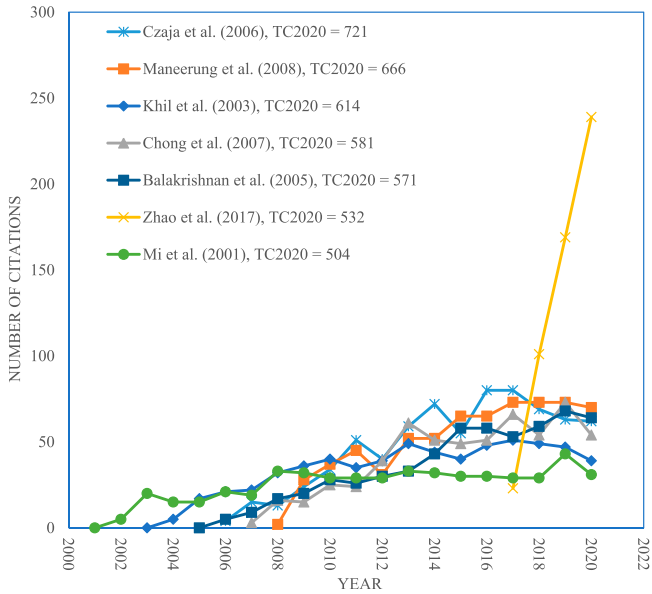


Figure 4. The citation life of the top seven most frequently cited articles with search keywords in their title or author keywords (TP > 500).

10 articles with the most citations followed by India (2 articles), Singapore (2), and one by each of China, Japan, Poland, South Korea, Taiwan, and Thailand, respectively. The Sree Chitra Tirunal Institute for Medical Sciences & Technology in India published two of the top 10 most frequently cited articles.

Research focuses and their trends

Ho's group recommended using the distribution of words in article title, abstract, author keywords, and *KeyWords Plus* in different periods as information to assess major research objectives and then uncover their development patterns in research subjects.^{56,57} In this study, words in article titles, abstracts, author keywords, and *KeyWords Plus* were examined and ranked accordingly for the full study duration and study period of 10 years (Supplementary material A, B, C). Table 6 shows the 20 most commonly used author keywords based on their ranking.

Except for search keywords: chitosan, electrospinning, and hydrogel were found to be the most frequently used author keywords.

The six possible research hotspots of wound dressing research were “tissue engineering”, “biomaterials”, “antimicrobials”, “drug delivery”, “advanced wound dressings”, and “electrospinning.” Each word cluster consists of several supporting words obtained from the results of word analysis.

Table 5. The top 10 most frequently cited articles with search keywords in their title or author keywords.

R (TC ₂₀₂₀)	R (C ₂₀₂₀)	Title	Country	Reference
4 (721)	27 (62)	Microbial cellulose: The natural power to heal wounds	USA, Poland	50
5 (666)	17 (70)	Impregnation of silver nanoparticles into bacterial cellulose for antimicrobial wound dressing	Thailand, Japan	51
6 (614)	66 (39)	Electrospun nanofibrous polyurethane membrane as a wound dressing	South Korea	40
9 (581)	33 (54)	Evaluation of electrospun PCL/gelatin nanofibrous scaffold for wound healing and layered dermal reconstitution	Singapore	52
11 (571)	25 (64)	Evaluation of an in situ forming hydrogel wound dressing based on oxidized alginate and gelatin	India	46
12 (532)	1 (239)	Antibacterial anti-oxidant electroactive injectable hydrogel as self-healing wound dressing with hemostasis and adhesiveness for cutaneous wound healing	China, USA	49
13 (504)	92 (31)	Fabrication and characterization of a sponge-like asymmetric chitosan membrane as a wound dressing	Taiwan	47
14 (497)	55 (43)	Silver as biocides in burn and wound dressings and bacterial resistance to silver compounds	USA	53
15 (483)	21 (67)	Development of a chitosan-based wound dressing with improved hemostatic and antimicrobial properties	Singapore	54
18 (425)	23 (66)	Flexible and microporous chitosan hydrogel/nano ZnO composite bandages for wound dressing: In vitro and in vivo evaluation	India	55

TC₂₀₂₀: the total number of citations from Web of Science Core Collection since publication year to the end of 2020; C₂₀₂₀: the number of citations of an article in 2020 only; R: ranking in 5351 wound dressing articles.

Tissue engineering

All articles that included supporting words, for example, scaffold, scaffolds, skin, skins, *vitro*, in vitro, *invitro*, cell, cells, biocompatibility, biocompatible, and cytobiocompatibility on their front page were contained in Figure 5, which shows that studies on “tissue engineering” rose rapidly and have taken the lead in the last decade (2010–2020). When the skin suffers full-thickness injuries, an excision (surgical removal) of the damaged skin is followed by skin grafting. Nowadays, the split-thickness autologous skin graft (autograft) is considered the clinical “gold standard” for this type of severe wound on the skin. Unaffected healthy skin removed from the patient is transplanted onto the full-thickness wound. Split-thickness transplantation contains thin slices of the epidermis and the initial part of the dermis leading to scar formation.⁵⁸ The split skin donor site heals

Table 6. Top 20 author keywords in publications related to wound dressing.

Author keywords	TP	1991-2020 rank (%)	1991-2000 rank (%)	2001-2010 rank (%)	2011-2020 rank (%)
Wound dressing	1145	1 (27)	1 (23)	1 (26)	1 (27)
Wound healing	632	2 (15)	3 (13)	2 (12)	2 (15)
Chitosan	476	3 (11)	7 (3.6)	2 (12)	3 (11)
Electrospinning	434	4 (10)	N/A	5 (6.7)	4 (11)
Hydrogel	296	5 (6.9)	4 (7.2)	4 (6.9)	5 (6.9)
Wound dressings	239	6 (5.6)	2 (16)	6 (5.5)	6 (5.2)
Antibacterial	196	7 (4.6)	50 (0.90)	26 (1.4)	6 (5.2)
Antibacterial activity	180	8 (4.2)	N/A	13 (2.3)	8 (4.6)
Silver nanoparticles	155	9 (3.6)	N/A	26 (1.4)	9 (4.1)
Alginate	152	10 (3.5)	6 (4.5)	9 (3.1)	10 (3.6)
Biocompatibility	145	11 (3.4)	7 (3.6)	8 (3.8)	11 (3.3)
Collagen	129	12 (3.0)	4 (7.2)	9 (3.1)	14 (2.8)
Antimicrobial	121	13 (2.8)	N/A	16 (2.0)	12 (3.0)
Gelatin	119	14 (2.8)	7 (3.6)	12 (2.7)	15 (2.8)
Nanofibers	114	15 (2.6)	N/A	37 (1.1)	13 (3.0)
Biomaterials	111	16 (2.6)	19 (1.8)	13 (2.3)	16 (2.6)
Hydrogels	109	17 (2.5)	7 (3.6)	7 (4.7)	21 (2.1)
Bacterial cellulose	97	18 (2.3)	N/A	61 (0.63)	17 (2.6)
Drug delivery	97	18 (2.3)	19 (1.8)	32 (1.3)	18 (2.4)
Nanofiber	89	20 (2.1)	N/A	26 (1.4)	20 (2.3)

TP: total number of articles; N/A: not available.

within 7 days and can be used for harvesting up to 3 to 4 times; however, the treatment lengthens the duration of the hospital stay since re-cropping is affected by the time required for re-epithelialization.⁵⁹

Moreover, in the case of a more extensive injury, such as occurs in patients with more than 50% total body surface area, the availability of donor sites is extremely limited. The severity of the injury might leave the patient with too little undamaged skin to harvest sufficient autografts.⁶⁰ Interestingly, full-thickness skin transplantation is usually scar-free, but at the same time, its application is very much limited by the fact that only a victim with an injured area of less than 2% total body surface area can benefit from this technique.⁶¹

Allografts are clinically indicated as possible therapeutic alternatives when a donor source of autografts is limited.⁶² Allografts are grafts taken from other people that are effective at preventing fluid loss, and infection, reducing discomfort, and promoting underlying tissue repair. However, allografts are in limited supply, costly, variable in quality, and present ethical and safety issues related to disease transmission. Allografts require rigorous screening and standardized sterilization and may lead to immune rejection.⁵⁸

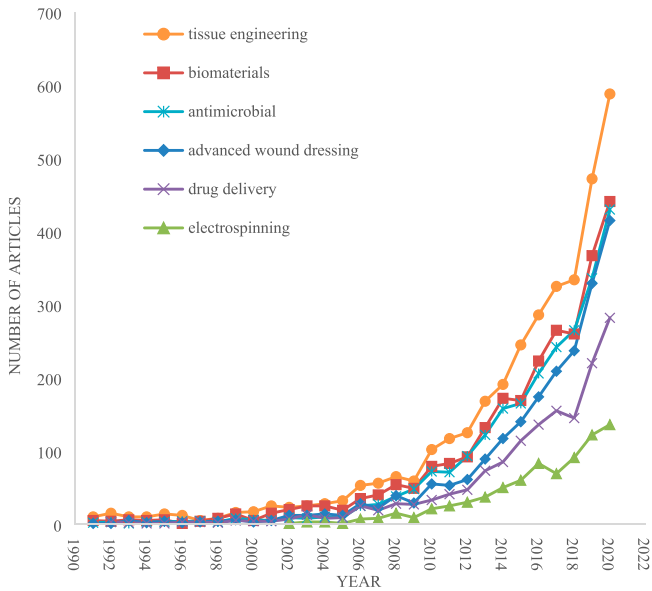


Figure 5. Development trends of the six topics in wound dressing research.

The above discussion highlights the need for alternative approaches to providing permanent solutions for skin tissue regeneration. Tissue engineering thus emerged as a field of research, which develops functional substitutes for damaged tissue by applying the principles of biology and engineering technology.⁶³ The ultimate goal of tissue engineering is to provide engineered products that are recognizable and exploitable by the desirable native tissue so that the body can repair and regenerate its own tissue defects and damage, respectively.⁶⁴ Many research groups worldwide have been working on in vitro studies for the creation of skin substitution because of the great importance and high demand for skin substitute products.⁶⁵ Today, researchers have developed several skin substitutes, and some of them are already used in the clinic.

Biomaterials

All articles that included supporting words, for example, biomaterials, biomaterial, gelatin, chitosan, chitosans, collagen, collagens, collagenase, cellulose, biocellulose, nanocellulose, alginate, alginates, and gelatine on their front page were considered studies on “biomaterials.” Biomaterials were identified as the second important research topic for wound dressing research in the last decade (Figure 5). It was clear from the published articles that researchers working on the wound dressing area are increasingly investigating the scope, physical and biological properties of biomacromolecules that have been used in wound dressings, including collagen,⁴¹ chitosan,⁵⁴ alginate,⁴⁶ gelatin,⁵² keratin,⁶⁶ fibroin,⁶⁷ microbial cellulose.⁵⁰ The choices of biomaterials depend on their functional

properties, such as biocompatibility, biodegradability, noncytotoxicity, antimicrobial properties, and wound healing capabilities.³⁵

Alginates are generally capable of absorbing 20 times their weight, which makes them suitable as a dressing material for use in highly exudative wounds. Alginate dressing is made of sodium and calcium salt of alginic acid derived from seaweed. The sodium and calcium ions undergo interaction with the serum of the wound bed to form a hydrophilic gel.^{68,69} Collagen is a natural extracellular matrix (ECM) component of many tissues, which makes it a perfect candidate for wound dressing and skin tissue engineering. ECM proteins, for example, type I and type IV collagen, help stimulate cellular attachment and spread.⁴¹ Collagen is a key protein in the body having hemostatic characteristics that help wounds heal and mend. Thus, collagen dressings may provide a substrate for fibroblasts and serve as a matrix to facilitate wound healing. Chitosan is the most common biopolymer used for wound healing applications next to collagen. The use of chitosan is principally due to its many admirable properties such as biocompatibility, biodegradability, hemostatic, and antimicrobial activity. It also has exhibited low immunogenicity, scar reduction capability, and an ability to promote tissue regeneration.⁷⁰ Keratin represents the most important biopolymer in mammals after collagen.⁷¹ Keratin can be utilized as a natural protein in biomedical applications instead of collagen and gelatin.⁷² Due to its biodegradable, bioactive, biocompatible characteristics, and natural abundance, keratin has been manufactured into films, hydrogels, electrospun mats, and dressings for biomedical applications.

Antimicrobial

All articles that included supporting words, for example, antibiotics, antibiotic, antimicrobial, antimicrobials, anti-microbial, antibacterial, anti-bacterial, nanosilver, silver, nano-silver, anti-infection, antibiosis, antiviral, anti-fungal, antifungal, anti-staphylococcal, anti-biofouling, and anti-inflammation on their front page were considered studies on “antimicrobial”. Figure 5 shows that antimicrobials emerged as the third main research focus of the wound dressing research field. Although it appeared as 3rd in the position, it is actually behind the Biomaterials with a very low margin as if both Antimicrobials and Biomaterials tie in the race. One of the main functions of wound dressing is protecting the wound from infection. Wound dressing limits the risk of infection by acting as a barrier between the wound and environment, thus limiting the access of all kinds of contamination, including microorganisms, to the wound surface. Research is moving towards the functionalization of a wound dressing with antimicrobial agents. Dressings impregnated with antimicrobials can benefit superficially infected wounds by killing microorganisms on the wound surface or under the dressing for up to 1 week. Antimicrobial agents start being released from the carrier dressings in contact with the fluid of the wound bed. Silver⁵³ and Povidone-iodine⁷³ are considered broad-spectrum antimicrobial agents and are indicated for the treatment of superficial microbial infections. Other antimicrobial agents, Chlorhexidine, Quaternary ammonium compounds, Octenidine hydrochloride, etc., have also been used for producing antimicrobial dressings.⁷⁴

Hydrogels,⁴⁹ alginates,⁶⁸ gelatin mats,⁷⁵ and other forms of wound dressing can be loaded with antimicrobial agents.







Silver is well established as an antimicrobial substance and has been registered as a broad-spectrum biocide in the United States since 1954⁷⁶ and is highly efficient in killing a wide range of microorganisms. Inhalation, ingestion, or dermal application of silver do not pose any threat to life. In the human body system, silver makes a complex with protein and can be removed by the liver and kidneys. As a result, silver is safe to be administered to the body in the proper chemical form and concentration.^{45,77} Antibiotic resistance is becoming one of the most serious problems in treating infection, and pathogenic bacteria have been developing resistance to antibiotics while the AgNPs are effective against multidrug-resistant bacteria.⁷⁸

Generally, silver does not show a negative effect on the viability of mammalian cells.⁷⁹ The highest effect of silver as an antimicrobial agent can be achieved by optimizing silver ions' production by increasing the surface area of the silver metal particle.⁸⁰ AgNPs, a very popular silver form for antimicrobial applications, such as in electrospun mats containing AgNPs used for wound dressing, show antimicrobial attributes against *E. coli* and *S. aureus*.

Advanced wound dressing

All articles that included supporting words, for example, advanced wound dressing, coaxial electrospinning, electrospin, electrospinning, coelectrospinning, electrospun collagen, electrospun fibers, co-electrospun, hydrogel, hydrogels, nanofibers, nanofiber, nanofiber-based, and nanofiber mats were considered studies on “advanced wound dressing”. An advanced category of wound dressing has made a place in the main research focus of wound dressing (Figure 5). Research on advanced wound dressings has shot up rapidly since 2012, making it 4th in the main research area of the wound dressing field. A range of commercial wound dressings reported in the literature is summarized in Table 7. Gauge and Tulle are some examples of common passive wound dressings available in the market. These are passive as they do not actively take part in the wound healing process; rather, their function is mainly limited to covering the wound bed to facilitate healing beneath the dressing.⁴ In search of an ideal wound dressing that will promote wound healing and tissue regeneration, various types of interactive advanced dressings have emerged. The hydrogel was clinically applied for the treatment of partial-thickness skin loss as a novel wound dressing in the year 1984.⁸¹ Hydrogel has been under study for further development to make them more efficient in wound management, such as antimicrobial hydrogels⁴⁹ and in situ hydrogels.⁴⁶ The nanofibrous scaffold was directly produced onto a polyurethane dressing via electrospinning as a new advanced wound dressing for dermal wound healing. The cell was grown on both sides of the nanofibrous scaffold, and its fibroblast adhesion and proliferation were evaluated. This was a successful first step in the construction of a suitable three-dimensional scaffold for the treatment of dermal wounds through the layered application.⁵² Other natural biomacromolecules have been tried, such as dextran on polyurethane and loaded with ciprofloxacin HCl drug as well to produce advanced type wound dressings.⁸²

Table 7. Examples of commercially available passive, interactive and advanced wound dressings.

Type	Product	Examples (manufacturer)	Image	Description	Limitations	Reference
Passive	Gauze	Gauze™ (Mölnlycke health care)		Made of cotton fibers, cheap and readily available	Does not provide a moist environment; can stick to wounds; may inhibit the healing process	83
	Tulle	BACTIGRAS™ (Smith & Nephew)		Greasy gauzes consisting of Tulle gauze and petroleum jelly	Bacteria may migrate from the sides	84
	Bandages	Propax® (BSN medical)		Made from natural (cotton, wool) and synthetic (polyamide) materials	Only gives support for other dressings	85
Interactive	Semi-permeable film	Bioclusive® (Johnson & Johnson)		Made of plasticized polyvinyl polymer, porous, transparent and permeable to water vapour and gases	Not suitable against maceration (tissue softening)	86
	Semi-permeable foam	Allevyn® (Smith & Nephew)		Made of polyurethane or silicone foam, highly absorbent	Requires secondary dressings	87
	Hydrogel	Carrasyn® (Carrington laboratories)		Made from insoluble, swellable hydrophilic polymers in the form of amorphous gel or elastic, solid sheet or film	Fluid accumulation within the dressing can cause skin maceration and bacterial proliferation	88

(continued)

Table 7. (continued)

Type	Product	Examples (manufacturer)	Image	Description	Limitations	Reference
Advanced Hydrocolloids	Comfeel®	Comfeel® (Coloplast AS)		Made from colloidal materials combined with elastomers or adhesive materials	Will not work against maceration in heavily exuding wounds	89
Hydrofibers	Aquacel®	Aquacel® (ConvaTec)		Soft nonwoven pad or ribbon made from sodium carboxymethyl cellulose fibers	Requires secondary dressing to adhere in place	90
Alginate	Sorbstan®	Sorbstan® (Dow Hickam)		Made from the calcium and sodium salts of alginic acid. Highly absorbent	Requires secondary dressing to adhere in place; not recommended for dry wounds	91
Collagens	BIOSTEP®	BIOSTEP® (Smith & Nephew)		Available in pads, gels, or particles and promote deposition of newly formed collagen in the wound bed	Requires secondary dressing to adhere in place; difficult to apply	92,93
Composites	Alldress®	Alldress® (Mölnlycke health care)		Island dressing with a textile-based absorbent portion	Failed to fit all wound shapes and sizes	94
Antibacterial	Acticoat®	Acticoat® (Smith & Nephew)		Two layers of silver-coated polyethylene mesh	No strong clinical evidence implied supporting the use of a silver product on all chronic wounds	95,96

Drug delivery

All articles that included supporting words, for example, release, releases, delivery, deliver, and delivering, were considered studies on “drug delivery”. Drug delivery has also emerged as one of the important research themes under wound dressings (Figure 5). One of the earliest works on the sustained release of an antibiotic drug embedded in a bilayer artificial skin was reported by Matsuda et al.⁹⁷ Since then, several works on the controlled delivery of drugs from wound dressings or scaffolds have been continued, and more works were reported in the last 5 years.

The creation of a polymeric matrix such as a scaffold is a common option for the controlled release of drugs as it can protect drugs from biological degradation before their release. Generally, the drug is molecularly dispersed in the polymer phase as a solute. When a polymer is exposed to a solvent that is thermodynamically compatible, it begins to release the drug substance to the surrounding media due to the action of polymer swelling. Solute diffusion or polymer dissolution can control the release mechanism.⁹⁸ One potential application for the dissolution of polymer matrices is wound dressing and tissue engineering, such as scaffolds for tissue regeneration.⁶³ Here, polymers are shaped into scaffolds resembling the structure of the tissue or an organ such as skin. The scaffold is then loaded with a drug used to fight disease or risk of infection. For example, a scaffold for skin tissue engineering can be loaded with antimicrobial drugs to minimize the potential risk of infection.⁹⁹ The antimicrobial drug will then be released as the polymer gradually dissolves. Different types of wound dressings, including composite electrospun mat,¹⁰⁰ injectable composite hydrogel,¹⁰¹ and hybrid nanofiber mat¹⁰² have been loaded with different drugs such as curcumin,¹⁰³ AgNPs,⁷⁵ epidermal growth factor,⁹⁹ and salicylic acid.¹⁰⁴

Electrospinning

All articles that included supporting words, for example, electrospin, coelectrospinning, co-electrospinning, electrospinning, electrospun collagen, electrospun fibers, electrospun nanofibers, and co-electrospun, were considered studies on “electrospinning”. Electrospinning has received great attention in wound dressing research, especially in the last decade (Figure 5), which is not surprising since research on tissue engineering got the most attention during a similar period. Tissue engineering research requires the use of a temporary scaffold, either synthetic or natural, or a combination of both, onto which cells are subsequently seeded, simulating the function of the natural ECM present in the human body. This assembly is then allowed to mature into a bioreactor, where embedded cells attach to the scaffold, multiply, secrete their own ECM, and trigger the creation of new tissue. Thus, in this approach, the scaffold provides the physical support on which the implanted cells organize the formation of the new tissue.¹⁰⁵ Electrospinning is considered one of the best techniques for the construction of these scaffolds, mostly due to its ability to produce micro- and nanoscale fibers. Other advantages offered by electrospun nanofibers include their high length to diameter ratio, enormous surface area per unit mass, and tuneable porosity.^{106,107}

One of the earliest works on wound dressings using electrospinning was reported by Jin et al.,⁶⁷ where nanoscale diameter fibers were formed from *Bombyx mori* silk with poly(ethylene oxide). One of the major contributions came from Khil et al.⁴⁰ when a porous membrane of polyurethane was prepared via electrospinning. This membrane showed controlled evaporative water loss with commendable permeability to oxygen and the ability to drain fluid. Moreover, it prevented the invasion of foreign microorganisms invasion because of its ultrafine porous structure. Many other natural, synthetic polymers and their combinations have been electrospun for biomedical applications.¹⁰⁸

Conclusion

Publication of wound dressing research increased sharply from the year 1991–2020 in SCI-EXPANDED. Wound dressing research is moving towards the tissue engineering field with appropriate biomaterials to find the platinum standard of skin loss management therapeutics. Choice of biomacromolecules for the preparation of an ideal wound dressing is leading the future of this field of biomaterials research as biomacromolecules can provide the template which is very close to the natural skin architecture. To fight the infection on wound beds, research is shifting rapidly towards antimicrobial dressing materials. Antibiotic drugs and antimicrobial agents are being embedded in the dressing. In the future, research on the low delivery of such drugs will also emerge alongside antimicrobial wound dressing. Nanofiber and hydrogel-based advanced wound dressings will probably be studied increasingly in the coming future. Future research will probably depend on the electrospinning technique to prepare an advanced wound dressing. Many studies in 129 Web of Science categories, including polymer science, biomaterials, materials sciences, surgery, and biomedical engineering, have been taken to develop an ideal solution for wound management. However, wound dressing articles were published mainly in the category of polymer science in the last decade, and the publishing tendency of wound dressing research in medical journals such as surgery was decreasing. Chinese universities took the leading position in the publication of wound dressing research, followed by Iranian universities, whereas the National University of Singapore had the highest CPP_{2020} (160). Six important future research hotspots of wound dressing have been predicted. Asian countries (seven countries among the top 10) were found to be more engaged in this field, followed by European countries. The USA was the most productive country in this area before falling behind China in 2013. The dominant publishing language was English (97% of the total articles), while 14 other languages were used as well. Although a single language dominated wound dressing research, the research works were found to be highly spread across the globe (97 different countries) with international collaborations from 93 different countries.

Author contributions

The manuscript was written with the contributions of all authors.

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