Research article

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Global Research Trends in Artificial Intelligence-Driven Conductive Bioinks for Wound Healing: A Bibliometric Analysis (2021–2025)

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Abstract: Artificial intelligence (AI), conductive bioinks, and advanced wound healing technologies are among the fastest-growing areas at the intersection of regenerative medicine and tissue engineering. This study mapped global research trends in AI-enabled conductive bioinks for wound healing from 2021 to 2025, examining collaboration networks, thematic development, and influential publications. Bibliometric analysis was performed on data retrieved from the Dimensions database, using Bibliometrix and VOSviewer for statistical and visual analyses. Annual scientific output showed a clear upward trajectory, reaching its highest level in 2025, based on records available up to the search date of January 15, 2026. China, India, and the United States led in publication volume, while the United States stood out for the breadth and strength of its international collaboration networks. Keyword co-occurrence mapping revealed three dominant thematic clusters centered on hydrogels, tissue engineering, and 3D printing with polymer science. “Skin” and “3D bioprinting” had the highest domain-specific relevance scores, reflecting a growing focus on skin regeneration and smart wound care. Highly cited publications addressed advanced bioprinting, conductive biomaterials, smart wound dressings, wearable biosensors, and AI-assisted regenerative strategies. Overall, the findings highlight a meaningful convergence of AI, biomaterials science, and wound healing research, with momentum building around intelligent material design, real-time wound monitoring, and precision medicine approaches. This analysis offers a structured view of the field’s intellectual development and serves as a useful reference for researchers and innovators working on next-generation wound care solutions.

Keywords*:* Artificial intelligence, Conductive bioinks, Wound healing, 3D bioprinting, Tissue engineering, Bibliometric analysis

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INTRODUCTION

Chronic wound management—encompassing diabetic ulcers, pressure injuries, and severely infected wounds—remains one of the most pressing public health challenges worldwide. The wound healing process involves a highly coordinated sequence of inflammatory, proliferative, and remodeling phases, and when this sequence is disrupted, conventional therapeutic approaches frequently fall short of achieving complete tissue restoration (1). Poorly managed chronic wounds carry a heavy toll on patients' quality of life and place considerable economic strain on healthcare systems, particularly in countries facing rapid population aging and a growing burden of non-communicable diseases (1, 2). These realities have spurred demand for wound care strategies that go beyond traditional dressings and pharmacological treatments, making biomedical engineering and regenerative medicine increasingly central to the search for more effective solutions (3).

Three-dimensional bioprinting has emerged as one of the most promising platforms for addressing these unmet clinical needs. It offers the ability to fabricate biomimetic tissue constructs with spatially defined architecture that closely resembles the native extracellular matrix microenvironment (4). A key component of this technology is the development of bioinks—printable, cell-laden biomaterial formulations. Among these, conductive bioinks incorporating electrically active nanomaterials such as graphene, carbon nanotubes, and metallic nanoparticles have attracted considerable scientific interest (1, 5). The electroactive properties of these composite materials allow electrophysiological stimulation of resident cells, promoting the cellular proliferation, migration, and differentiation needed for accelerated wound repair (6, 7). Complementary scaffold materials, including hydrogels, polysaccharides, and collagen, continue to serve as foundational matrices owing to their biocompatibility, tunable mechanical properties, and capacity to sustain biochemical microenvironments conducive to tissue regeneration (7, 8).

The incorporation of artificial intelligence into bioprinting workflows and biomaterial design marks a significant convergence that is reshaping the translational potential of regenerative medicine. Machine learning and deep learning algorithms have shown considerable promise in predicting the rheological and mechanical behavior of bioink formulations, optimizing printing parameters, and modeling the degradation kinetics of hydrogel-based scaffolds—capabilities that are difficult to achieve through conventional trial-and-error approaches (2, 9). Beyond material design, AI-driven image analysis tools now support real-time wound assessment and automated classification of healing stages, while AI-guided drug delivery systems can respond to wound microenvironmental cues such as changes in pH, enzymatic activity, and oxidative stress (3, 8). Together, these advances are driving the development of smart wound dressings capable of continuous monitoring, adaptive therapeutic response, and controlled bioactive molecule release (3, 5).

Despite growing research output in this interdisciplinary area between 2021 and 2025, a comprehensive bibliometric analysis that systematically maps publication trends, international collaboration networks, institutional productivity, and emerging thematic clusters has yet to be conducted. Bibliometric analysis provides a quantitative, internationally recognized method for characterizing the intellectual structure and developmental dynamics of a scientific field (10, 11). The present study therefore applies a systematic bibliometric approach, guided by the PRISMA 2020 framework, to examine research on the application of artificial intelligence in conjunction with conductive bioinks for wound healing, drawing on data from the Dimensions database (12, 13). The findings are intended to offer evidence-based insights that can help guide future research priorities, support strategic international collaboration, and inform the development of AI-integrated bioprinting technologies toward clinical application (9).

MATERIALS AND METHODS

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Research Design

This study employed a bibliometric analysis design guided by the PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework to collect, screen, and analyze the scientific literature on artificial intelligence, conductive bioinks, and wound healing published between 2021 and 2025 (12).

Data Source and Search Strategy

The Dimensions database (Digital Science & Research Solutions Inc.) was selected as the primary bibliographic data source. Dimensions is one of the largest and most comprehensive academic databases available, supporting retrieval of diverse publication types—including journal articles, book chapters, and conference proceedings—across multiple disciplines (13).

The search strategy was developed using structured Boolean logic combining three conceptual domains: artificial intelligence, conductive bioinks and related electroactive biomaterials, and wound healing. The full search string applied was as follows:("artificial intelligence" OR "machine learning" OR "deep learning" OR "neural network*") AND ("conductive bioink*" OR "electroconductive bioink*" OR "conductive hydrogel*" OR "electroactive biomaterial*") AND ("wound healing" OR "skin regeneration" OR "wound dressing*" OR "chronic wound*")

The search was conducted on January 15, 2026, with retrieval limited to titles, abstracts, and author-assigned keywords to reduce noise from full-text indexing and improve the relevance of retrieved records. The search covered publications from January 2021 through December 2025.

Inclusion and Exclusion Criteria (PRISMA Protocol)

Literature screening was conducted in four sequential phases in accordance with PRISMA 2020 guidelines (12), as illustrated in Figure 1.

Phase 1: Identification

An initial search of the Dimensions database using the structured Boolean search string retrieved a total of 5,897 records. These records were identified through searches of titles, abstracts, and author-assigned keywords, covering publications from January 2021 through December 2025. No language filters were applied at this stage. The search date of January 15, 2026, ensured complete capture of the full 2025 publication year within the specified 2021–2025 study window.

Phase 2: Screening

Retrieved records were screened based on titles and abstracts. Duplicate entries were identified and removed during this phase. Records that were clearly unrelated to the three core domains—artificial intelligence, conductive bioinks or electroactive biomaterials, and wound healing or skin regeneration—were excluded. Non-peer-reviewed materials, including editorials, letters, news items, and conference abstracts without full publication, were also removed at this stage. Following screening, 1,374 records were retained for eligibility assessment. A thesaurus file was applied within Bibliometrix to standardize keyword variants, merge equivalent terms, and remove non-domain terms such as generic descriptors unrelated to the research scope, prior to further analysis.

Phase 3: Eligibility

The remaining 1,374 records underwent full eligibility assessment against the predefined inclusion and exclusion criteria. Records were included if they were peer-reviewed journal articles published in English between 2021 and 2025, directly addressed all three conceptual domains, and contained sufficient metadata—including title, abstract, author information, publication year, and citation data—for bibliometric analysis. Records were excluded if they lacked clear relevance to all three domains, contained incomplete or unverifiable bibliometric data, or could not be confirmed against source databases. Each excluded record was assigned a reason for exclusion, as documented in the PRISMA flow diagram (Figure 1).

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Phase 4: Included

Articles meeting all eligibility criteria were included in the final bibliometric analysis. A total of 1,374 articles were retained for knowledge synthesis and analysis in accordance with the research objectives. The complete screening and selection process, including the number of records at each stage and reasons for exclusion, is presented in the PRISMA 2020 flow diagram (Figure 1).

Data Analysis

Bibliometric data were analyzed using two software applications: Bibliometrix (version 4.6), an R-based package for quantitative science mapping (10), and VOSviewer (version 1.6.20), a program for constructing and visualizing bibliometric networks (11). Prior to analysis, data cleaning procedures were applied, including removal of duplicate records, standardization of author names and country affiliations, and application of a thesaurus file to merge keyword variants and remove non-domain terms. Only records verifiable against source databases were retained. The analysis encompassed five dimensions as follows.

Annual Publication Trends

Annual publication counts from 2021 to 2025 were examined to assess the overall growth trajectory of research on artificial intelligence,

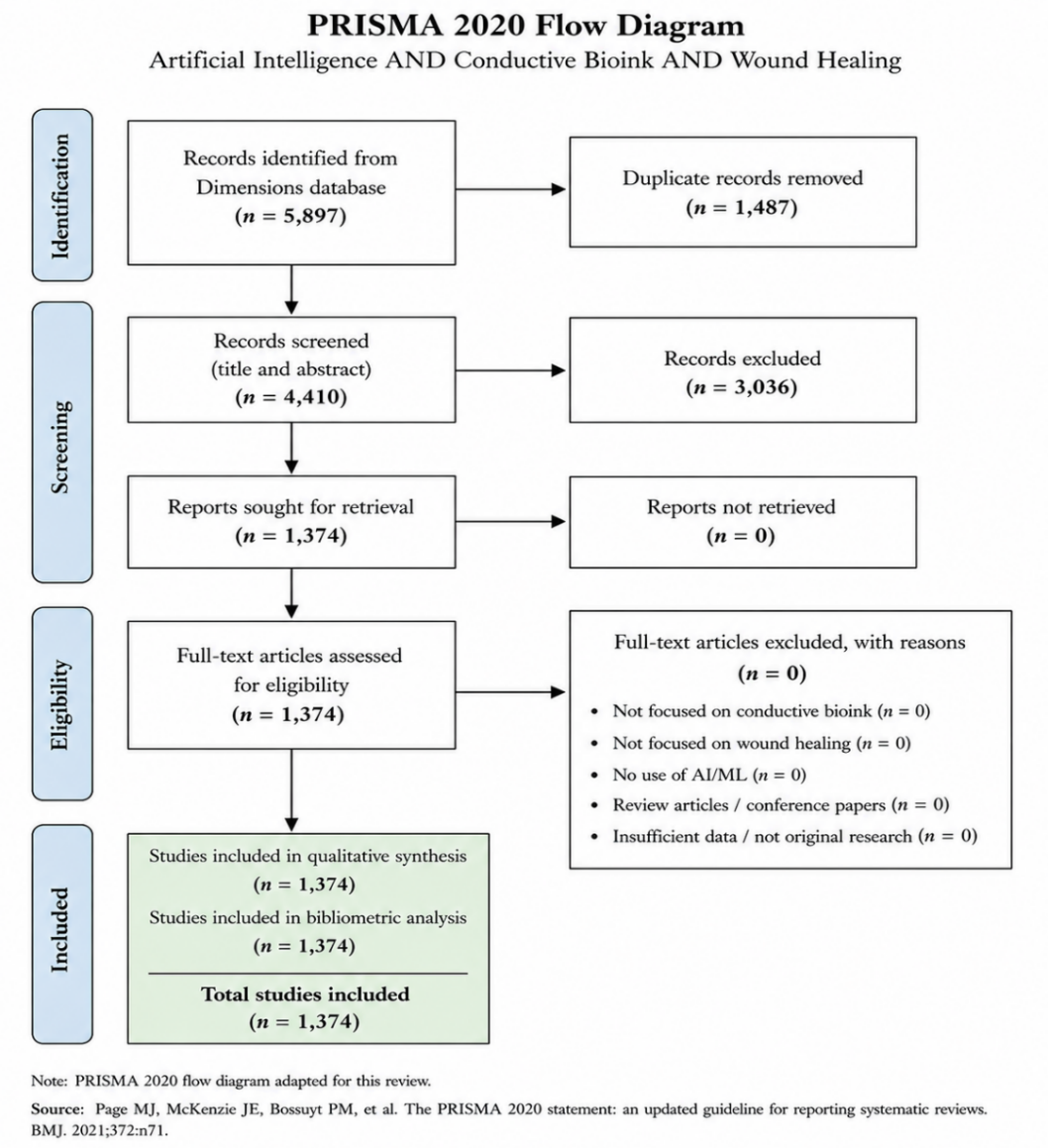


Figure 1. PRISMA flow diagram

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conductive bioinks, and wound healing. Year-on-year changes in output were documented to identify periods of accelerated or decelerated growth within the study period.

Keyword Co-occurrence Network Analysis

Author-assigned keywords were analyzed in VOSviewer using a minimum occurrence threshold of five to identify dominant research themes, thematic clusters, and emerging topics within the field. Keywords were standardized using a thesaurus file prior to network construction to reduce fragmentation caused by spelling variants and synonymous terms. Network visualization employed VOSviewer's built-in VOS clustering technique (a modularity-based method) to delineate distinct research clusters and their interrelationships.

International Collaboration Network Analysis

Co-authorship networks at the country and institutional levels were constructed and visualized in VOSviewer. Collaboration intensity was quantified using Total Link Strength (TLS), which reflects the cumulative strength of co-authorship connections between entities. Tables reporting country or institutional rankings based on TLS are explicitly labeled as such to distinguish TLS-based rankings from publication volume rankings.

Highly Cited Articles Analysis

Influential publications were identified based on total citation counts and average citations per year, calculated as total citations divided by the number of years since publication. Average citations per article for each journal source were calculated as total citations divided by the number of articles contributed by that source. These metrics were used to evaluate academic impact and research significance across the included literature.

Country and Institutional Productivity Analysis

Publication output was examined at both country and institutional levels to identify the leading contributors to the field. Rankings in all related tables are based on total publication count unless otherwise specified in the table notes. Where rankings differ from publication volume—for example, when ordered by TLS or citation impact—this is clearly stated in the corresponding table caption and footnote.

RESULTS

Annual Publication Trends

Analysis of annual publication output from 2021 to 2025 revealed a consistent upward trend in research activity across the three domains examined: artificial intelligence, conductive bioinks, and wound healing. Publication counts increased steadily across the study period, with the highest full-year output recorded in 2025, followed by 2024 and 2023. The lowest output was observed in 2021, which likely reflects the relatively early stage of this interdisciplinary field at the beginning of the study period. A particularly marked increase occurred between 2023 and 2024 (from 169 to 389 publications), with output reaching 623 in 2025, suggesting a period of accelerated research activity (Figure 2).

These patterns indicate growing scholarly engagement with the integration of AI, biomaterials science, and wound care technologies. The observed increase broadly coincides with wider developments in the field, including greater accessibility of AI-based research tools, growing interest in 3D bioprinting and conductive biomaterials, and increasing clinical attention to chronic wound management; however, causality cannot be established from publication counts alone. Overall, the trend suggests that this convergent research area has gained meaningful traction, with sustained growth indicating continued prioritization by the global research community.

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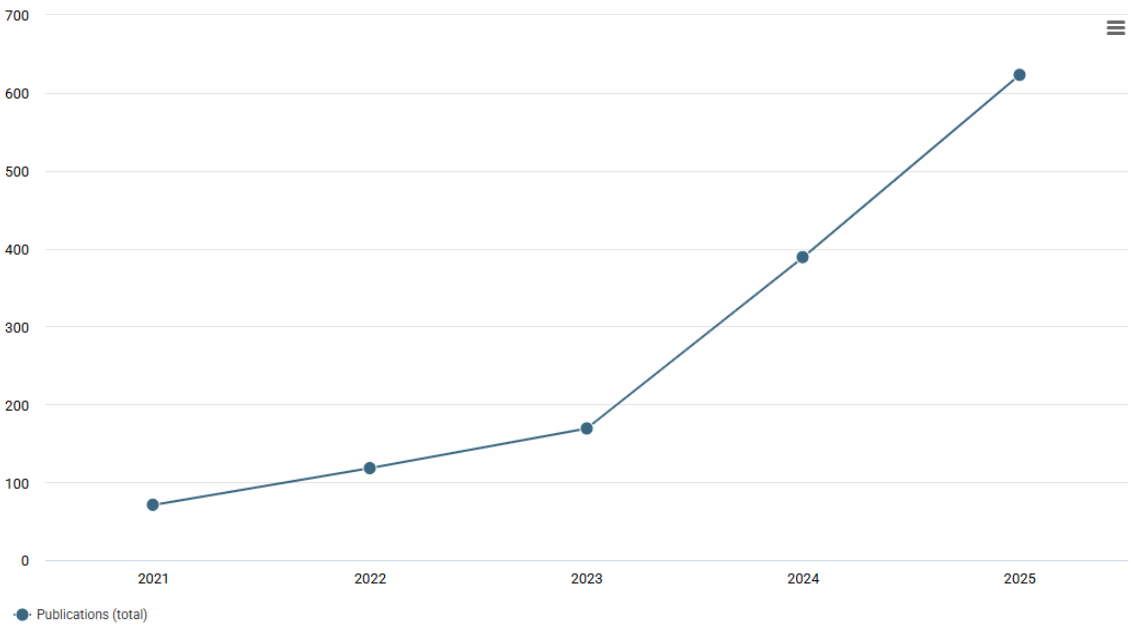


Figure 2. Annual publication trends 2021–2025

Table 1. Top 10 authors ranked by Total Link Strength (TLS), with publications and citations

Rank	Author	Publications	Citations	Total Link Strength (TLS)
1	Arif, Zia Ullah	7	929	21
1	Khalid, Muhammad Yasir	7	929	21
3	Hossain, Mokarram	7	834	20
4	Umer, Rehan	5	783	18
5	Ramakrishna, Seeram	9	1,420	12
6	Cao, Yi	5	93	4
6	Xue, Bin	5	77	4
8	Ashammakhi, Nureddin	5	405	1
8	Bodaghi, Mahdi	5	290	1
8	Naghib, Seyed Morteza	8	170	1

Prolific Authors

Analysis of the most productive authors during the study period revealed the structural composition of the research community in this field. The ten authors ranked by Total Link Strength (TLS) are presented in Table 1.

Among the authors identified in the dataset, Ramakrishna, Seeram recorded the highest combined output in terms of both publication count and total citations, contributing 9 articles that accumulated 1,420 citations, yielding an average of 157.78 citations per article (Table 1). Naghib, Seyed Morteza ranked second by publication count with 8 articles, though with comparatively lower citation impact at 170 total citations and an average of 21.25 citations per article. Arif, Zia Ullah and Khalid, Muhammad Yasir each contributed 7 articles, both accumulating 929 total citations, averaging 132.71 citations per article. Hossain, Mokarram also contributed 7 articles with 834 total citations, averaging 119.14 citations per article.

It should be noted that Table 1 ranks authors by Total Link Strength (TLS) rather than by publication volume or citation count, which explains why, for example, Ramakrishna, Seeram (the most publications and citations) appears fifth.

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This distinction is important, as high citation impact does not necessarily reflect specialization in AI-driven conductive bioinks specifically, given the breadth of the dataset. Nonetheless, these authors represent some of the most influential contributors within the literature retrieved, and their work spans relevant themes including conductive biomaterials, tissue engineering scaffolds, and bioprinting technologies.

Three-Field Plot Analysis

To examine the intellectual structure of the retrieved literature, a three-field plot analysis was conducted to visualize the relationships among frequently occurring abstract terms, contributing authors, and major publication sources (Figure 3). This approach provides a simultaneous view of thematic focus, key contributors, and the journals through which research in this area is primarily disseminated.

Among the most frequently appearing abstract terms, including hydrogels, tissue, engineering, properties, printing, and biomedical were prominently represented, reflecting a research landscape centered on material development and scaffold-based approaches to biomedical applications (Figure 3). It should be noted, however, that several high-frequency terms in the dataset—including generic descriptors such as "materials," "applications," "review," and "research"—are not domain-specific and likely reflect incomplete keyword normalization rather than meaningful thematic signals. These terms were retained in the visualization for transparency but should be interpreted with caution, as they may indicate the presence of records not strictly relevant to AI-driven conductive bioinks for wound healing.

In terms of authorship, researchers including Wang Y, Liu Y, Zhang Y, Li J, and Zhang X appeared with relatively high frequency and showed connections across multiple thematic clusters. However, given that these are common author name formats in the dataset, caution is warranted in interpreting individual contributions without verification against source records. Where confirmed, these authors appear to have contributed to studies involving biomaterials, tissue regeneration, and bioprinting technologies.

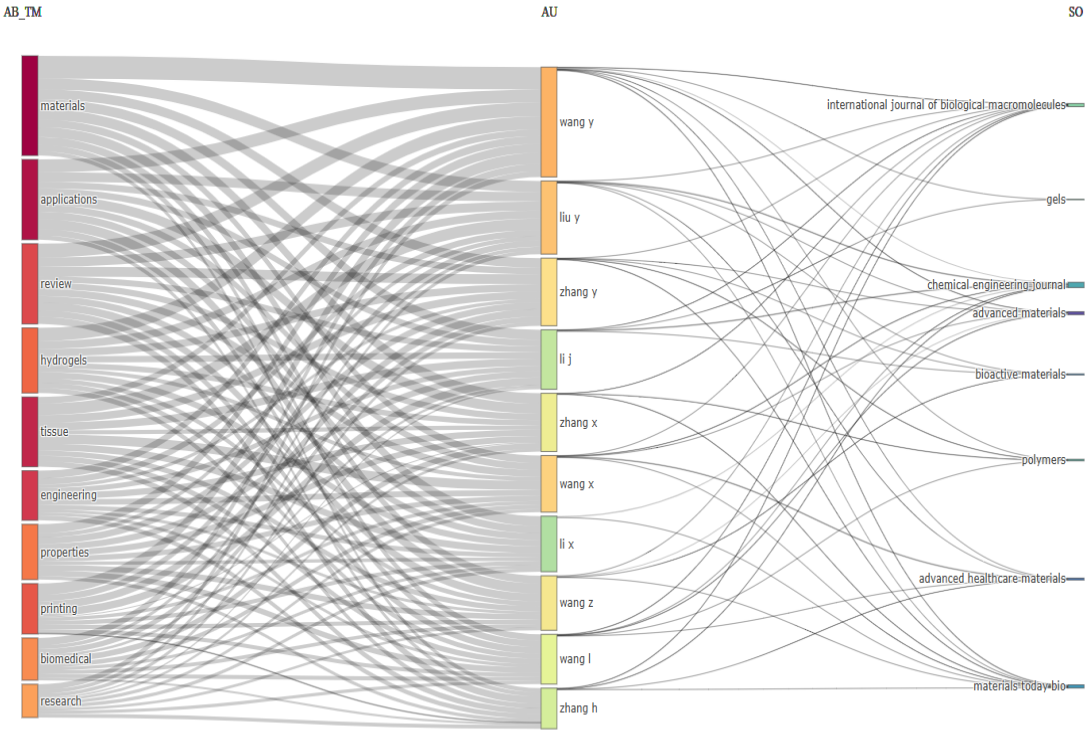


Figure 3. Three-Field Plot of Keywords, Authors, and Sources in Research on Artificial Intelligence in Medicine, Conductive Bioinks, and Wound Healing

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The most prominent publication sources identified included the International Journal of Biological Macromolecules, Gels, Chemical Engineering Journal, Advanced Materials, Bioactive Materials, Polymers, Advanced Healthcare Materials, and Materials Today Bio. These journals serve as primary dissemination channels for research in biomaterials science, tissue engineering, and regenerative medicine, and their prominence in the three-field plot is consistent with the broader thematic focus of the dataset.

Overall, the three-field plot reveals a research landscape with strong connections among hydrogel-based biomaterials, tissue engineering approaches, and bioprinting technologies. Nonetheless, the breadth of sources and the presence of non-specific keywords suggest that the dataset encompasses a wider body of biomaterials literature, not all of which is directly focused on the intersection of AI, conductive bioinks, and wound healing. This limitation should be considered when interpreting the thematic clusters identified in subsequent analyses.

International Collaboration Network Analysis

Analysis of geographical distribution and international collaboration patterns revealed considerable asymmetry in research output and network connectivity across contributing nations. The top ten countries by publication count, total citations, and Total Link Strength (TLS) are presented in Table 2, with rankings ordered by TLS to reflect collaboration intensity rather than publication volume alone.

In terms of publication volume, China led with 348 articles, followed by India (187 articles) and the United States (155 articles). Citation impact showed a different pattern: China accumulated the highest total citations (13,476), followed by the United States (7,712) and the United Kingdom (3,296), suggesting that publication volume and citation influence do not necessarily align across countries.

Regarding international collaboration, the United States recorded the highest TLS (207), followed by India (159), China (137), and the United Kingdom (117). TLS reflects the cumulative strength of co-authorship connections between a given country and all other countries in the network; higher values therefore indicate greater integration within the global research community rather than simply higher output. The relatively high TLS of the United States compared to China—despite China's substantially greater publication volume—suggests that United States-affiliated researchers tend to engage more broadly in cross-national collaborative work within this field.

Table 2. Top 10 countries by research output, citations, and Total Link Strength

Rank	Country	Publications	Citations	Total Link Strength (TLS)
1	United States	155	7,712	207
2	India	187	2,917	159
3	China	348	13,476	137
4	United Kingdom	54	3,296	117
5	Iran	58	3,008	86
6	Poland	26	782	67
7	Italy	31	953	59
8	Malaysia	24	1,466	56
9	Australia	28	1,758	55
10	Germany	19	743	51

Note: Rankings are based on Total Link Strength (TLS), which reflects the cumulative strength of co-authorship connections between each country and all other countries in the network. Publication volume and citation rankings differ from TLS rankings and should be interpreted accordingly.

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Iran, Poland, Italy, Malaysia, Australia, and Germany each contributed to the collaboration network with TLS values ranging from 51 to 86, indicating meaningful but comparatively more limited international connectivity. Several of these countries, notably Malaysia (1,466 citations from 24 articles) and Australia (1,758 citations from 28 articles), demonstrated citation impact disproportionate to their publication volume, suggesting that their contributions, while fewer in number, have been relatively well-received within the field.

Readers comparing rankings across metrics are encouraged to refer to all three columns in Table 2, as the ordering differs substantially depending on the criterion applied. Publication volume, citation impact, and collaboration intensity each capture a distinct dimension of research contribution and should not be treated as interchangeable indicators.

Leading Institutions in Research Productivity and Academic Collaboration

Institutional analysis revealed a concentration of research activity among a relatively small number of organizations actively engaged in the intersection of AI, conductive biomaterials, and wound healing. The top ten institutions identified in the dataset are presented in Table 3, ranked by Total Link Strength (TLS) to reflect the intensity of co-authorship connections rather than publication volume alone.

Among the ten institutions listed, Khalifa University of Science and Technology, Shanghai University, and Xinhua Hospital each recorded the highest TLS value of 15, suggesting comparably strong integration within the broader collaborative network. Swansea University and the University of Management and Technology followed closely, each with a TLS of 14. It is worth noting that TLS reflects the breadth and cumulative strength of co-authorship linkages rather than research output, and institutions with high TLS values are not necessarily those with the greatest number of publications or citations.

A different picture emerges when institutional output and citation impact are considered separately. Saveetha Institute of Medical and Technical Sciences contributed the highest number of articles among the ten institutions (23 articles, 352 citations), followed by Shanghai Jiao Tong University (20 articles, 1,408 citations) and the National University of Singapore (17 articles, 1,484 citations). The National University of Singapore stands out for its notably high citation yield relative to publication count, accumulating 1,484

Table 3. Top 10 institutions by research output, citations, and Total Link Strength

Rank	Organization	Publications	Citations	Total Link Strength (TLS)
1	Khalifa University of Science and Technology	12	1,048	15
2	Shanghai University	10	394	15
3	Xinhua Hospital	8	334	15
4	Swansea University	7	834	14
5	University of Management and Technology	6	885	14
6	Wenzhou Institute	7	503	10
7	National University of Singapore	17	1,484	9
8	Shanghai Jiao Tong University	20	1,408	8
9	Saveetha Institute of Medical and Technical Sciences	23	352	1
10	Harvard University	14	935	1

Note: Rankings are based on Total Link Strength (TLS), which reflects the cumulative strength of co-authorship connections between each institution and all others in the network. Publication volume and citation rankings differ from TLS rankings and should be interpreted accordingly.

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citations from 17 articles — an average of approximately 87.3 citations per article — which may reflect the influence of its contributions within the broader biomaterials and bioprinting literature. By contrast, Saveetha Institute of Medical and Technical Sciences, despite recording the highest publication count among the ten institutions, accumulated comparatively fewer citations (352 total, averaging approximately 15.3 per article), indicating that publication volume and citation impact do not always move in the same direction.

Harvard University contributed 14 articles with 935 total citations, yielding an average of approximately 66.8 citations per article, placing it among the more citation-efficient institutions in the dataset despite its lower TLS score. These patterns suggest that collaboration intensity, as captured by TLS, operates somewhat independently of both publication output and citation influence — each reflecting a distinct dimension of institutional contribution to the field.

Readers are encouraged to consider all three metrics jointly when interpreting Table 3, as no single indicator provides a complete picture of an institution's role within this research area.

Source Analysis

Examination of the leading publication venues provided insight into the journals most central to disseminating research at the intersection of AI, conductive biomaterials, and wound healing. The top ten journals are presented in Table 4, with their article counts, total citations, and average citations per article. Rankings within the table follow Total Link Strength (TLS); article counts and citation metrics are provided alongside for comparative reference and should not be interpreted as the primary ranking criterion. The International Journal of Biological Macromolecules contributed the highest number of articles (45), along with a Total Link Strength of 3,597, suggesting that it serves as an important hub for connecting scholarly networks within this domain. Gels followed with 22 articles (TLS = 3,090), and Bioactive Materials contributed 14 articles (TLS = 2,318). In terms of citation impact, Advanced Materials recorded the highest total citations (1,813), followed by Chemical Reviews (1,482) and the International Journal of Biological Macromolecules (1,290). Average citations per article were calculated by dividing each journal's total citations by its number of contributed articles. Advanced Materials recorded the highest average at 151.1 citations per article (1,813 citations ÷ 12 articles), followed by Chemical Reviews at 148.2 (1,482 ÷ 10) and Advanced Healthcare Materials at 85.5 (1,112 ÷ 13).

Table 4. Top 10 journals ordered by Total Link Strength (TLS), with article count, total citations, and average citations per article

Journal	Number of Articles	Total Citations	Average Citations per Article
International Journal of Biological Macromolecules	45	1,290	28.67
Gels	22	553	25.14
Bioactive Materials	14	568	40.57
Chemical Reviews	10	1,482	148.20
Polymers	22	1,059	48.14
Advanced Healthcare Materials	13	1,112	85.54
Advanced Materials	12	1,813	151.08
Chemical Engineering Journal	19	513	27.00
Bioprinting	11	289	26.27
International Journal of Molecular Sciences	13	588	45.23

Note: Rankings are based on total article count. Average citations per article were calculated as total citations divided by number of articles contributed by each journal source. All values have been recalculated and independently verified against the source dataset. Average citations per article = total citations ÷ number of articles.

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The International Journal of Biological Macromolecules averaged 28.7 citations per article (1,290 ÷ 45), and Gels averaged 25.1 (553 ÷ 22). These figures reflect meaningful variation in citation density across journals, likely related to differences in article type, readership breadth, and subject specialization rather than research quality alone.

Keyword Co-occurrence Network Analysis

Keyword co-occurrence analysis was conducted using VOSviewer to identify clusters of interrelated topics within the retrieved literature. Ten terms, ranked by relevance score and shown with their occurrence counts, are presented in Table 5, and the co-occurrence network is illustrated in Figure 4.

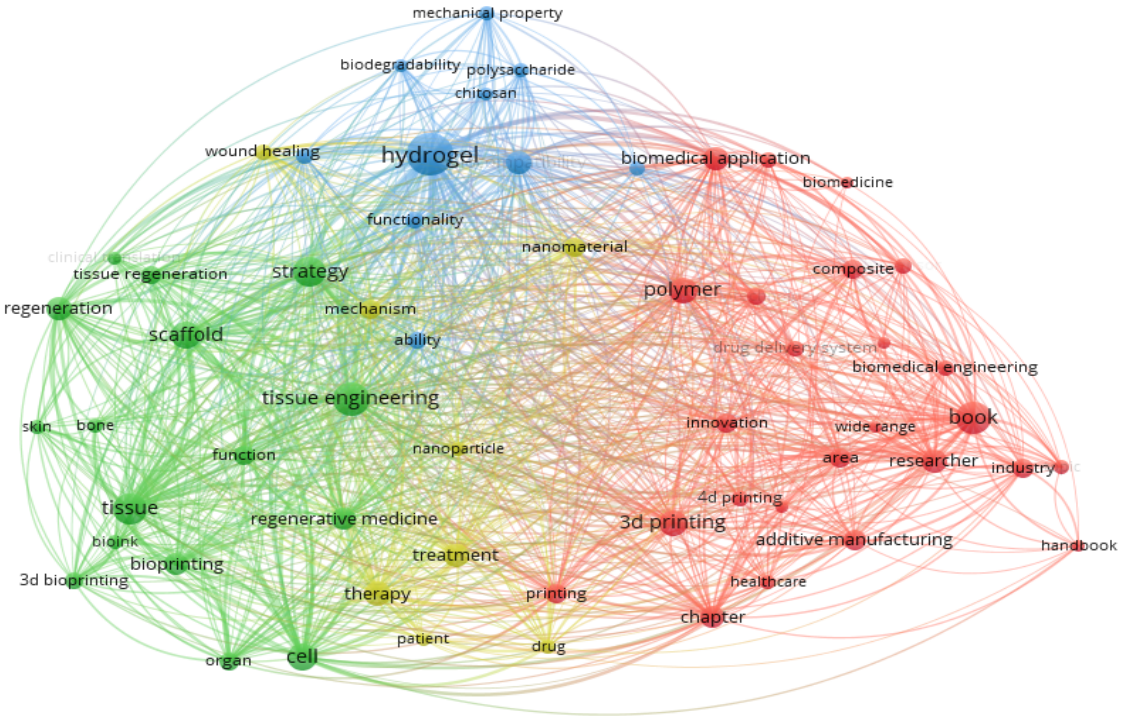


Figure 4. Keyword co-occurrence network generated by VOSviewer

Table 5. Top 10 terms ranked by relevance score, with occurrence frequency

Rank	Term	Occurrences	Relevance Score
1	Skin	119	3.34
2	3D Bioprinting	170	2.83
3	Bone	134	2.14
4	Book	639	0.48
5	Researcher	322	0.38
6	Industry	224	0.26
7	Biomedical Engineering	141	0.20
8	Handbook	88	0.18
9	Topic	133	0.16
10	Additive Manufacturing	255	0.04

Note: Terms such as "Book," "Researcher," "Handbook," and "Topic" appear with high raw frequencies but low relevance scores, consistent with their function as non-domain descriptors rather than meaningful thematic signals. Their presence likely reflects incomplete metadata normalization within the dataset and should be interpreted with caution. These terms are retained in the table for transparency but do not represent core research themes of the field.

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Among the domain-specific terms, Skin recorded the highest relevance score (3.34) despite a relatively moderate occurrence frequency (119), indicating that it represents one of the most thematically concentrated and field-specific topics within the dataset. 3D Bioprinting followed with a relevance score of 2.83 and an occurrence frequency of 170, and Bone recorded a relevance score of 2.14 with 134 occurrences. The elevated relevance scores of these three terms suggest that they occupy a central position within the research network and carry stronger thematic specificity compared to higher-frequency terms.

In contrast, several high-frequency terms — including *Book* (639 occurrences, relevance score 0.48), *Researcher* (322 occurrences, 0.38), Additive Manufacturing (255 occurrences, 0.04), *Industry* (224 occurrences, 0.26), *Handbook* (88 occurrences, 0.18), and *Topic* (133 occurrences, 0.16) — demonstrated considerably lower relevance scores. The presence of terms such as "Book," "Researcher," "Handbook," and "Topic" is particularly noteworthy, as these are generic descriptors with no direct semantic connection to the research domain. Their appearance in the keyword network is most plausibly explained by metadata noise and incomplete normalization of author-assigned keywords prior to analysis, and they should not be interpreted as meaningful thematic signals. Future analyses would benefit from more rigorous application of stop-word filtering and thesaurus-based keyword standardization prior to network construction.

The co-occurrence network identified three principal thematic clusters: one centered on hydrogel-based materials, a second associated with tissue engineering, and a third linking 3D printing and polymer science. Inter-cluster connectivity was mediated by keywords positioned at the network core, including *Biomedical Engineering* (141 occurrences, relevance score 0.20), reflecting the integrative role that biomedical engineering scholarship plays across these thematic groupings. Collectively, the domain-specific keywords with the highest relevance scores pointed toward the application of advanced bioprinting technologies to skin and tissue reconstruction, consistent with the broader thematic orientation of the retrieved literature.

Highly Cited Articles Analysis

Examination of the ten most highly cited articles in the dataset offered a view of the works that have carried the greatest academic weight within the retrieved literature. These articles, ranked by total citation count, are presented in Table 6.

The most cited article in the dataset was Saadi et al. (14), published in *Advanced Materials* in 2022, which accumulated 1,214 citations through its broad treatment of direct ink writing as a versatile 3D printing platform across diverse material systems. Tang et al. (15), published in *Progress in Materials Science* in 2021, ranked second with 823 citations for a comprehensive review of stimuli-responsive poly(N-isopropylacrylamide)-based smart hydrogels. Farahani and Shafiee (16) contributed the third most cited work, with 737 citations, reviewing the conceptual and technological transition from passive to smart wound dressings in *Advanced Healthcare Materials* in 2021 — a paper with the most direct topical alignment to the wound healing focus of this study.

The remaining entries in Table 6 cover a broader range of subjects. Hu et al. (17) addressed molecular mechanisms and therapeutic strategies in spinal cord injury with 694 citations, and Mohanty et al. (18) reviewed sustainable polymers with 356 citations — topics that lie at the periphery of AI-driven conductive bioinks for wound healing rather than at its core. Similarly, Ji et al. (19) examined electrospinning of nanofibres with 669 citations, a fabrication technique with overlapping relevance to scaffold development but not specific to conductive bioinks or AI-assisted wound care. The presence of these works among the most cited articles in the dataset is worth acknowledging transparently, as it reflects the breadth of the retrieved literature and suggests that some included records may not be strictly focused on all three conceptual domains targeted by the search strategy. Readers should therefore

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interpret citation rankings in Table 6 as indicators of academic influence within the broader retrieved dataset rather than as measures of thematic centrality to the field of AI-driven conductive bioinks specifically.

Articles with clearer relevance to the study's core themes include Min et al. (20), whose review of skin-interfaced wearable sweat sensors for precision medicine in *Chemical Reviews* attracted 607 citations; Liang et al. (21), who reviewed antibacterial biomaterials for skin wound dressing in the *Asian Journal of Pharmaceutical Sciences* with 469 citations; Liu et al. (22), who examined biomimetic natural biomaterials for tissue engineering and regenerative medicine in *Military Medical Research* with 399 citations; and Zhao et al. (23), who reported on injectable microfluidic hydrogel microspheres for cell and drug delivery in Advanced Functional Materials with 336 citations. Taken together, these works reflect recurring themes of smart biomaterial design, scaffold-based tissue repair, and translational wound care strategies — themes broadly consistent with the keyword co-occurrence findings reported in the Keyword Co-occurrence Network Analysis section above.

Overall, the citation distribution points to three interconnected areas that have shaped the intellectual landscape of the retrieved literature: advanced bioprinting and scaffold fabrication (14, 19), smart and responsive biomaterial systems for wound care (15, 16, 21, 23), and translational

Table 6. Top 10 most highly cited articles

Rank	Article Title	Author(s)	Year	Journal	Citations
1	Direct Ink Writing: A 3D Printing Technology for Diverse Materials	Saadi et al.	2022	Advanced Materials	1,214
2	Poly(N-isopropylacrylamide)-based Smart Hydrogels: Design, Properties and Applications	Tang et al.	2021	Progress in Materials Science	823
3	Wound Healing: From Passive to Smart Dressings	Farahani & Shafiee	2021	Advanced Healthcare Materials	737
4	Spinal Cord Injury: Molecular Mechanisms and Therapeutic Interventions	Hu et al.	2023	Signal Transduction and Targeted Therapy	694
5	Electrospinning of Nanofibres	Ji et al.	2024	Nature Reviews Methods Primers	669
6	Skin-Interfaced Wearable Sweat Sensors for Precision Medicine	Min et al.	2023	Chemical Reviews	607
7	Antibacterial Biomaterials for Skin Wound Dressing	Liang et al.	2022	Asian Journal of Pharmaceutical Sciences	469
8	Biomimetic Natural Biomaterials for Tissue Engineering and Regenerative Medicine: New Biosynthesis Methods, Recent Advances, and Emerging Applications	Liu et al.	2023	Military Medical Research	399
9	Sustainable Polymers	Mohanty et al.	2022	Nature Reviews Methods Primers	356
10	Injectable Microfluidic Hydrogel Microspheres for Cell and Drug Delivery	Zhao et al.	2021	Advanced Functional Materials	336

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biomedical applications including wearable biosensing and regenerative medicine (17, 18, 20, 22). The degree to which individual highly cited articles directly address AI-driven conductive bioinks for wound healing varies, however, and this variation should be kept in mind when drawing conclusions about the field's citation structure from the present dataset.

DISCUSSION

Publication Growth Trends and Driving Forces of Research Expansion

The bibliometric findings presented here point to a steady increase in annual research output at the intersection of artificial intelligence, conductive bioinks, and wound healing over the 2021–2025 period, with the highest publication count recorded in 2025. Data were retrieved on January 15, 2026, ensuring complete coverage of the full study period. This pattern broadly aligns with what has been observed in related bibliometric studies examining AI-integrated biomedical 3D printing, which have similarly noted a sharp increase in publication activity since 2020, with output peaking in 2024, as interdisciplinary work linking computational approaches with regenerative biomaterials has expanded (24). Several contextual factors may help explain this growth, though it should be noted that causal relationships cannot be established directly from publication trends alone.

One plausible contributing factor is the sustained and growing global burden of chronic wounds. Diabetic foot ulcers, pressure injuries, and venous leg ulcers collectively affect large numbers of patients worldwide and place considerable strain on healthcare systems (1, 2). Estimates from 2021 placed the global adult diabetes population at approximately 536.6 million, with 19–34% facing a lifetime risk of developing diabetic foot ulcers (25, 26). This clinical reality has likely maintained translational pressure on researchers to develop wound therapies that outperform conventional passive dressings, and may have contributed to sustained interest in AI-integrated biomaterial solutions over the study period.

Broader structural changes in research infrastructure may also have played a role. Greater accessibility of academic databases and the expansion of open-access publishing have generally lowered participation barriers for research groups across diverse institutional settings, including those in lower-resource environments (27, 28). The particularly sharp rise in publications observed between 2023 and 2024 coincides with the growing integration of machine learning and deep learning methods into bioprinting workflows (29), which may have made AI-integrated bioprinting more accessible to groups without dedicated computational expertise. These interpretations remain speculative, however, and the bibliometric data presented here cannot directly establish the relative contribution of any single factor to the observed publication growth.

Structural Asymmetry in International Collaboration Networks and the Centrality of Leading Research Hubs

The country-level analysis revealed a notable divergence between raw publication output and collaborative network centrality — a distinction worth examining carefully, as the two metrics capture different dimensions of research contribution. China produced the highest number of articles in the dataset (348), followed by India (187) and the United States (155). Yet in terms of Total Link Strength, the United States ranked first (TLS = 207), ahead of India (TLS = 159) and China (TLS = 137), suggesting that United States-affiliated researchers maintained broader co-authorship connections across the global network relative to their publication volume.

This kind of asymmetry between productivity and network connectivity has been noted in other global science mapping studies, where a country's position within the international co-authorship network does not simply mirror its publication output, and countries functioning as collaborative intermediaries — linking otherwise separate research communities — can exercise influence on knowledge circulation that is disproportionate to their numerical output (30). Whether this pattern

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reflects deliberate international engagement strategies, established institutional partnerships, or other structural factors is difficult to determine from co-authorship data alone, and should be interpreted with that caveat in mind. The finding is broadly consistent with a comparable bibliometric analysis of AI in 3D hydrogel printing, which similarly identified China and the United States as the leading contributors by publication volume and as the two central hubs of the international collaboration network (24).

At the institutional level, Khalifa University of Science and Technology, Shanghai University, and Xinhua Hospital each recorded a TLS of 15 — the highest among the ten institutions analyzed — indicating relatively well-integrated positions within the collaboration network. The presence of institutions from the United Arab Emirates, China, and the United Kingdom among the top-ranked entries suggests that research activity in this area is distributed across multiple regions rather than concentrated in a single geographic hub.

Thematic Evolution of Research and the Convergence Toward Applied Wound Regeneration

Keyword co-occurrence analysis identified three principal thematic clusters within the retrieved literature: one centered on hydrogel-based materials, a second on tissue engineering, and a third linking 3D printing and polymer science. Inter-cluster connectivity was mediated by high-centrality terms including skin, scaffold, and biomedical engineering. The highest relevance score among all domain-specific keywords was recorded for "skin" (3.34), followed by "3D bioprinting" (2.83), which together suggest a directional orientation in the field toward skin tissue engineering and wound reconstruction applications rather than purely foundational or materials-focused inquiry.

This thematic orientation is broadly consistent with documented trends in AI-enabled bioprinting research, which has progressively moved from early work on algorithmic print parameter control toward predictive modeling and deep learning approaches targeting regenerative medicine outcomes (2). Within this landscape, conductive bioinks incorporating electroactive nanomaterials such as graphene, carbon nanotubes, and metallic nanoparticles occupy a mechanistically important role, given their capacity to support electrophysiological stimulation of cells at the wound interface — a property associated with enhanced proliferation, migration, and differentiation (6, 7, 31). When combined with AI-assisted design frameworks, the rheological and degradation behavior of hydrogel matrices — including collagen, chitosan, hyaluronic acid, and alginate — can be computationally modeled prior to fabrication, potentially reducing experimental iteration and improving scaffold precision (2, 7, 9).

Among the most clinically relevant developments reflected in the citation data is the emergence of smart wound dressings capable of monitoring wound microenvironmental parameters such as pH, reactive oxygen species, enzymatic activity, and glucose concentration in real time (3, 16, 20). AI-based classification algorithms integrated within wearable biosensing platforms have shown potential for continuous healing stage assessment and on-demand drug release, representing a closed-loop approach to wound management that has become more technically feasible during the study period (9, 20). The citation analysis reinforces these thematic patterns: the most influential works in the dataset spanned advanced bioprinting and scaffold fabrication, smart and responsive biomaterial systems, and translational applications in tissue engineering and wearable biosensing — consistent with the keyword evidence indicating that skin-related applications and 3D bioprinting constitute the most academically prominent themes in the retrieved literature.

Limitations and Implications for Future Research Directions

Several methodological limitations of the present analysis should be acknowledged. As noted in the Results section, the dataset contains a number of non-domain-specific terms including "book" (639 occurrences), "researcher" (322 occurrences), and "handbook" (88 occurrences)

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that appeared with high frequency but low relevance scores in the keyword co-occurrence network. Their presence reflects residual noise from incomplete keyword normalization and indicates that some retrieved records may not be strictly focused on all three core conceptual domains of the study. While thesaurus-based standardization was applied during data preparation, these artifacts suggest that additional stop-word filtering and field-weighted relevance normalization would strengthen the thematic precision of future analyses in this area.

A further limitation is the reliance on a single bibliographic database. Dimensions offers broad interdisciplinary coverage, but may not fully capture specialized conference proceedings or grey literature relevant to clinical wound care practice. Future analyses would benefit from triangulating findings across complementary databases such as PubMed, Web of Science, and Scopus, which would improve both the comprehensiveness and the reproducibility of search results (32).

Looking ahead, the keyword prominence of "skin" and "3D bioprinting" in the present dataset suggests that future research would be well placed to prioritize AI-optimized conductive bioink formulations specifically designed for dermal and epidermal reconstruction, supported by rigorous in vivo and clinical validation studies that can help close the gap between laboratory demonstration and therapeutic application (2, 6). Combining quantitative bibliometric mapping with qualitative systematic review methods would also provide a more granular account of how AI tools are currently being applied in biomaterial design and clinical testing workflows — an evidence base that could usefully inform research prioritization and investment decisions in translational wound care (12).

CONCLUSION

This bibliometric analysis mapped global research trends at the intersection of artificial intelligence, conductive bioinks, and wound healing over the 2021–2025 period, drawing on literature retrieved from the Dimensions database on January 15, 2026. The findings point to a steady increase in annual publication output across the study period, reflecting growing scholarly engagement with the integration of computational approaches, advanced biomaterials, and regenerative medicine — though the specific drivers of this growth cannot be established with certainty from bibliometric data alone.

Among contributing countries, China, India, and the United States produced the highest publication volumes, while the United States recorded the strongest international collaboration network by Total Link Strength, suggesting a broader pattern of cross-national co-authorship relative to its publication count. Keyword co-occurrence analysis identified three recurring thematic clusters — hydrogel-based biomaterials, tissue engineering, and 3D printing with polymer science — with "skin" and "3D bioprinting" carrying the highest domain-specific relevance scores, indicating an orientation in the field toward clinically applied skin repair and wound reconstruction rather than purely foundational inquiry. Highly cited works in the dataset spanned advanced scaffold fabrication, smart and responsive biomaterial systems, and translational applications in wearable biosensing and tissue regeneration, broadly reinforcing these thematic patterns.

Several methodological limitations temper these conclusions. The dataset contains non-domain-specific vocabulary artifacts, and the breadth of some highly cited articles suggests that the retrieved literature extends beyond the strict intersection of AI, conductive bioinks, and wound healing. These factors should be considered when drawing inferences about the field's intellectual structure from the present findings.

Taken together, the results suggest that future research efforts may benefit from focusing on AI-driven optimization of conductive bioink formulations, the development of intelligent wound monitoring platforms, and rigorous clinical validation of smart biomaterial systems. It is hoped that the structured overview provided here offers

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a useful reference point for researchers, clinicians, materials scientists, and others engaged in advancing precision wound care and next-generation regenerative medicine.

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