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Research landscape of 3D printing in bone regeneration and bone repair: A bibliometric and visualized analysis from 2012 to 2022

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Abstract

Three-dimensional printing (3DP) is a popular manufacturing technique with versatile potential for materials processing in tissue engineering and regenerative medicine. In particular, the repair and regeneration of significant bone defects remain as substantial clinical challenges that require biomaterial implants to maintain mechanical strength and porosity, which may be realized using 3DP. The rapid progress in 3DP development in the past decade warrants a bibliometric analysis to gain insights into its applications in bone tissue engineering (BTE). Here, we performed a comparative study using bibliometric methods for 3DP in bone repair and regeneration. A total of 2,025 articles were included, and the results showed an increase in the number of publications and relative research interest on 3DP annually worldwide. China was the leader in international cooperation in this field and also the largest contributor to the number of citations. The majority of articles in this field were published in the journal *Biofabrication*. Chen Y was the author who made the highest contribution to the included studies. The keywords included in the publications were mainly related to BTE and regenerative medicine (including "3DP techniques," "3DP materials," "bone regeneration strategies," and "bone disease therapeutics") for bone regeneration and repair. This bibliometric and visualized analysis provides significant insights into the historical development of 3DP in BTE from 2012 to 2022, which will be beneficial for scientists to conduct further investigations into this dynamic field.

Keywords: Bibliometrics; 3D printing; Bone regeneration; Bone repair; Tissue engineering; Visualization research

1. Introduction

Bone is an anisotropic load-bearing tissue with the potential to undergo self-healing after injury under normal circumstances. However, in a critical-sized defect (CSD) that may be caused by trauma/accidents or the surgical removal of cancerous tissue, delayed healing may lead to permanent defects or a nonunion[1]. Currently, bone grafting techniques involving autografts, allografts, and xenografts are commonly used to treat bone CSDs[2]. However, these biological grafts have inherent limitations, such as limited donor tissue availability for autografts and disease transmission risks, mismatch, as well as immune response after implantation for allografts and xenografts[3]. An ideal bone graft should also possess both high mechanical strength and bioactivity to provide structural support to the defect area while actively inducing natural bone formation[4]. The drawbacks of existing grafting methods and the complex requirements for bone regeneration in CSDs have motivated researchers to develop strategies for bone tissue engineering (BTE), which are commonly considered to involve a combination of scaffolds, cells, and growth factors to promote bone regeneration[5]. BTE scaffolds are expected to mimic the extracellular matrix (ECM) of bone tissue while promoting oxygen diffusion, nutrient delivery, and waste removal. Additionally, the scaffold should be able to resist external forces to maintain structural support within the defect and gradually degrade over time to make space for new bone formation[6]. In order to facilitate bone ingrowth, BTE scaffolds should have a porosity greater than 90% and pore diameter between 300 and 500 μm. The success of bone regeneration outcomes is largely determined by the functional capabilities of BTE scaffolds, thus justifying the significant emphasis of research on scaffold design and fabrication[7].

BTE scaffolds can be fabricated using conventional manufacturing techniques, such as solvent casting, gas foaming, particulate leaching, freeze drying, and melt molding[8-10]. However, these techniques rely on manual operation and often give rise to inconsistencies in fabrication outcomes among studies due to difficulties in controlling the pore size, geometry, interconnectivity, and spatial distribution as well as the material distribution and mechanical properties of scaffolds[11]. Since their development and continual evolution over the last decade, 3DP techniques are considered the most promising techniques for BTE scaffold manufacturing. The main categories of 3DP techniques for BTE include fused filament fabrication (FFF), selective laser sintering (SLS), stereolithography (SLA) or digital light processing (DLP), and direct ink writing (DIW)[12-16]. In addition, recent developments in 3D bioprinting have allowed simultaneous incorporation of living cells together with growth factors into scaffolds in a spatially controlled manner, opening up new avenues for creating biomimetic tissue[17]. 3DP and 3D bioprinting also allow convenient fine-tuning of scaffold designs through computer control, enabling customization for individual patient needs[18].

3DP allows complex scaffold compositions and structures to be designed and fabricated through a layer-by-layer process[19]. Some recent advances show that the hierarchical porosity and biomimetic features of natural bone tissue can be replicated in BTE scaffolds using 3DP. For instance, a scaffold comprising hydroxyapatite and tricalcium phosphate (HA/TCP) has been fabricated through a slurry-based mask-image-projection-based stereolithography (MIP-SL) process to realize an intricate design of hierarchical pores[20]. By tailoring scaffold fabrication using 3DP, the effects of pore structure on the outcome of BTE can be thoroughly studied. For instance, a study has found that the mechanical properties or cell compatibility of polylactic acid (PLA) scaffolds were not affected by different pore sizes (50, 200, and 250 μm)[21]. Interestingly, another study has shown that 3DP PLA scaffolds with 300, 600, and 900 μm pores were found to have different effects on human articular cells, with 600 μm pore scaffolds showing the highest cell adherence and proliferation after 7 days[22]. Four-dimensional printing (4DP), which incorporates a temporal component into 3DP, has also recently gained attention. 4DP utilizes the same technologies and methods as 3DP, but its scaffolds can alter their form once in contact with environmental factors and enable broader functionalities.

In recent years, a range of 3DP techniques have been applied in clinical practice for treating bone defects or related conditions. Many reviews have predominantly focused on specific areas of 3DP for bone regeneration. For example, Wang *et al*. have reviewed the recent advances in 3DP for BTE and presented the philosophy and research of fabrication and design in this field[23]. Hassan *et al*. have analyzed the factors of bioresorbable/degradable templates and their influence on BTE as well as the comparison of achieved BTE for different types of templated materials[24]. Additionally, Bose *et al*. have reported recent advances in 3DP using natural medical compounds (NMCs) with powerful osteogenic potential and also highlighted the immense capacity of NMCs to integrate within BTE[25]. Interestingly, Wang *et al*. have focused on pharmaceutical electrospinning and 3DP for BTE, including the different types of materials, electrospun nanofibrous scaffolds, and the diverse designs of 3DP scaffolds[26]. Li *et al*. have summarized the progress of mineralized collagen scaffolds (MCSs) for BTE. In their review, they proposed different fabrication methods for MCSs, described the three aspects of physical, chemical, and biological cues, as well as discussed the opportunities and challenges associated with MCSs for BTE[27]. Bandyopadhyay *et al*. have illustrated the

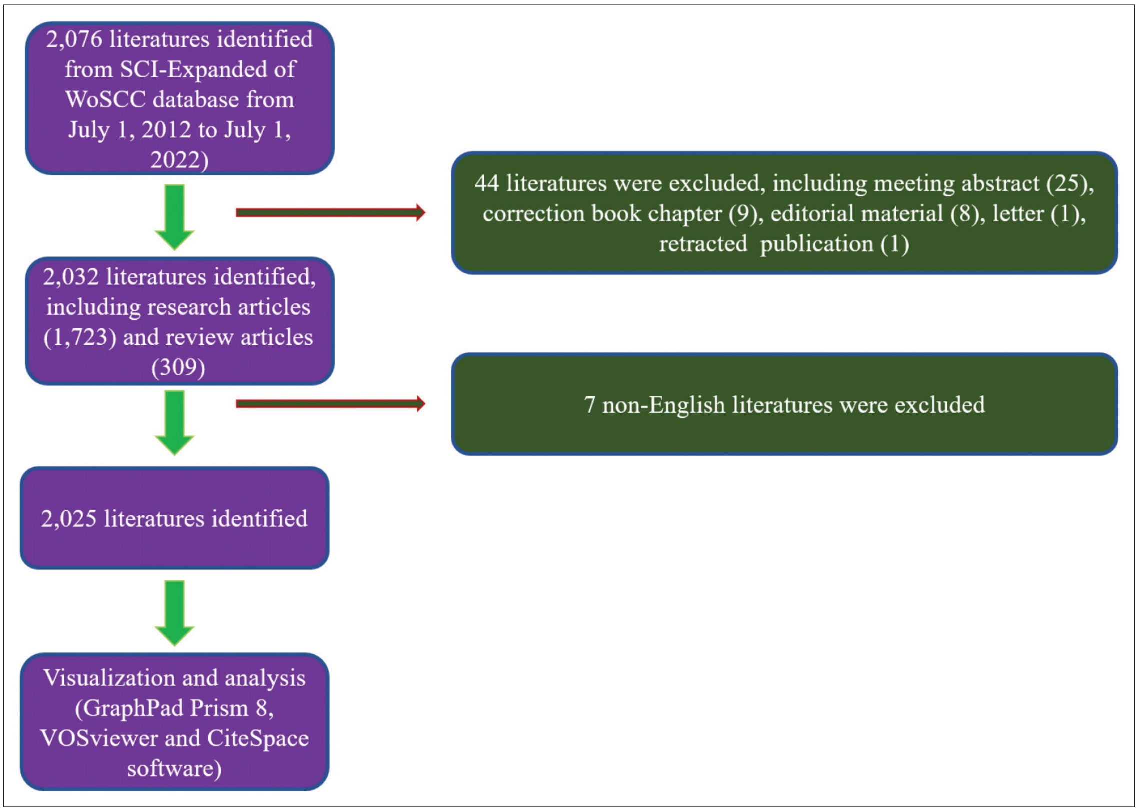


Figure 1. Flowchart showing the article selection process. Abbreviations: SCI, Science Citation Index; WoSCC, Web of Science Core Collection.

correlating materials and structural design aspects of 3DP with biological response after implantation[19].

Despite rapid and dynamic developments in the field of 3DP for BTE, a comprehensive and meaningful analysis of publication trends in this research area has not been performed. This demonstrates the need for a more in-depth understanding and summarization of the current frontiers in 3DP for bone repair and regeneration in preparation for more large-scale clinical implementation. Bibliometrics is a quantitative analysis using mathematical and statistical methods to analyze published research[28]. It provides objective scientific indicators for researchers to track quantitative changes and distributions of published literature. In this study, we comprehensively analyze the quantity and quality of 3DP studies in BTE research, presenting a summary of the current status of this research area and a prediction of the most relevant keywords, which will assist researchers in identifying the imminent trends and frontiers in this rapidly evolving field.

2. Materials and methods

2.1. Data acquisition and search strategies

Papers relating to research on 3DP in bone regeneration and repair were collated from the Science Citation Index (SCI) Expanded database of Clarivate Analytics' Web of Science Core Collection (WoSCC). The included studies were then analyzed using bibliometric techniques and visual analytics tools in accordance with previous studies[29,30]. The search date was set between July 1, 2012 and July 1, 2022, and the following search formula was used: TS = (3D bioprinting OR 3D printing OR 3D printed OR 3D print OR three dimensional bioprinting OR three dimensional printing OR three dimensional printed OR three dimensional print) AND TS = (bone regeneration OR bone repair). The inclusion criteria were as follows: (1) publications that focused on the theme of 3DP in bone regeneration and repair; (2) original research or review articles; and (3) studies that were written in English. The exclusion criteria were as follows: (1) publications that were not related to using 3DP in bone regeneration and repair; (2) meeting abstracts, proceedings papers, book chapters, editorials, letters, news, *etc*. (Figure 1). All publications were analyzed by two reviewers (Z.Y. and H.L.), and any potentially irrelevant studies were identified and manually filtered and discussed with the experienced corresponding authors to determine whether they should be included or excluded from the analysis. In 2011, Fedorovich *et al*. have reported the progress of organ printing in bone regeneration[31]. Additionally, only

33 publications, including 31 research articles and 2 review articles, were searched before July 1, 2012. In order to report the recent research progress in a timely manner and accurately predict the trend of publication in the field of 3DP for bone regeneration and repair, the beginning year was set as 2012.

The publication information of the selected studies, including the journal name, title, authors, keywords, institutions, country/region, publication date, total and average number of citations, as well as the H-index, were downloaded and imported into Excel 2021 for analysis by the authors (Z.Y. and H.L.). The database expiration date was set to August 9, 2022. A bibliometric and visualized analysis was performed using the following software: GraphPad Prism 8, Origin 2021, VOSviewer 1.6.14 (Leiden University, Leiden, the Netherlands)[32], and CiteSpace 6.1.2[33]. The sum and annual number of publications in the top 10 countries as well as the model fitting curves were calculated using Origin 2021. VOSviewer was used to analyze journals that were co-cited in more than 20 citations and the distribution of keywords with a minimum number of occurrences of 20 as well as for citation analysis of documents with more than 25 citations.

2.2. Bibliometric analysis and visualization

The annual trend of publications and relative research interest (RRI), defined by the number of publications in a certain field divided by that in all fields per year, was depicted using the curve-fitting function of GraphPad Prism 8. A world map was constructed in accordance with previous studies[34]. The total publications in the top 10 countries between 2012 and 2022 as well as the global trend prediction were analyzed using Origin 2021. The impact factor (IF) of journals was obtained from Journal Citation Reports 2021.

Country/region and institution collaboration analysis, dual-map overlay of journals, author collaboration and co-cited authors analysis, cluster detection of co-cited references and keywords, as well as analysis of references and keywords with intense citation bursts were all conducted using CiteSpace 6.1.2. In accordance with a previous study, the parameters of CiteSpace used for analysis were as follows: link retaining factor (LRF = 3), look back years (LBY = 5), e for top N (e = 1), time span (2012–2022), years per slice (1), links (strength: cosine; scope: within slices), selection criteria (g-index: k = 25), and minimum duration (MD = 2 for keywords; MD = 5 for references)[30].

The construction and visualization of bibliometric networks were performed using VOSviewer. Comprehensive information on (1) co-citation analysis of journals and references as well as (2) co-occurrence analysis of keywords was captured in VOSviewer figures. In these figures, each node represents an item (such as co-cited reference or keyword), with the node size representing the number of publications and color representing different years. The line thickness between nodes indicates the strength of the collaboration or co-citation relationship.

3. Results

3.1. Global contribution to the field

Based on the search strategy (Figure 1), a total of 2,025 publications met the inclusion criteria and were used for analysis. The RRI in 3DP for bone regeneration and repair increased approximately linearly between 2012 and 2022, which is also reflected by the number of annual publications increasing from 1 to over 500 in the given timeframe (Figure 2A). In total, 72 countries/regions contributed publications to this research area. China contributed the most papers (817, 40.346%), followed by the United States of America (USA; 408, 20.148%), South Korea (197, 9.728%), Germany (118, 5.827%), and England (117, 5.778%) (Figure 2B–C, Table 1). Furthermore, China exhibited the highest increase in publication number since 2012, with the volume of publications equivalent to the total number of publications from the remaining 9 countries/regions (Figure 2D). A generalized additive model showing the predicted number of publications by year was also constructed (Figure 2E). According to this time curve, the annual growth trend was in line with the fitting curve $y = 59.867x - 120557.289$ ($R^2 = 0.917$), verifying a linearly increasing rate of annual publications in this area.

3.2. Distribution of countries/regions and institutions contributing to the field

All publications that were included in this study originated from 72 countries and 1,967 institutions. The top 10 contributing countries/regions were distributed in Asia, North America, and Western Europe (Table 1). Among these, China and the USA accounted for over 60% of total publications, far exceeding any other country/region. As shown in Table 1, China had the highest number of total citations at 19,817 and an H-index of 70, while the USA had the second highest number of total citations and the highest average citation of 37.16. Although Italy and the Netherlands contributed to less than 8% of the total number of publications, their average citation per publication ranked second and third, respectively. The mapping of collaborations among countries/regions contributing to the field is shown by the connections among nodes, where the node size represents the total number of publications (Figure 3A). It is interesting to note that although China had the highest number of publications in the field, the

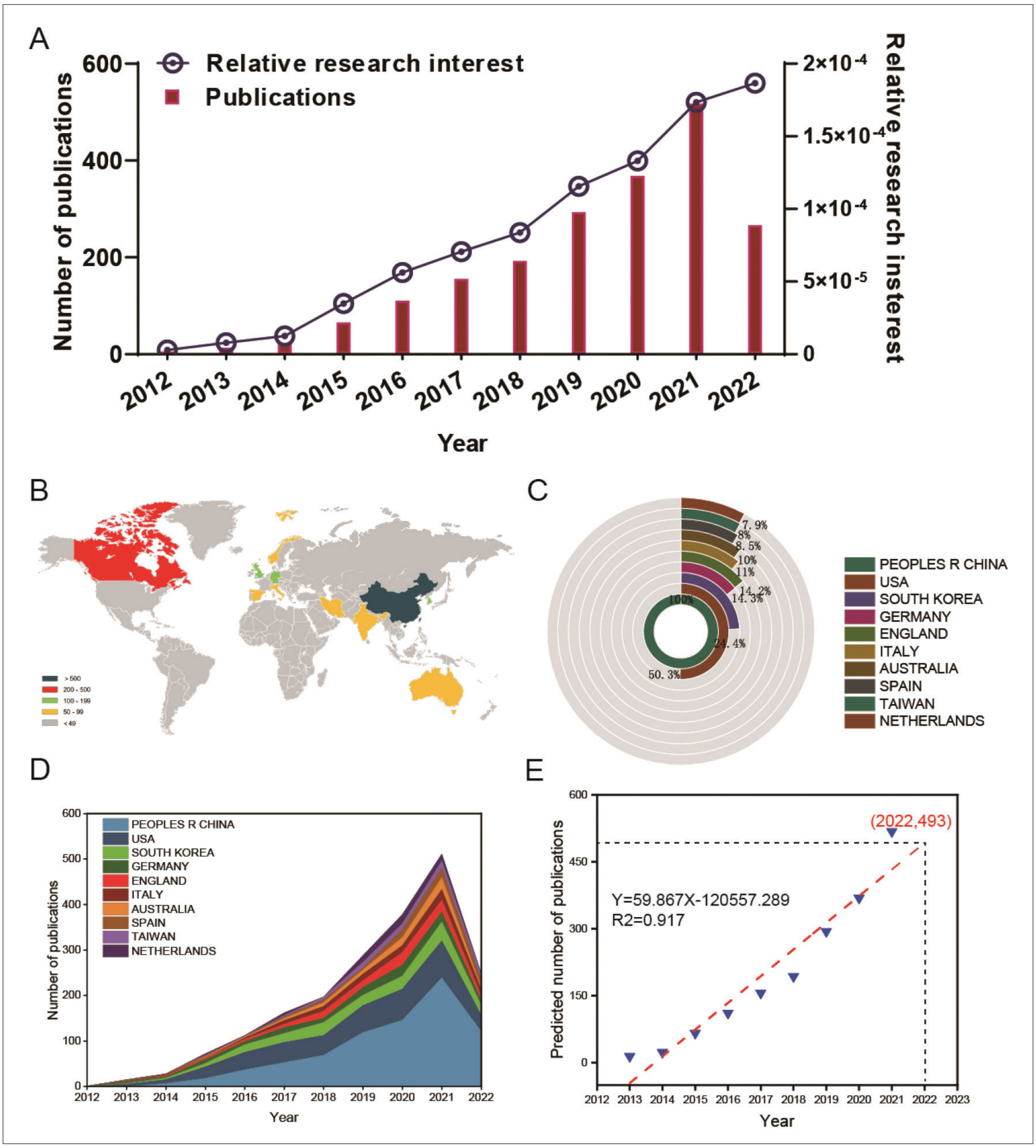


Figure 2. Global trends and countries/regions contributing to the research field of three-dimensional printing in bone regeneration and bone repair. (A) Annual number of publications in the field. (B) A world map showing the distribution of publications. (C) Sum of related publications in the top 10 countries/regions. (D) Annual number of publications in the top 10 most productive countries from 2012 to 2022. (E) Model fitting curves of global trends in publications.

strength of collaborations with other countries/regions was not as extensive as other contributors.

Table 2 demonstrates that the top 10 most productive institutions in the field were all from China, including Shanghai Jiao Tong University, the Chinese Academy of Sciences, Sichuan University, the Shanghai Institute of Ceramics Chinese Academy of Sciences (CAS), and Zhejiang University. The top contributors were Shanghai Jiao Tong University with 135 papers and 4,802 citations, followed by the Chinese Academy of Sciences with 117 papers and 5,030 citations and Sichuan University with 72 papers and 1,613 citations. Among the top 10 most productive institutions, the Shanghai Institute of Ceramics CAS had the highest number of average citations (51.94), followed by the Chinese Academy of Sciences (42.99) and the University of Chinese Academy of Sciences CAS

Table 1. Top 10 most productive countries/regions that contributed publications on three-dimensional printing in bone regeneration and bone repair

Rank	Country/region	Article count	Percentage (%, N/2,025)	Citation	Average citation	H-index
1	China	817	40.346	19,817	24.26	70
2	USA	408	20.148	15,162	37.16	61
3	South Korea	197	9.728	4,893	24.84	39
4	Germany	118	5.827	3,171	26.87	30
5	England	117	5.778	3,906	33.38	32
6	Italy	90	4.444	3,244	36.04	28
7	Australia	84	4.148	2,364	28.14	24
8	Spain	70	3.457	1,309	18.70	16
9	Taiwan	65	3.21	926	14.25	20
10	Netherlands	64	3.16	2,313	36.14	25

(39.07). Additionally, an institutional cooperation analysis showed that Shanghai Jiao Tong University, the Chinese Academy of Sciences, and Sichuan University were the top 3 three institutions involved in collaborations with other institutions (**Figure 3B**).

3.3. Analysis of journals and research areas

From 2012 to 2022, a total of 2,025 articles were published in 422 journals. Table 3 shows the top 10 journals with the highest number of publications in the research area together with their latest IF (SCImago Journal Rank [SJR], Clarivate Analytics). *Biofabrication* produced the most publications (71 publications, 3.506% of all articles), followed by *Materials* (67, 3.309%), *Acta Biomaterialia* (65, 3.21%), *Advanced Healthcare Materials* (45, 2.222%), and *Frontiers in Bioengineering and Biotechnology* (45, 2.222%). Among the top 10 journals, *Biomaterials* had the highest IF (15.304), followed by *Advanced Healthcare Materials* (11.092) and *Biofabrication* (11.061). A total of 681 journals were co-cited more than 20 times by the included publications, among which the top 5 journals with the highest total link strength were *Biomaterials* (863,355), *Acta Biomaterialia* (510,660), *Biofabrication* (286,502), *Materials Science Engineering C: Materials for Biological Applications* (273,876), and *Journal of Biomedical Materials Research Part A* (218,226) (Figure 4A).

Table 4 shows the top 10 co-cited journals with published articles in this research area, including *Biomaterials* (108,90 citations), *Acta Biomaterialia* (5,933), *Materials Science and Engineering C: Materials Science and Engineering C* (3,139), *Biofabrication* (2,762), and *Journal of Biomedical Materials Research Part A* (2,450). There were also 4 highly co-cited journals, including *ACS Applied Materials & Interfaces*, *Tissue Engineering Part A*, *Advanced Materials*, and *Scientific Reports*, all of which were not from the top 10 most productive journals.

The included publications were also divided into 57 research areas. Materials Science (1,171 records, 57.827% of all articles), Engineering (679, 33.531%), and Chemistry (322, 15.901%) (Table 5) were among the top 10 well-represented research areas. A dual-map overlay of journals was used to depict the citation relationship between cited and citing journals (Figure 4B), as seen in a previous study[30]. The cited journals are on the right, while the citing journals are on the left, and they are linked by spline waves from left to right, with the citation relationship characterized by colored paths; the primary citation paths are marked by two pink lines and one orange line. One of the pink paths indicates that papers published in the area of physics/materials/chemistry were primarily cited by papers in chemistry/materials/physics, while the other pink path indicates that papers published in the area of physics/materials/chemistry were mainly cited by papers in medical/biology/genetics. The orange path shows that papers published in the area of molecular/biology/immunology were cited by papers in chemistry/materials/physics. The different citing trajectories of cited and citing journals are better depicted in enlarged figures (Figure 4B).

3.4. Analysis of authors and funding sources

Table 6 shows the contribution of the top 10 authors in the field by their number of publications and citations. Seven of these top 10 authors were from China, of whom Chen Y and Wu CT both had the highest number of publications (39 publications), followed by Zhu YF (30 publications) and Chang J (27 publications) (Figure 5A). Other highly contributing authors were from the USA and South Korea, where Lee SJ had 26 publications, and both Lee J and Park SA each had 24 publications. Among the top 10 most productive authors, Wu CT had the highest number of total citations (2,017 citations), followed by Chang J (1,895 citations) and Zhu YF (1,613 citations).

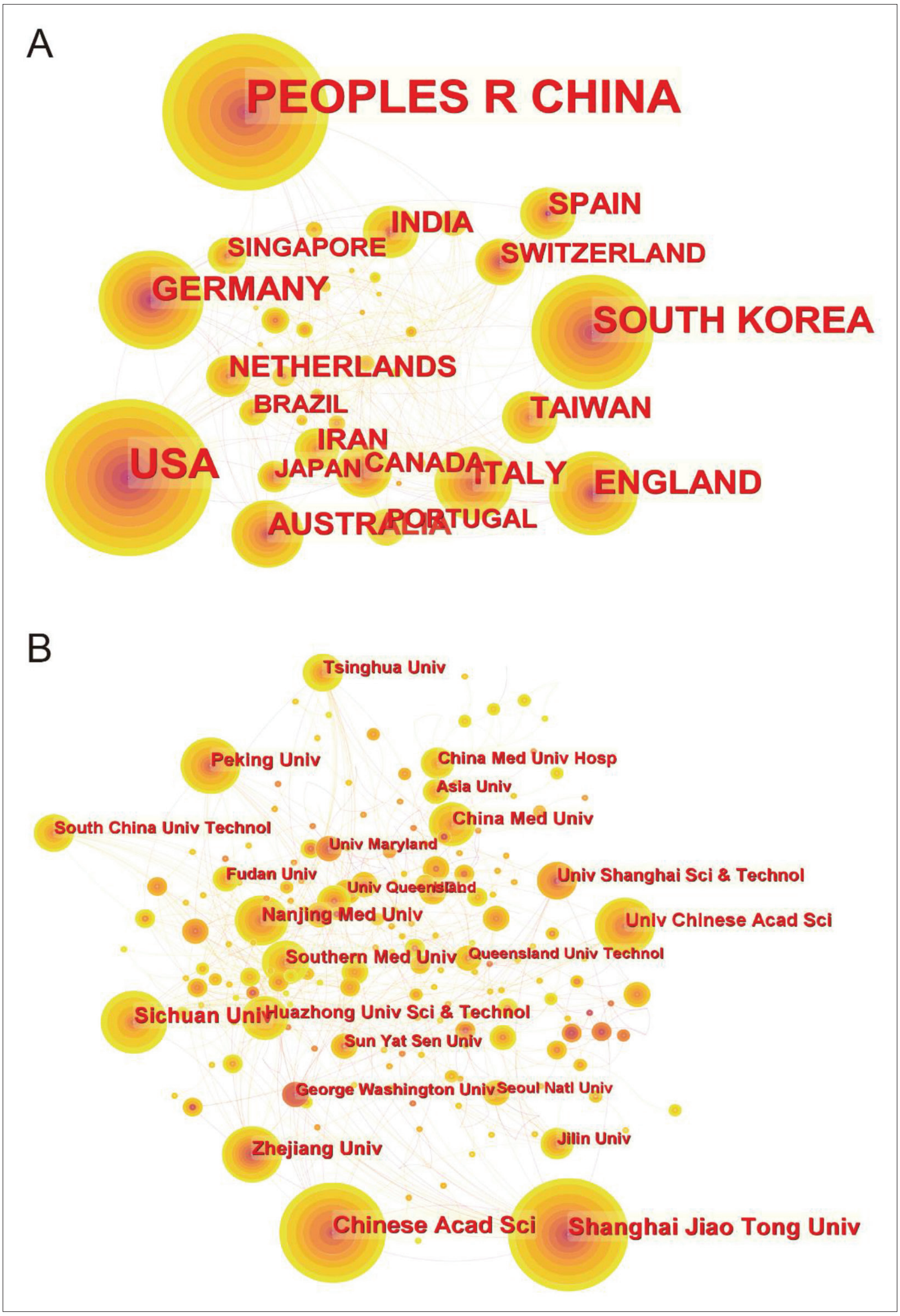


Figure 3. Mapping of countries/regions and institutions that contributed publications on 3D printing in bone regeneration and bone repair. (A) Country/region collaboration analysis. (B) Institutional collaboration analysis. The nodes represent countries/regions or institutions, connected by lines indicating collaboration. The number of publications is represented by the size of the nodes. The lines between the nodes represent the cooperation relationship, while the thickness of the connecting lines represents the strength of their cooperation. From 2012 to 2022, the color changes from purple to yellow.

Table 2. Top 10 institutions that contributed publications on three-dimensional printing in bone regeneration and bone repair

Rank	Institution	Country	Article count	Percentage (%, N/2,025)	Total citation	Average citation
1	Shanghai Jiao Tong University	China	135	6.667	4,802	35.57
2	Chinese Academy of Sciences	China	117	5.778	5,030	42.99
3	Sichuan University	China	72	3.556	1,613	22.40
4	Shanghai Institute of Ceramics CAS	China	51	2.519	2,649	51.94
5	Zhejiang University	China	47	2.321	1,226	26.09
6	Peking University	China	45	2.222	1,175	26.11
7	University of Chinese Academy of Sciences (CAS)	China	43	2.123	1,680	39.07
8	Nanjing Medical University	China	41	2.025	1,013	24.71
9	Southern Medical University China	China	41	2.025	708	17.27
10	Huazhong University of Science Technology	China	36	1.778	913	25.36

Table 3. Top 10 productive journals that contributed publications on three-dimensional printing in bone regeneration and bone repair

Rank	Journal	Article count	Percentage (%, N/2025)	Citation per article	IF
1	*Biofabrication*	71	3.506	41.87	11.061
2	*Materials*	67	3.309	19.12	3.748
3	*Acta Biomaterialia*	65	3.21	64.15	10.633
4	*Advanced Healthcare Materials*	45	2.222	47.76	11.092
5	*Frontiers in Bioengineering and Biotechnology*	45	2.222	8.96	6.064
6	*Polymers*	45	2.222	12.27	4.967
7	*ACS Biomaterials Science Engineering*	39	1.926	22.69	5.395
8	*Biomaterials*	38	1.877	71.84	15.304
7	*International Journal of Molecular Sciences*	37	1.827	11.81	6.208
10	*Materials Science Engineering C: Materials for Biological Applications*	37	1.827	39.76	8.457

Abbreviation: IF, impact factor.

An author cooperation analysis was performed and illustrated through a co-cited author network visualization diagram (Figure 5A and B). The node size represents the number of co-citations, while the colors indicate the different years of publication. The most prominent co-cited authors were Bose S (126 citations), Lee J (121 citations), Karageorgiou V (102 citations), Wang X (97 citations), and Hutmacher D (94 citations). It is interesting to note that these most highly co-cited authors had little overlap with the top 10 contributing authors in publications and citations and were also mostly not based in China. Additionally, a temporal author co-citation analysis was presented in a timeline view (Figure 5C). Earlier research hotspots in the field of 3DP for BTE included "bacterial cellular" (cluster 7), "animal study" (cluster 2), "mesoporous bioactive materials" (cluster 3), "melt electrowriting" (cluster 9), "fused deposition" (cluster 11), "macrophage polarization" (cluster 5), and "tumor therapy" (cluster 8). More recent mid-term research hotspots included "osteogenic peptide" (cluster 0), "bioactive glass" (cluster 1), and "selective laser" (cluster 6). The current research hotspots included "osteogenic peptide" (cluster 0), "bioactive glass" (cluster 1), "animal study" (cluster 2), "mesoporous bioactive materials" (cluster 3), "3dgp" (cluster 4), "tumor therapy" (cluster 8), "bacterial cellular" (cluster 7), and "selective laser" (cluster 6), where some terms overlapped with those found in earlier research hotspots, thus indicating persistent research interest over the last decade.

An analysis of the funding sources for publications in this field was also performed, and the top 10 are shown in Table 7. In total, 527 publications (26.025%) were funded

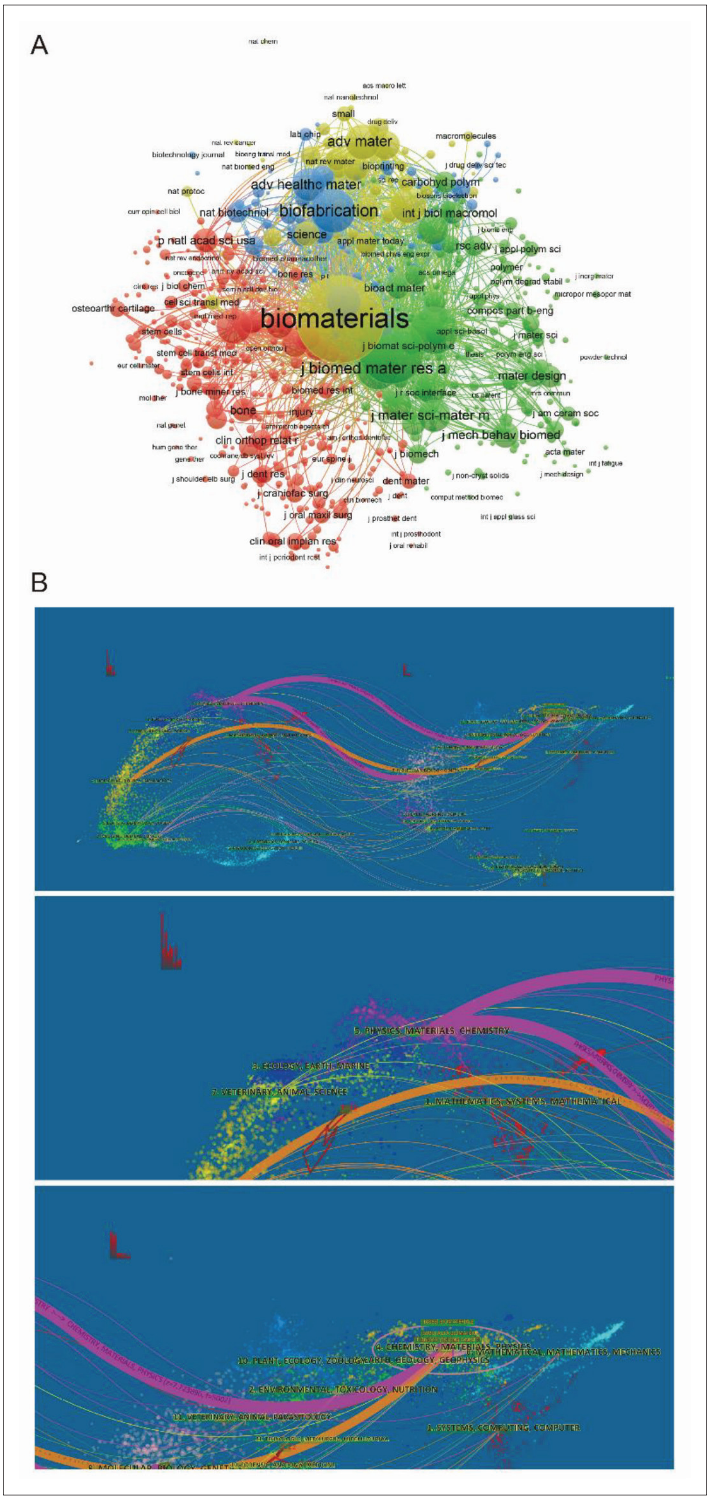


Figure 4. Articles published in different journals on three-dimensional (3D) printing in bone regeneration and bone repair. (A) Network map of journals that were co-cited in more than 20 citations. (B) A dual-map overlay of journals depicting citation relationships between cited and citing journals for publications on 3D printing in bone regeneration and bone repair.

Table 4. Top 10 co-cited journals on three-dimensional printing in bone regeneration and bone repair

Rank	Cited journal	Citations	IF
1	*Biomaterials*	10,890	15.304
2	*Acta Biomaterialia*	5,933	10.633
3	*Materials Science and Engineering* C	3,139	8.457
4	*Biofabrication*	2,762	11.061
5	*Journal of Biomedical Materials Research Part A*	2,450	4.854
6	*ACS Applied Materials & Interfaces*	1,814	10.383
7	*Tissue Engineering Part* A	1,760	4.080
8	*Advanced Materials*	1,728	32.086
9	*Scientific Reports*	1,573	4.379
10	*Advanced Healthcare Materials*	1,543	11.092

Abbreviation: IF, impact factor.

Table 5. Top 10 well-represented research areas related to three-dimensional printing in bone regeneration and bone repair

Rank	Research areas	Records	Percentage (%, N/2,025)	Total citations
1	Materials Science	1,171	57.827	34,297
2	Engineering	679	33.531	22,132
3	Chemistry	322	15.901	7,391
4	Science Technology Other Topics	299	14.765	10,186
5	Physics	182	8.988	4,558
6	Cell Biology	162	8.000	3,890
7	Polymer Science	149	7.358	2,087
8	Biochemistry Molecular Biology	121	5.975	2,925
9	Biotechnology Applied Microbiology	119	5.877	3,222
10	Research Experimental Medicine	87	4.296	1,750

by the National Natural Science Foundation of China (NSFC), followed by the United States Department of Health Human Services (180, 8.889%) and the National Institutes of Health (NIH) USA (179, 8.845%). Among the top 10 funding sources, half came from China, while the remaining came from the USA and the European Union.

3.5. Citation and co-citation analysis

A total of 601 documents in this field with more than 25 citations were analyzed by VOSviewer (Figure 6A). The top five most cited review or research publications are shown in Table 8. There were 957 citations for "Recent advances in 3D printing of biomaterials" (2015), followed by "Bone regenerative medicine: classic options, novel strategies, and future directions" (2014), with 596 citations, and "Scaffolds for Bone Tissue Engineering: State of the art and new perspectives" (2017), with 588 citations. However, the top 5 research publications were as follows: "3D printing of composite calcium phosphate and collagen scaffolds for bone regeneration" (2014), with 522 citations, followed by "Reinforcement of hydrogels using three-dimensionally printed microfibers" (2015), with 433 citations, and "High-resolution PLA-based composite scaffolds via 3-D printing technology" (2013), with 295 citations.

The co-cited references were visualized by CiteSpace (Figure 6B). Table 9 shows the top 5 references with the highest number of citations, which were published by the corresponding authors Kaplan D (2005; 276 citations), Atala A (2014; 241 citations), Ma PX (2013; 212 citations), Hollister SJ (2005;144 citations), and Hutmacher DW (2000; 139 citations). Subsequently, the co-cited references were clustered based on indexing terms (Figure 6C), forming 18 major clusters: "bone regeneration," "macrophage polarization," "osteogenic peptide," "hybrid constructs," "bioink," "3D printing," "dental tissue regeneration," "cranial defects," "osteoinduction," "bone scaffolds," "computer-aided tissue design," "tibial tuberosity advancement," "periodontal regeneration," "osteointegration," "indirect solid free form fabrication," "*in vivo* biomaterials," "microporous materials," and "nanomaterials."

Table 6. Top 10 authors with the most publications and citations on three-dimensional printing in bone regeneration and bone repair

Rank	Authors	Country	Article count	Percentage (%, N/2,025)	Total citations	H-index
1	Chen Y	China	39	1.926	1,138	16
2	Wu CT	China	39	1.926	2,017	22
3	Zhu YF	China	30	1.481	1,613	19
4	Chang J	China	27	1.333	1,895	21
5	Lee SJ	USA	26	1.284	815	14
6	Wang H	China	26	1.284	626	14
7	Wang Y	China	26	1.284	347	8
8	Lee J	South Korea	24	1.185	390	11
9	Park SA	South Korea	24	1.185	702	14
10	Li L	China	23	1.136	686	14

Rank	Authors	Country	Article count	Percentage (%, N/2,025)	Total citations	H-index
1	Chen Y	China	39	1.926	1,138	16
2	Wu CT	China	39	1.926	2,017	22
3	Zhu YF	China	30	1.481	1,613	19
4	Chang J	China	27	1.333	1,895	21
5	Lee SJ	USA	26	1.284	815	14
6	Wang H	China	26	1.284	626	14
7	Wang Y	China	26	1.284	347	8
8	Lee J	South Korea	24	1.185	390	11
9	Park SA	South Korea	24	1.185	702	14
10	Li L	China	23	1.136	686	14

References with citation bursts are considered a valuable indicator of literature that authors have frequently cited in a particular domain over a certain period[29]. The top 25 references with the strongest citation bursts are shown together with their reference duration (Figure 7). The article titled "Rapid casting of patterned vascular networks for perfusable engineered three-dimensional tissues" that was published in 2012 ranked first (strength = 4.73). Meanwhile, the citation bursts of an article published by Fielding G ("Multisociety consensus quality improvement revised consensus statement for endovascular therapy of acute ischemic stroke") had the longest duration from 2012 to 2017.

3.6. Co-occurrence analysis of keywords

CiteSpace and VOSviewer were used to conduct a co-occurrence cluster analysis of keywords to capture research frontiers in the field. They were classified into 11 clusters: "extracellular matrix" (cluster 0), "reconstruction" (cluster 1), "photothermal therapy" (cluster 2), "digital light processing" (cluster 3), "titanium" (cluster 4), "3D printing" (cluster 5), "calcium phosphate" (cluster 6), "additive manufacturing" (cluster 7), "bone ingrowth" (cluster 8), "mechanobiology" (cluster 9), and "finite element analysis" (cluster 10) (Figure 8A). A network map by VOSviewer was used to analyze the distribution of keywords according to the average publication year (dark blue: earlier; yellow: later) (Figure 8B). A total of 138 keywords were obtained with a minimum number of occurrences of a keyword set to 25. The 5 keywords with the highest occurrences were "*in vitro*" (total link strength: 2,557), "scaffolds" (total link strength: 2,390), "regeneration" (total link strength: 2,322), "tissue engineering" (total link strength: 2,168), and "bone" (total link strength: 2,167). The majority of the keywords were published before 2019, while relatively new keywords that emerged after 2020 included "bioink," "cartilage tissue," and "nanofibers."

The time dynamic evolution of keyword clusters was visualized using CiteSpace (Figure 8C). Seven main clusters were identified: "bone tissue engineering" (cluster 0), "3D bioprinting" (cluster 1), "photothermal therapy" (cluster 2), "phosphate" (cluster 3), "osteoinduction" (cluster 4), "reconstruction" (cluster 5), "tissue engineering" (cluster 6), and "three-dimensional printing" (cluster 7), among which cluster 0 and cluster 6 were hotspots from former studies, cluster 2 was a mid-period research hotspot, and

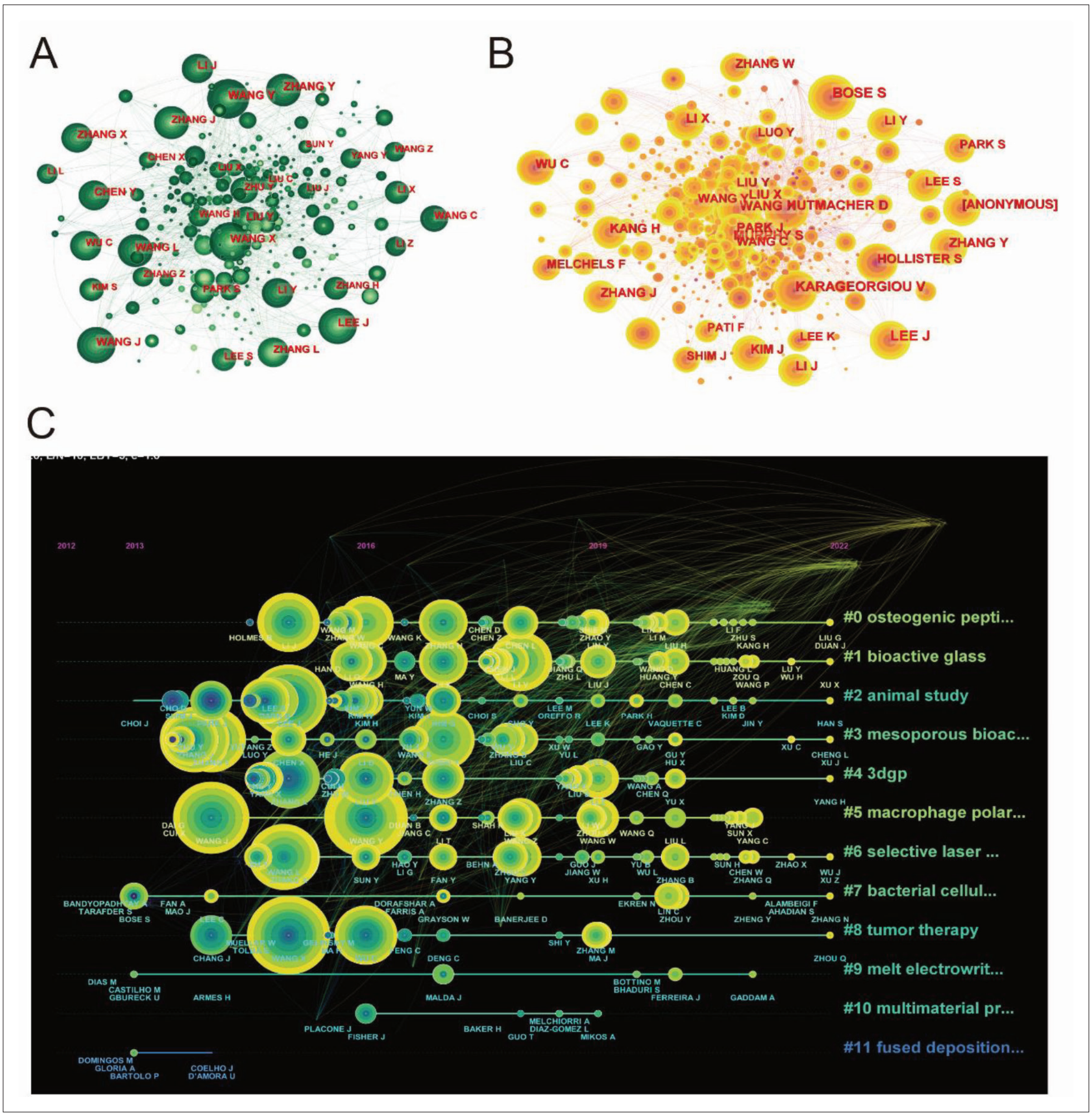


Figure 5. CiteSpace network visualization of author collaboration analysis and co-cited authors of publications on three-dimensional printing in bone regeneration and bone repair. (A) Author collaboration analysis. (B) Network visualization diagram of the co-cited authors of the publications. (C) Author timeline visualization from 2012 to 2022. The nodes indicate author collaboration or co-cited authors. The line connecting the nodes indicates the co-citation relationship. The node area enlarges as the number of co-citations increases. The colors represent different years; in A, the color changes from white to green from 2012 to 2022; in B, the color changes from brown to yellow from 2012 to 2022.

all the other clusters excluding cluster 6 were current research hotspots.

The CiteSpace algorithm was utilized to investigate keyword bursts, showing the top 25 keywords with the strongest citation bursts (Figure 9). The keyword with the strongest citation bursts was "rapid prototyping" (strength = 7.05), followed by "marrow stromal cell" (strength = 5.59) and "therapy" (strength = 4.96). The keyword with the longest burst duration was "rapid prototyping," which lasted 7 years (2012–2018), followed by "bone morphogenetic protein" (2013–2017) and "growth factor delivery" (2015–2019). Interestingly, the keywords "drug delivery system" and "progenitor cell" had the most recent burst citations during 2020–2022, suggesting that these topics are likely to be the next potential research hotpots in the near future.

4. Discussion

In the last decade, 3DP technology has gained significant global research interest and proven to be a powerful tool

Table 7. Top 10 funding sources for publications on three-dimensional printing in bone regeneration and bone repair

Rank	Funds	Records	Percentage (%, N/2,025)	Country
1	National Natural Science Foundation of China (NSFC)	527	26.025	China
2	United States Department of Health Human Services	180	8.889	USA
3	National Institutes of Health (NIH) USA	179	8.84	USA
4	National Key Research and Development Program of China	114	5.63	China
5	National Key R D Program of China National Key Research and Development Program of China	80	3.951	China
6	European Commission	78	3.852	European Union
7	National Science Foundation (NSF)	66	3.259	China
8	Science Technology Commission of the Shanghai Municipality (STCSM)	66	3.259	China
9	NIH National Institute of Arthritis Musculoskeletal and Skin Diseases (NIAMS)	55	2.716	USA
10	NIH National Institute of Biomedical Imaging and Bioengineering (NIBIB)	50	2.469	USA

in fabricating scaffolds for bone regeneration and repair. 3DP has several advantages over conventional scaffold fabrication techniques, particularly in realizing hierarchical or geometrically distinct pore structures, controlling scaffold stiffness, and implementing personalized features. In this study, we performed the first bibliometric analysis of literature on 3DP in relation to BTE applications based on publications in this area from 2012 to 2022 using CiteSpace and VOSviewer. Our analysis highlighted recent research trends and potential future hotspots in this rapidly evolving field.

4.1. Publication trends of 3DP in bone regeneration and bone repair

Our study showed a linear increase in the average number of publications per year on 3DP in bone repair and regeneration over the last decade, which was accompanied by an increase in RRI. With more than 800 papers representing 40% of total publications over a given timeframe, China was identified as the country making the highest overall contribution of publications to this field and was also associated with the highest number of total publications. This was followed by the USA, which had the highest average citation number per publication, thus possibly suggesting higher output quality or impact.

The analysis of major journal outlets in this field indicated that *Biofabrication*, *Materials*, and *Acta Biomaterialia* were the three highest contributors. This was an interesting observation when considering the IF of the top 10 journals, as those with lower IF, including *Materials*, are in fact recently established, open access journals. This may indicate a recent trend in the preference of authors to use open access outlets so that their publications are accessible by a broader audience and a possible preference for trying out newer journals, which may have a more expedited editorial process, as opposed to "traditional" journals from more established publishers. It is also interesting to note that, although not unexpected, the majority of journals in the top 10 were related to biomaterials due to the nature of 3DP with high involvement of biomaterial design and processing. According to our journal co-citation analysis, *Biomaterials* and *Acta Biomaterialia* were the top contributors to the field based on the number of citations, which corresponded to their IF. Among the top 10 research directions, 6 were broadly classified under physical and chemical science, while 4 were under biological science, suggesting frequent interdisciplinary interactions within this field. The dual-map analysis also reflected research focus on materials, medical, and physico-chemical studies.

The top-ranked authors contributing to this field were relatively early entrants who had been contributing to this research area for a long time. Interestingly, the collaboration analysis revealed that the research relationships among authors were restricted to the same country, suggesting the need for more cross-continental collaboration in the field, especially in light of the fact that all of the top 10 contributing institutions and the majority of the top contributing authors were from China.

The most cited article in the field was a review of the recent advances in 3DP of biomaterials that was published in 2015[35], followed by a review on bone regenerative medicine that was not specifically focused on 3DP, published in 2014[36]. The top five most cited articles were generally focused on the topics of biomaterials, bone regenerative medicine, and preclinical experimental studies of 3D-printed scaffolds. These popular topics were verified by co-citation analysis of references to the included studies, which were classified into 18 clusters that were mostly related to BTE scaffold materials, mechanisms, and manufacturing strategies.

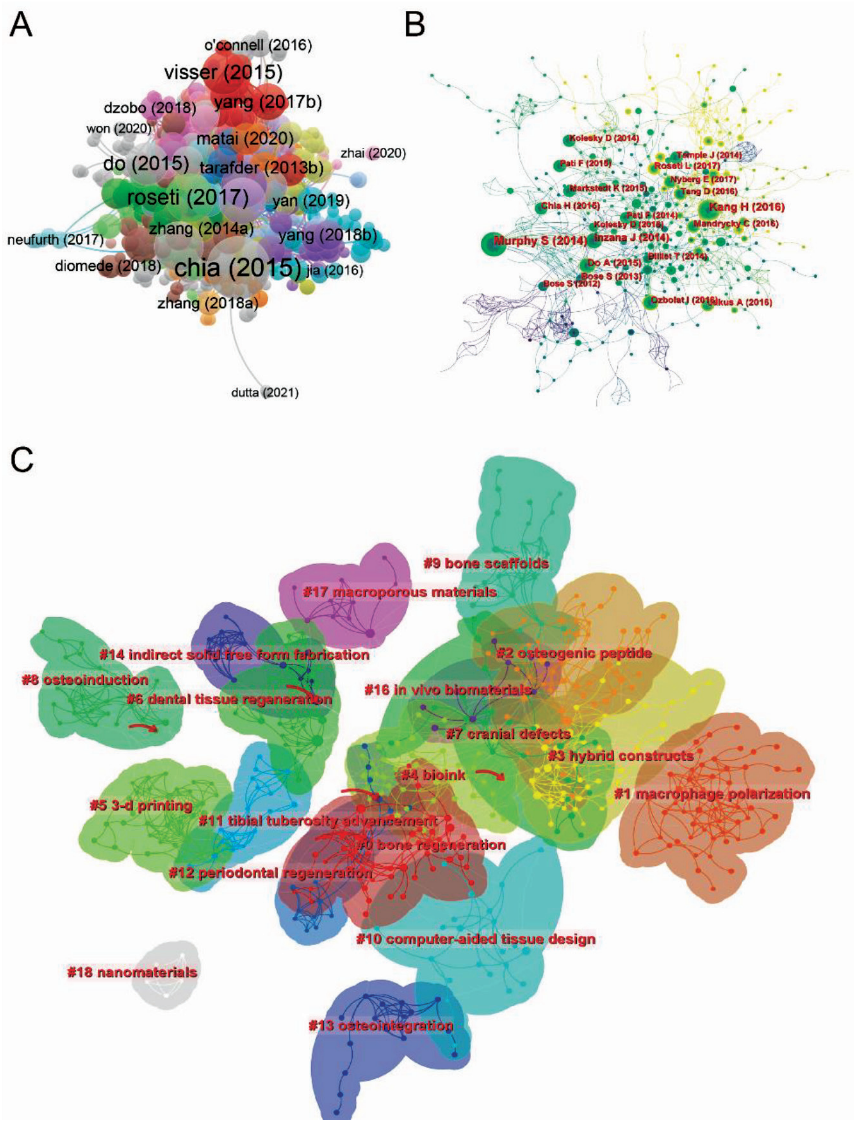


Figure 6. Mapping of publications and references for studies on three-dimensional printing in bone regeneration and bone repair. (A) Network map of citation analysis for documents with more than 25 citations. (B) Network map of the co-citation analysis of references based on CiteSpace. (C) Clustering analysis of the co-citation network based on CiteSpace.

4.2. Research hotspots and frontiers

The co-occurrence analysis of keywords and burst appearances reflected research hotspots of 3DP in bone repair and regeneration. The co-occurrence network of keywords, which reflected keyword appearance in the titles/abstracts of all included publications, was divided into four main categories: "3DP techniques," "3DP materials," "bone regeneration," and "bone disease therapeutics." The research related to these four groups of keywords not only represents current hotspots in the field but also forecasts the direction of future studies.

4.2.1. 3DP techniques

The co-occurrence analysis of keywords identifying "digital light processing," "additive manufacturing," and "finite element analysis" as important research hotspots deserves further attention. The digital light processing (DLP) method has been considered an attractive 3DP approach because it can fabricate a single layer of 3D scaffold through spatially controlled solidification using a projector light[37]. Notably, DLP has been developed to produce BTE scaffolds with highly interconnected pore architectures. For example, a recent study has developed bioceramic scaffolds mimicking the Haversian bone structure using DLP-based 3DP, demonstrating the ability to increase blood vessel ingrowth and bone formation[38]. Moreover, computational methods, including finite element analysis, have been used to assist biomimetic modeling of 3DP scaffolds. For example, computational

Table 8. Top five research and review articles with the most citations in the field of three-dimensional printing in bone regeneration and bone repair

Document type	Rank	Title	Corresponding author	Journal	IF	Publication year	Total citations
Review	1	Recent advances in 3D printing of biomaterials	Wu BM	*Journal of Biological Engineering*	6.248	2015	957
	2	Bone regenerative medicine: classic options, novel strategies, and future directions	Maffulli N	*Journal of Orthopaedic Surgery and Research*	2.677	2014	596
	3	Scaffolds for Bone Tissue Engineering: State of the art and new perspectives	Grigolo B	*Materials Science & Engineering C: Materials for Biological Applications*	8.457	2017	588
	4	3D bioactive composite scaffolds for bone tissue engineering	Shu W	*Bioactive Materials*	16.874	2018	530
	5	3D Printing of Scaffolds for Tissue Regeneration Applications	Salem AK	*Advanced Healthcare Materials*	11.092	2015	451
Research	1	3D printing of composite calcium phosphate and collagen scaffolds for bone regeneration	Awad HA	*Biomaterials*	15.304	2014	522
	2	Reinforcement of hydrogels using three-dimensionally printed microfibers	Malda J	*Nature Communications*	17.694	2015	453
	3	High-resolution PLA-based composite scaffolds via 3-D printing technology	Navarro M	*Acta Biomaterialia*	10.633	2013	295
	4	Structurally and Functionally Optimized Silk-Fibroin-Gelatin Scaffold Using 3D Printing to Repair Cartilage Injury In Vitro and In Vivo	Ao YF	*Advanced Materials*	32.086	2017	252
	5	Ornamenting 3D printed scaffolds with cell-laid extracellular matrix for bone tissue regeneration	Cho DW	*Biomaterials*	15.304	2015	231

Abbreviations: 3D, three-dimensional; IF, impact factor; PLA, polylactic acid.

Table 9. Top five co-citation analyses of cited references on three-dimensional printing in bone regeneration and bone repair

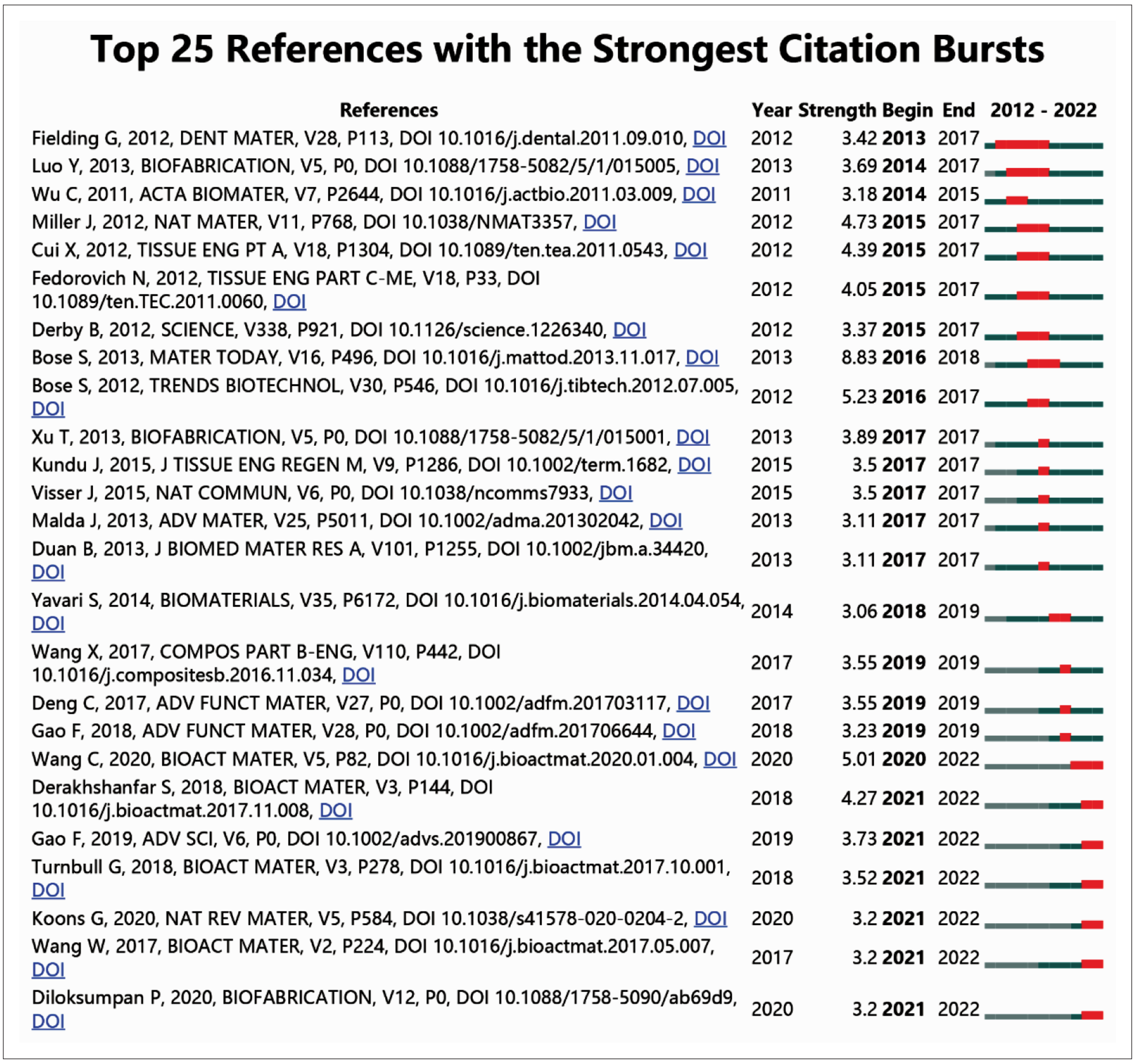
Rank	Title	Corresponding author	Journal	IF	Publication year	Total citations
1	Porosity of 3D biomaterial scaffolds and osteogenesis	Kaplan D	*Biomaterials*	15.304	2005	276
2	3D bioprinting of tissues and organs	Atala A	*Nature Biotechnology*	68.164	2014	241
3	Mimicking the nanostructure of bone matrix to regenerate bone	Ma PX	*Materials Today*	26.943	2013	212
4	Porous scaffold design for tissue engineering	Hollister SJ	*Nature Materials*	47.656	2005	144
5	Scaffolds in tissue engineering bone and cartilage.	Hutmacher DW	*Biomaterials*	15.304	2000	139

Abbreviations: 3D, three-dimensional; IF, impact factor.

simulation and optimization was used to design diamond-like pores for a 3DP scaffold in a study, and this biomimetic scaffold was shown to promote load-bearing bone reconstruction[39].

4.2.2. 3DP materials

A primary topic in 3DP is the development of new material options for tissue regeneration, including BTE. The results of the keyword co-occurrence analysis suggested



Top 25 References with the Strongest Citation Bursts

References	Year	Strength	Begin	End	2012 - 2022
Fielding G, 2012, DENT MATER, V28, P113, DOI 10.1016/j.dental.2011.09.010, DOI	2012	3.42	**2013**	2017	
Luo Y, 2013, BIOFABRICATION, V5, P0, DOI 10.1088/1758-5082/5/1/015005, DOI	2013	3.69	**2014**	2017	
Wu C, 2011, ACTA BIOMATER, V7, P2644, DOI 10.1016/j.actbio.2011.03.009, DOI	2011	3.18	**2014**	2015	
Miller J, 2012, NAT MATER, V11, P768, DOI 10.1038/NMAT3357, DOI	2012	4.73	**2015**	2017	
Cui X, 2012, TISSUE ENG PT A, V18, P1304, DOI 10.1089/ten.tea.2011.0543, DOI	2012	4.39	**2015**	2017	
Fedorovich N, 2012, TISSUE ENG PART C-ME, V18, P33, DOI 10.1089/ten.TEC.2011.0060, DOI	2012	4.05	**2015**	2017	
Derby B, 2012, SCIENCE, V338, P921, DOI 10.1126/science.1226340, DOI	2012	3.37	**2015**	2017	
Bose S, 2013, MATER TODAY, V16, P496, DOI 10.1016/j.mattod.2013.11.017, DOI	2013	8.83	**2016**	2018	
Bose S, 2012, TRENDS BIOTECHNOL, V30, P546, DOI 10.1016/j.tibtech.2012.07.005, DOI	2012	5.23	**2016**	2017	
Xu T, 2013, BIOFABRICATION, V5, P0, DOI 10.1088/1758-5082/5/1/015001, DOI	2013	3.89	**2017**	2017	
Kundu J, 2015, J TISSUE ENG REGEN M, V9, P1286, DOI 10.1002/term.1682, DOI	2015	3.5	**2017**	2017	
Visser J, 2015, NAT COMMUN, V6, P0, DOI 10.1038/ncomms7933, DOI	2015	3.5	**2017**	2017	
Malda J, 2013, ADV MATER, V25, P5011, DOI 10.1002/adma.201302042, DOI	2013	3.11	**2017**	2017	
Duan B, 2013, J BIOMED MATER RES A, V101, P1255, DOI 10.1002/jbm.a.34420, DOI	2013	3.11	**2017**	2017	
Yavari S, 2014, BIOMATERIALS, V35, P6172, DOI 10.1016/j.biomaterials.2014.04.054, DOI	2014	3.06	**2018**	2019	
Wang X, 2017, COMPOS PART B-ENG, V110, P442, DOI 10.1016/j.compositesb.2016.11.034, DOI	2017	3.55	**2019**	2019	
Deng C, 2017, ADV FUNCT MATER, V27, P0, DOI 10.1002/adfm.201703117, DOI	2017	3.55	**2019**	2019	
Gao F, 2018, ADV FUNCT MATER, V28, P0, DOI 10.1002/adfm.201706644, DOI	2018	3.23	**2019**	2019	
Wang C, 2020, BIOACT MATER, V5, P82, DOI 10.1016/j.bioactmat.2020.01.004, DOI	2020	5.01	**2020**	2022	
Derakhshanfar S, 2018, BIOACT MATER, V3, P144, DOI 10.1016/j.bioactmat.2017.11.008, DOI	2018	4.27	**2021**	2022	
Gao F, 2019, ADV SCI, V6, P0, DOI 10.1002/advs.201900867, DOI	2019	3.73	**2021**	2022	
Turnbull G, 2018, BIOACT MATER, V3, P278, DOI 10.1016/j.bioactmat.2017.10.001, DOI	2018	3.52	**2021**	2022	
Koons G, 2020, NAT REV MATER, V5, P584, DOI 10.1038/s41578-020-0204-2, DOI	2020	3.2	**2021**	2022	
Wang W, 2017, BIOACT MATER, V2, P224, DOI 10.1016/j.bioactmat.2017.05.007, DOI	2017	3.2	**2021**	2022	
Diloksumpan P, 2020, BIOFABRICATION, V12, P0, DOI 10.1088/1758-5090/ab69d9, DOI	2020	3.2	**2021**	2022	

Figure 7. Top 25 references with the strongest citation bursts for publications on three-dimensional printing in bone regeneration and bone repair.

biomaterial-related terms, including "extracellular matrix," "titanium," and "calcium phosphate." Since bone is a complex tissue and its ECM consists of an organic and inorganic phase, certain types of decellularized extracellular matrices have been investigated as potential material sources for BTE applications[40]. There are benefits in preserving the bone's native structure, as shown in a study that cultured adipose-derived stem cells on a 3DP decellularized matrix scaffold, which increased calcification *in vivo* and helped induce greater bone regeneration[41]. Calcium phosphate is a popular inorganic material frequently used as a component of 3DP scaffolds for BTE. In one study, calcium phosphate was hybridized with decellularized bone matrix to fabricate a 3DP polycaprolactone scaffold, which was shown to induce effective bone regeneration in rabbit calvarial defect[42]. Titanium is commonly used in metal-based implants for bone repair. For example, Ti-6Al-4V is an alloy with high biocompatibility and superior mechanical qualities that has been widely used in orthopedic implants[43]. However, metals have the risk of causing stress shielding, which may lead to peri-implant osteolysis[44]. The average pore size of Ti-6Al-4V scaffolds can significantly influence the outcome of osseointegration and bone repair. For instance, a study has confirmed that Ti-6Al-4V scaffolds with an average pore size of 400 μm exhibited better osseointegration than those with larger or smaller pores[45]. Although mesoporous bioactive materials are not yet in routine clinical use, they have emerged as effective preclinical strategies for bone regeneration. For example, the high osteogenic capability of mesoporous bioactive nanoparticles has been demonstrated in an osteoporotic rabbit model[46]. Novel biomaterial developments are needed to further improve 3DP scaffold systems so that the

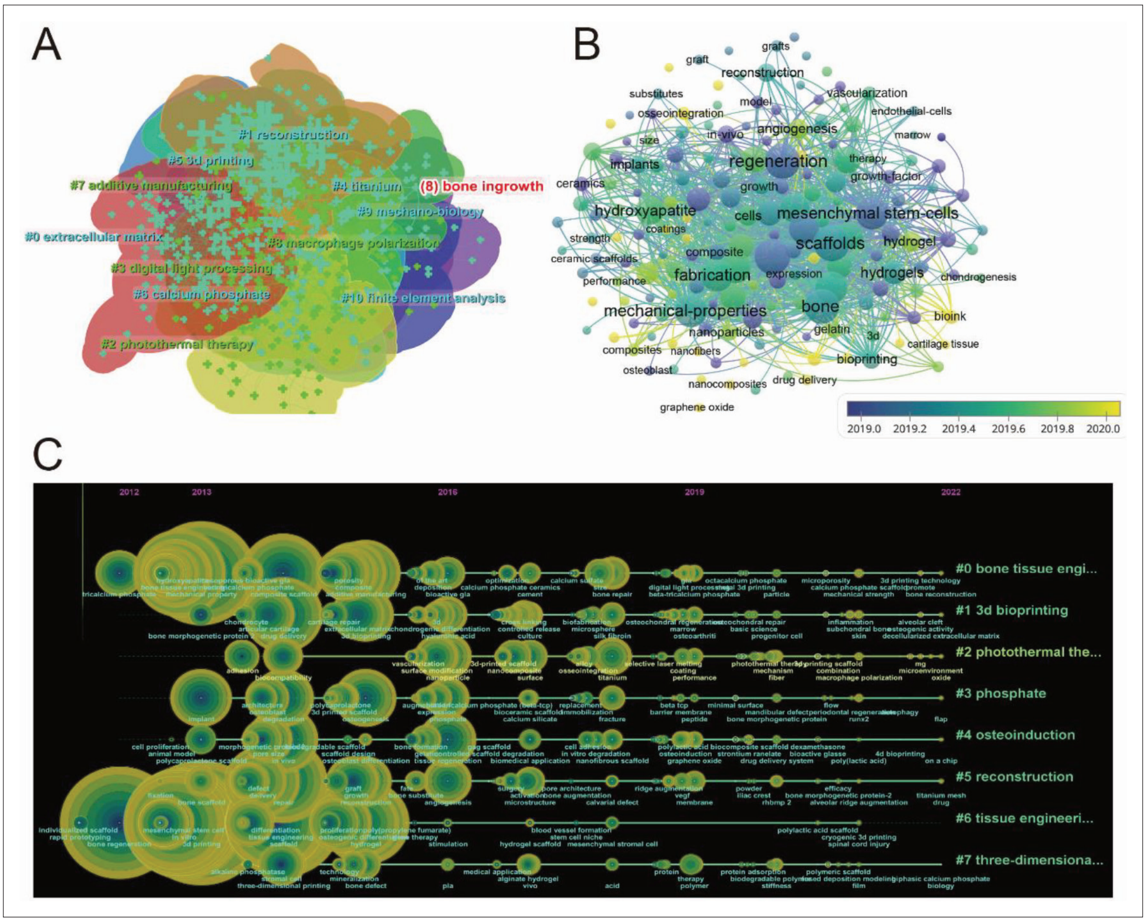


Figure 8. Mapping of keywords in studies on three-dimensional printing in bone regeneration and bone repair. (A) Network visualization of keywords by CiteSpace. (B) Distribution of keywords according to average publication year (blue: earlier; yellow: later) by VOSviewer. (C) Keyword timeline visualization from 2012 to 2022 by CiteSpace.

simultaneous requirements for mechanical and bioactive properties to induce successful bone healing can be met.

4.2.3. Bone regeneration strategies

Regeneration strategies that incorporate integrated elements are becoming increasingly popular in BTE and are often associated with higher success rates than individual strategies, such as those that only focus on biomaterial development or scaffold design. These multidisciplinary strategies are particularly important for complex bone reconstruction, such as defects resulting from various bone diseases, including bone infection and bone tumors, as well as large areas of bone loss from significant traumatic injuries[47]. Macrophage polarization is now known to play a fundamental role in bone healing[48], and many efforts have been made to explore related targets in order to modulate or accelerate the progress of regeneration. As an example, magnetic responsive hydrogels grafted with superparamagnetic nanoparticles have been developed as a unique cell-carrying platform[49]. This platform can respond to static magnetic field as needed and specifically polarize macrophages to the regenerative M2 phenotype in the middle/late stages of injury repair, thus eventually optimizing immunomodulatory bone healing *in vivo*. In another aspect, investigating the underlying mechanobiology of bone is an important research direction for enhanced bone healing. Since bone formation occurs under a specific mechanical microenvironment[50], some studies have attempted to achieve mechanobiological optimization of the healing environment. For example, one study has computationally investigated the optimal mechanical properties of a biomaterial based on Young's modulus throughout the bone healing period and successfully identified the best mechanical stimulus at each time point during the healing process[51]. These new approaches that integrate biomaterial, mechanical, and biological aspects into 3DP scaffold systems may be promising for improving bone repair and regeneration.

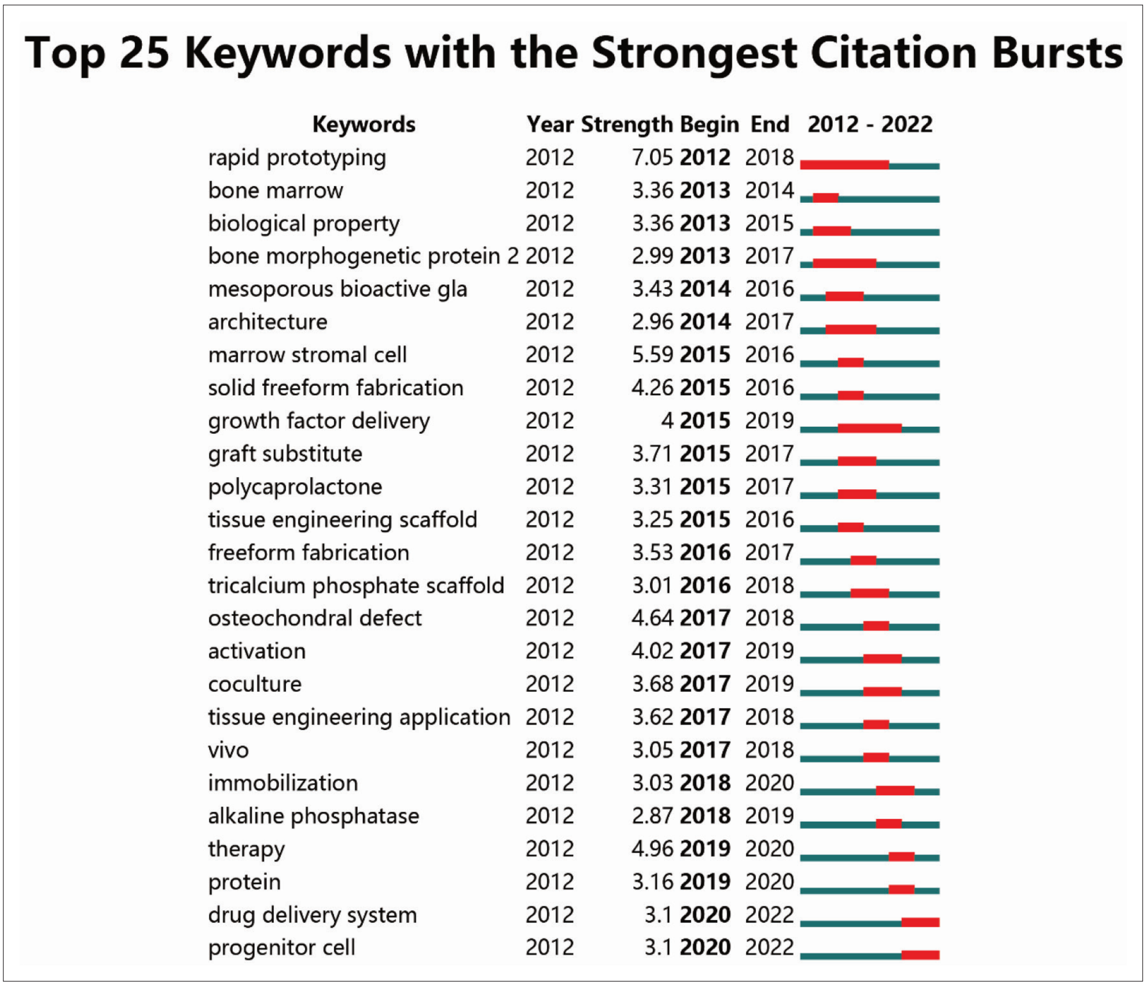


Figure 9. Top 25 keywords with the strongest citation bursts of publications related to three-dimensional printing in bone regeneration and bone repair.

4.2.4. Bone disease therapeutics

Multidisciplinary regeneration strategies involving 3DP scaffolds, along with their capabilities for cell recruitment, osteogenic differentiation, and immunomodulation have been applied with much success in preclinical studies of bone repair and regeneration. However, complex cases of bone reconstruction remain a challenge, particularly for different types of bone diseases that require multimodal treatment in addition to just inducing bone formation. In the case of bone tumor therapeutics, photothermal therapy is often required along with bone regeneration therapy to enable the dual function of eradicating residual tumor cells while preserving healthy bone cells and encouraging new bone formation. In this respect, a functionalized 3DP scaffold comprising photothermal-triggered Wesselsite nanosheets, which can simultaneously induce osteosarcoma ablation through extensive hyperthermia triggered by near-infrared-II (NIR-II) light and promote vascularized bone regeneration, has been developed[52]. For bone infection, a 3DP composite hydrogel scaffold comprising gelatin methacryloyl (GelMA)/β-tricalcium phosphate (β-TCP)/sodium alginate (Sr^{2+})/MXene has shown dual photothermal antibacterial and osteogenic capability, with photothermal effects endowed by MXene. This scaffold has also shown strong potential in accelerating *in vivo* healing of infected bone defects[53]. These studies collectively suggest the necessity to develop multifunctional 3DP implants that possess potent bone regeneration capability while targeting the treatment of specific bone diseases.

4.3. Outlook for BTE in bone regeneration and bone repair

3DP for BTE has advanced at producing products with tailored structures, adjustable compositions, customized shapes, *etc.*[23]. Over the past 10 years, 3DP for bone regeneration and bone repair has made great progress in the fields of material and technology development, regenerative strategy innovation, and bone disease therapeutics. However, there are some problems that need to be solved: (1) as natural bone contains cortical and cancellous multiscale hierarchical structures, 3DP is expected to precisely reconstruct complex microstructures; as mentioned before, the DLP method combined with finite element analysis can produce highly interconnected pore architectures; advanced printing technology should be designed in such a way to allow for significantly higher solution concentrations without clogging the nozzle; (2) novel 3DP materials should be created with specific properties, such as good cell biocompatibility, controlled biodegradability, superior mechanical properties, and excellent vascularization and osteogenic differentiation; however, most of the present materials fail to meet the aforementioned properties, thus hindering their applications in clinical practice; (3) multidisciplinary therapeutic strategies for bone regeneration and bone repair should be developed as well; as defects might result from significant traumatic injuries, bone tumors, and bone infection, printed scaffolds should not only have the capacity for bone reconstruction, but also target the treatment of specific bone diseases with antibacterial and tumor cell eradication abilities; (4) the molecular and cellular mechanisms underlying bone repair remain unclear; the development of 3DP for BTE is governed by a detailed knowledge of these regenerative mechanisms; the process of bone regeneration can be divided into four overlapping stages, which are hemostasis, inflammation, repair, and remodeling[54]; one of the important stages is dependent on the regulatory role of immune cells, particularly macrophages, with the M1 phenotype producing pro-inflammatory cytokines and the M2 phenotype producing anti-inflammatory effects; it is widely accepted that the M2 phenotype is permissive to bone regeneration and repair, but excessive infiltration of M2 macrophages might not be conducive to bone regeneration; instead, it may impair tissue healing; therefore, an in-depth exploration of the underlying mechanisms would additionally enable 3DP development to be effectively harnessed to improve bone regeneration.

4.4. Study strengths and limitations

Our study provided a comprehensive bibliometric and visualized analysis of current literature reporting 3DP in bone repair and regeneration. Some limitations should be considered when interpreting the results of our study. First, literature searches using PubMed, Cochrane, Scopus, and Embase library databases were not performed, as all studies were collected from the WoSCC. Although the WoSCC is considered a comprehensive database that captures all available literature in the field, study retrieval from a single database could nevertheless result in selection bias. Second, non-English language articles and nonresearch/review articles were not included in this study, resulting in the omission of a large body of relevant studies published in other languages, particularly considering China's high contribution of publications in the area. Moreover, it was entirely up to an experienced expert to make the final decision when disagreements occurred during the data selection process. Last, recently published articles that were not in press during the search period were excluded, and the citation data for high-impact publications that appeared recently might not have reflected their true impact, which could lead to some prediction bias when analyzing time-dependent trends and keywords based on the included publications.

5. Conclusion

Our study presents the first comprehensive bibliometric and visualized analysis of 3DP in bone repair and regeneration, reflecting research trends in the field over the last 10 years. This study systematically shows the global trends in this rapidly evolving area and may assist researchers in identifying influential authors, institutions, and journals. Moreover, the keyword and co-citation clustering analyses enable researchers to identify research directions mainly in four categories: "3DP techniques," "3DP materials," "bone regeneration strategies," and "bone disease therapeutics." Gaining an in-depth understanding of current studies in this growing field of research will be beneficial for researchers to further contribute to the advancement of knowledge and push the frontiers of 3DP in bone repair and regeneration from preclinical studies to clinical implementation.

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Conflict of interest

The authors declare no conflicts of interest.

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Writing – original draft: Zhen Yang, Hao Li
Writing – review & editing: Jiao Jiao Li, Elise M. Cribbin, Alice M. Kim

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data

All data are reported in the present manuscript and not elsewhere.

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