RESEARCH ARTICLE

Uncovering 3D bioprinting research trends: A keyword network mapping analysis

Leonardo Azael Garcia-Garcia, Marisela Rodriguez-Salvador*

Tecnologico de Monterrey, Escuela de Ingenieria y Ciencias, Laboratorio Nacional de Manufactura Aditiva y Digital (MADiT), Monterrey, N.L., Mexico

Abstract: A scientometric analysis as part of a Competitive Technology Intelligence methodology was used to determine the main research efforts in 3D bioprinting. Papers from Scopus and Web of Science (WoS) published between 2000 and 2017 were analysed. A network map of the most frequently occurring keywords in these articles was created, and their average publication year (APY) was determined. The analysis focused on the most relevant keywords that occurred at least five times. A total of 1,759 keywords were obtained, and a co-occurrence analysis was developed for APYs with more keywords: 2011–2016. The results indicated that Polylactic Acid (PLA) is the material used most often. Applications mainly focused on bone tissue engineering and regeneration. The most frequently used technique was inkjet printing, and the main cell sources were Mesenchymal Stem Cells (MSC). From a general perspective, 'Treatment' and 'Bioink' were the most frequent keywords. The former was mainly related to cancer, regenerative medicine, and MSC and the latter, to multicellular spheroid deposition and the use of hydrogels like GelMA (gelatin methacryloyl). This analysis provides insights to stakeholders involved in 3D bioprinting research and development who need to keep abreast of scientific progress in the field.

Keywords: scientometric analysis; data mining; competitive technology intelligence; 3D bioprinting

*Correspondence to: Marisela Rodriguez-Salvador, Tecnologico de Monterrey, Escuela de Ingenieria y Ciencias, Mexico; marisrod@itesm.mx

Received: May 30, 2018; **Accepted:** June 28, 2018; **Published Online:** July 9, 2018

Citation: Garcia-Garcia L A, Rodriguez-Salvador M, 2018, Uncovering 3D bioprinting research trends: A keyword network mapping analysis. *Int J Bioprint*, 4(2): 147. http://dx.doi.org/10.18063/IJB.v4i2.147

1. Introduction

In recent years, advanced manufacturing systems have attracted industrial and academic interest since they can overcome the limitations of traditional manufacturing. Issues such as material waste reduction, production of complex forms, tailored product design, and long manufacturing times have been mitigated greatly by using three-dimensional (3D) printing. In the last decade, 3D printing has been used in wide-ranging applications, from prototyping to printing medical devices and even living tissue through the deposition of cell aggregates[1–4]. A major challenge in printing living tissue is fabricating complex organs, and this objective will likely remain unachieved for some years[1,5–7]. However, it is now possible to build 3D scaffolds using biocompatible materials, to which cell aggregates are added to promote tissue growth[5,8,9]. 3D bioprinting refers to simultaneously writing living cells and biomaterials with a prescribed layer-by-layer stacking organization[10]. It is one of the most promising technologies for addressing diverse health problems, and therefore, numerous research efforts have focused on further developing this technique. To support research and development (R&D) decision-making processes, it is important to keep abreast of global scientific advancements. In this regard, scientometric and patentometric methods enable the analysis of scientific documents and patents to determine trends related to research areas, materials, and methods. Two of the most widely used tools for this purpose are co-citation and co-occurrence analyses[11,12]. Co-citation analysis

is used to determine how often a pair of documents are cited together by other documents, and it allows the identification of authors with predominant influence on a field. Co-occurrence analysis focuses on how often a set of keywords occurs together, and it provides relevant information on the focus of research. At present, scientometric and patentometric analyses of 3D printing still remain scarce. A few of the studies in this area include a US patent analysis on the evolution of 3D printing for biomedical applications from 1980 to 2014[13], a scientific literature (Scopus) and patent analysis on 3D printing in Latin America from 1984 to mid-2015[14] and a Competitive Technology Intelligence (CTI) analysis on scientific literature (Scopus and Web of Science) and patents from 2000 to mid-2016[15]. Of these, the CTI analysis has the most recent and complete information, being published in 2017; it covered the knowledge landscape of 3D bioprinting and identified the leading countries, institutions, journals, and major areas in this field. These studies have noted the exponential growth in the number of patents and publications in recent years. Therefore, it is important to stay updated with and to identify current research trends in this field. The present study aims to add value in this respect by developing a keyword network mapping from Scopus and Web of Science from 2000 to 2017. It pursues to determine the main research efforts from a global perspective and to consider specific elements that have not yet been discussed, including materials, biological components, and applications as well as to identify bioprinting techniques, cell sources, and tissue/organs research. The objective is to contribute to R&D decision-making processes in this field.

2. Methods

For this study, a scientometric analysis was developed as a part of a CTI methodology. CTI involves an ethical and legal process through which information is transformed into an actionable result, thereby contributing to R&D strategic decision-making processes. CTI is developed through a virtuous cycle of information that includes planning, source determination, gathering, analysis, and establishment of results. It goes beyond being a simple information-gathering process. Instead of collecting the largest amount of information, it is more important to collect the most relevant information. In this sense, information gathering represents a crucial step for further analysis. To collect the right information, the identification of keywords and design of a search query must be as accurate as possible. With the advent of 3D bioprinting, the number of publications in this field has increased exponentially, and sometimes, this can produce information noise (*i.e.*, repeated documents, documents that mention 3D bioprinting only from a general perspective and do not necessarily present advances in the area, *etc*.). To reduce the uncertainty in determining keywords for the query definition, this study considered the most frequently cited articles from Scopus containing the word 'bioprinting' in their abstracts, titles, and keywords. Scopus is one of the largest scientific databases, and it contains information about more than 20,000 scientific journals across various disciplines such as social, engineering, and health sciences[16]. Results show in Table 1 that the three most cited papers discuss scientific progress in tissue engineering and vascularization. Precisely, one of the current field's biggest challenges is to develop scaffold-free blood vessels that are as mechanically strong as native vessels.

Table 1. Top cited Scopus papers according to the keyword 'bioprinting' contained in titles, abstracts, or keywords.

	Title	Authors	Year	Source	Cites
1	3D bioprinting of tissue and organs[6].	Murphy S V, Atala A.	2014	*Nature Biotechnology*, 32(8): 773–785	1138
2	Scaffold-free vascular tissue engineering using bioprinting[17].	Norotte C, Marga F S, Niklason L E, Forgacs G.	2009	*Biomaterials*, 30(30): 5910–5917	529
3	3D bioprinting of vascularized, heterogeneous cell-laden tissue constructs[5].	Kolesky D B, Truby R L, Gladman A S, Homan K A, Lewis J A.	2014	*Advanced Materials*, 26(19): 3124–3130	446
4	Printing and prototyping of tissues and scaffolds[7].	Derby B.	2012	*Science*, 338(6109): 921-926	426
5	Additive manufacturing of tissues and organs[18].	Melchels F P W, Domingos M A N, Klein T J, Bartolo P J, Hutmacher D W.	2012	*Progress in Polymer Science,* 37(8): 1079–1104	417
6	25th anniversary article: Engineering hydrogels for biofabrication[19].	Malda J, Visser J, Melchels F P, Groll J, Hutmacher D W.	2013	*Advanced Materials*, 25(36): 5011–5028	376
7	A 3D bioprinting system to produce human-scale tissue constructs with structural integrity[20].	Kang H W, Lee S J, Ko I K, Yoo J J, Atala A.	2016	*Nature Biotechnology*, 34(3): 312–319	310
8	Printing three-dimensional tissue analogues with decellularized extracellular matrix bioink[8].	Pati F, Jang J, Ha D H, Kim D H, Cho D W.	2014	*Nature Communications*, 5: 3935	302
9	Tissue engineering by self-assembly and bioprinting of living cells[21].	Jakab K, Norotte C, Marga F, Vunjak-Novakovic G, Forgacs G.	2010	*Biofabrication*, 2(2): 022001	252
10	3D bioprinting of heterogeneous aortic valve conduits with alginate/gelatin hydrogels[22].	Duan B, Hockaday L A, Kang K H, Butcher J T.	2013	*Journal of Biomedical Materials Research-Part A*, 101A(5): 1255–1264	244

These papers were published by Nature Biotechnology, Biomaterials, and Advanced Materials and Science.

Next, a software program was specially developed to text mine these articles and to determine the most relevant words in each according to their frequency of occurrence. Single words and pairs of words with the highest frequencies were identified, and a cleaning task was performed to remove those not related to bioprinting. An iterative process was developed to validate the retrieved information and to design the search query, finally arriving at the following:

(((((3d OR 3-d OR three-dimensional) W/1 (bioprint* OR engineer* OR print* OR tech* OR fabricat* OR process* OR manufact* OR building OR built)) OR ((bio-engineer* OR bioengineer* OR biofabricat* OR bioprint* OR biotech* OR biomanufact*)) OR (bioadditive W/1 manufact*) OR (3d AND bioprint*))) W/5 (scaffold* OR construct* OR spheroid* OR channel* OR structure* OR matr* OR crosslinking OR block* OR aggregate* OR sheet* OR biomim* OR bioactiv* OR biohybrid* OR bioresorbable OR bioscaffolds OR biosensors OR bioassembl* OR bioartificial OR bioerodible OR biopatterning OR biopaper OR microextrusion) W/5 (cell* OR tissue* OR stem OR multicellular OR organ* OR biolog* OR embryonic OR vascular OR vessels OR collagen OR bone* OR osseo* OR adipose OR vascular OR cardiac OR heart OR cartilage* OR muscle) AND NOT ("data storage" OR photonic OR pcl OR "social capital"))

Here, W/# refers to the proximity of # words, and OR, AND, and AND NOT are Boolean operators used to combine or exclude terms. This study aimed to provide the most complete landscape of scientific progress worldwide, and therefore, information was collected from the two largest scientific databases, Scopus, whose coverage was mentioned previously, and Web of Science (WoS), which contains information from more than 13,000 journals over an even wider range of areas from social science to medical disciplines to engineering[23]. The above query was used to search the titles, abstracts, and keywords of published documents from both resources. Considering that 3D bioprinting represents a novel technology with major innovations starting in the early 2000s, the research was limited to articles published from 2000 to 2017. Bibliographic information of Scopus and WoS documents was obtained, and a further cleaning process was applied to homogenise articles' titles and keywords and to remove duplicate articles. Subsequently, the data was imported into VOSviewer, a software developed for the creation and visualisation of network maps[24]. This tool facilitated the determination of the average publication year (APY) and occurrence of each keyword. Only those keywords with five or more occurrences were selected, as this analysis sought to identify only the most relevant terms.

3. Results and Discussion

Initially, 3,573 articles were identified for 2000 to 2017, of which 2,066 were from Scopus and 1,507 were from WoS. Their bibliographic information was retrieved for further analysis, and a cleaning process was applied to narrow the results to 2,021 papers, whose bibliographic data were used to create keyword co-occurrence maps.

VOSviewer was used to determine the keywords with the highest frequency as well as the relevance scoring of each keyword. This score was calculated to identify terminology particularly related to the topic under study. A threshold of five or more occurrences was established, resulting in 2,956 keywords. Of these, 60% (1,773) with the highest relevance score were included in the analysis. A manual cleaning process was applied to these keywords to strengthen the analysis and to eliminate general words such as 'control' or 'patient' that, although related to the topic, did not provide specific information related to the study's focus (materials, applications, or methods). This resulted in a final total of 1,759 keywords from 2000 to 2017.

All 1,759 keywords were plotted using Gephi software. This tool aids in the visualization of network maps over a wide range of areas to determine the interaction of their components[25–28]. Figure 1 shows the keywords' network co-occurrence map. Each keyword is represented by a node, and all nodes are connected by 81,339 links. The node size is proportional to the occurrence frequency of

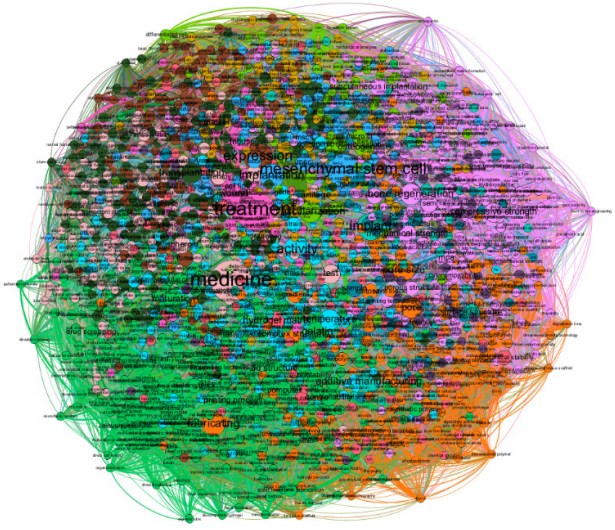

Figure 1. Keyword network map of 1,759 nodes and their 81,339 links.

each keyword.

In order to identify trends of research on 3D bioprinting the APY of the keywords contained on the network map was determined. This was obtained by averaging the publication years of each article containing each keyword. Results showed that the APYs ranged from 2002 to 2016. However, for co-occurrence analysis, APYs of only 2011 to 2016 were considered as the majority of keywords (67% of 1,759) were found in these years.

Figure 2 shows the co-occurrence network maps obtained for each APY from 2011 to 2016; again, the keywords are represented by nodes and are connected by links. Number of keywords and links are shown in Table 2.

Table 2. Number of keywords and links by average publication year (APY)

APY	Number of keywords	Number of links
2011	207	1,825
2012	279	4,231
2013	303	4,386
2014	203	1,233
2015	148	620
2016	53	66

The keywords for APY 2011 to 2016 were analysed to determine which of them dominated the discussion of 3D bioprinting materials, applications, or methods during these years.

Table 3 shows the results of the most frequent terminology for materials, biological elements, and applications for each of the APYs analysed (APY 2011–2016). The most frequent keyword was 'Treatment' with 235 occurrences in APY 2013. For materials, the most frequent keyword was 'PLA' (Polylactic acid) with 56 occurrences in APY 2014. For biological elements, the most frequent keyword was 'Mesenchymal Stem Cells' with 188 occurrences in APY 2013; furthermore, it was found as 'MSCs' with 54 occurrences in APY 2014. For applications, the most frequent keywords were 'Bone Tissue Engineering' with 153 occurrences in APY 2012 and 'Bone Regeneration' with 112 occurrences in APY 2014.

From a general perspective, from APY 2011 to 2016, the most frequent keywords were 'Treatment' (in APY 2013) and 'Bioink' (in APY 2016), indicating that these terms have been widely researched for the past three years (2015–2017). The results obtained indicated that studies on treatment were primarily focused on cancer, regenerative medicine, and MSC analysis. The keyword 'Treatment' was also related to other keywords such as 'Osteochondral Defect', 'Implant', 'Medicine', and 'Bone Defect'. By contrast, 'Bioink', a fundamental element in bioprinting, was mainly found in relation to multicellular spheroid deposition for guaranteeing maximal cell density[17,19,29,30] as well as in relation to hydrogels (*e.g.*, 'gelation' and 'GelMA' or 'Gelatin Methacryloyl') and 'Cell Sheet' and 'Printability', which are crucial factors in the fabrication of living tissue.

Table 3. Most frequent terminology for materials, biological components, and applications in papers analysed from APY 2011 to 2016.

APY	Most frequent keywords (Occurrences)	Material (Occurrences)	Biological component (Occurrences)	Application Occurrences)
2011	'Cell Sheet' (148)	'PLGA' (25)	'Bone Marrow' (44)	'Bioengineered Construct' (20)
2012	'Expression' (212)	'Biopolymer' (52)	'Progenitor Cell' (60)	'Bone Tissue Engineering' (153)
2013	'Treatment' (235)	'Hydroxyapatite' (33)	'Mesenchymal Stem Cells' (188)	'Vascular Network' (69)
2014	'Bone Regeneration' (112)	'PLA' (56)	'MSCs' (54)	'Bone Regeneration' (112)
2015	'Spheroid' (127)	'GelMA' (37)	'Pluripotent Stem Cells' (31)	'Cartilage Repair' (28)
2016	'Bioink' (230)	'Photocurable Resin' (6)	'IPSC' (18)	'Organoid' (24)

Additionally, to identify the predominant keywords in papers published in the last three years (2015–2017), the APY 2016 was analysed; the identified terminology can be considered to reflect recent research efforts in bioprinting. The results showed that the keyword 'Bioink' occurred most frequently (230 occurrences) followed by 'Organoid' and 'ADSC' or 'Adipose Tissue-Derived Stem Cells' (24 occurrences each); 'Cell Spheroid' (19 occurrences); 'GelMA' (9 occurrences); and 'Calcium Ion', 'Concave Microwell', and 'Integrin Binding' (7 occurrences each). Four of these keywords ('GelMA', 'Calcium Ion', 'Concave Microwell', and 'Integrin Binding') are directly related to bioprinting with cell spheroids for the retention of 3D cellular structures[30]. In terms of applications, the most frequent keyword was 'Drug Development' (12 occurrences), which reflects one of the emerging applications of bioprinting[1,9,22].

Finally, a specific outlook of bioprinting trends was developed by considering the following elements: bioprinting techniques, cell sources, and tissue/organs. For this task, a keyword analysis of previously identified

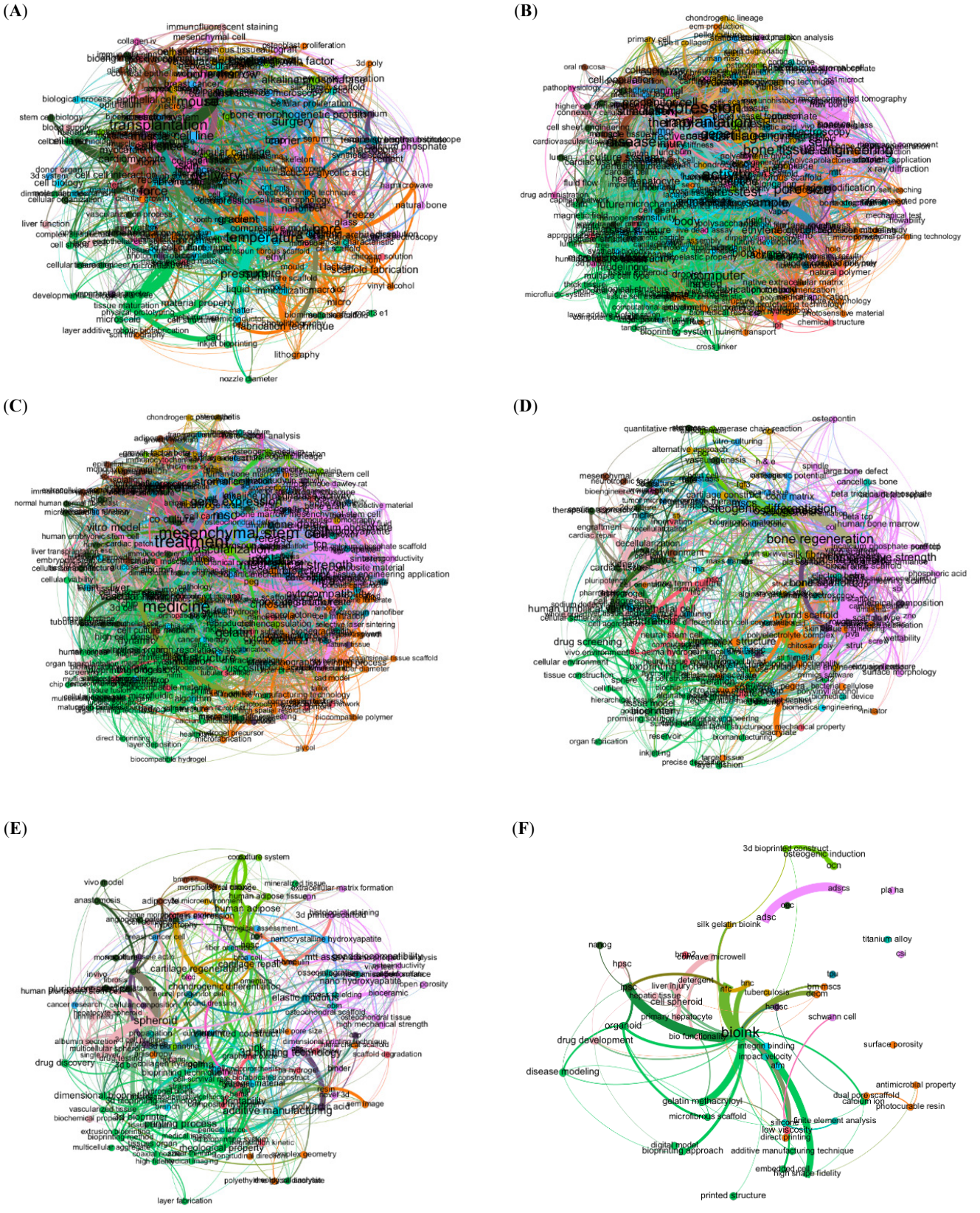

Figure 2. Keyword co-occurrence network maps: (**A**) APY 2011, (**B**) APY 2012, (**C**) APY 2013, (**D**) APY 2014, (**E**) APY 2015, and (**F**) APY 2016.

papers (2000–2017) was developed based on individual APYs with the same range as before (2011–2016).

Tables 4–9 show that for techniques, cell sources, and tissue/organs, the most frequently occurring keywords respectively in APY 2011 were 'Electrospinning' (12 occurrences), 'Bone Marrow Stromal Cell' (26 occurrences), and 'Skeletal Muscle' (34 occurrences); in APY 2012, 'Inkjet Printer' (10 occurrences), 'Fibroblast Cell' (17 occurrences), and 'Graft' (113 occurrences); in APY 2013, 'Inkjet' (26 occurrences), 'Mesenchymal Stem Cells' (MSC) (132 occurrences), and 'Organ' (430 occurrences); in APY 2014, 'Inkjet Printing' (30 occurrences), 'Human Mesenchymal Stem Cells' (HMSC) (78 occurrences), and 'Liver' (84 occurrences); and in APY 2015, 'Extrusion' (59 occurrences), 'Human Adipose Stem Cells' (HASC) (22 occurrences), and

Table 4. Most frequent keywords related to bioprinting techniques, cell sources, and tissue/organs in APY 2011.

APY 2011	Bioprinting techniques (Occurrences)	Cell sources (Occurrences)	Tissue/organs (Occurrences)
1	'Electrospinning Technique' (12)	'Bone Marrow Stromal Cell' (26)	'Skeletal Muscle' (34)
2	'Calcium Deposition' (11)	'Embryonic Stem Cell' (25)	'Bone Construct' (28)
3		'Bone Cell' (21)	'Bone Structure' (25)
4			'Neovascularization' (23)
5			'Xenograft' (12)

Table 5. Most frequent keywords related to bioprinting techniques, cell sources, and tissue/organs in APY 2012.

APY 2012	Bioprinting techniques (Occurrences)	Cell sources (Occurrences)	Tissue/organs (Occurrences)
1	'Inkjet Printer' (10)	'Fibroblast Cell' (17)	'Graft' (113)
2		'Human Bone Marrow Derived Mesenchymal Stem Cell' (HBMSC) (16)	'Muscle' (65)
3		'Stem Cell' (12)	'Heart' (61)
4		'Adult Stem Cell' (11)	'Lung' (34)
5			'Cardiac Cell' (27)

Table 6. Most frequent keywords related to bioprinting techniques, cell sources, and tissue/organs in APY 2013.

APY 2013	Bioprinting techniques (Occurrences)	Cell sources (Occurrences)	Tissue/organs (Occurrences)
1	'Inkjet' (26)	'Mesenchymal Stem Cell' (MSC) (132)	'Organ' (430)
2	'Photon Polymerization' (20)	'Progenitor Cell' (88)	'Bone Tissue Engineering' (148)
3	'Selective Laser Sintering' (12)	'Bone Marrow Derived Mesenchymal Stem Cells' (BMSC) (54)	'Vessel' (142)
4	'Calcium Deposition' (11)	'Stromal Cell' (47)	'Cartilage Tissue Engineering' (74)
5	'Electrospinning Process' (11)	'Bone Marrow Mesenchymal Stem Cell' (33)	'Bone Tissue' (53)

Table 7. Most frequent keywords related to bioprinting techniques, cell sources, and tissue/organs in APY 2014.

APY 2014	Bioprinting techniques (Occurrences)	Cell sources (Occurrences)	Tissue/organs (Occurrences)
1	'Inkjet Printing' (30)	'Human Mesenchymal Stem Cell' (HMSC) (78)	'Liver' (84)
2		'Mesenchymal Stem Cell' (MSC) (60)	'Bone Matrix' (34)
3		'Human Mesenchymal Stem Cell' (50)	'Bone Graft' (33)
4		'Pluripotent Stem Cell' (30)	'Cardiac Tissue Engineering' (19)
5		'Human Umbilical Vein Endothelial Cell' (23)	

Table 8. Most frequent keywords related to bioprinting techniques, cell sources, and tissue/organs in APY 2015.

APY 2015	Bioprinting techniques (Occurrences)	Cell sources (Occurrences)	Tissue/organs (Occurrences)
1	'Extrusion' (59)	'Human Adipose Stem Cell' (HASC) (22)	'Cartilage Regeneration' (30)
2	'Binder' (30)	'Human Adipose' (15)	'Cartilage Repair' (30)
3	'SLM' (11)	'Human Pluripotent Stem Cell' (14)	'Cartilage Construct' (33)
4			'Microtissue' (19)
5			'Neural Tissue Engineering' (18)

Table 9. Most frequent keywords related to bioprinting techniques, cell sources, and tissue/organs in APY 2016.

APY 2016	Bioprinting techniques (Occurrences)*	Cell sources (Occurrences)	Tissue/organs (Occurrences)
1		'Adipose Derived Stem Cell' (ADSC) (21)	'Organoids' (29)
2		'Induced Pluripotent Stem Cell' (IPSC) (17)	
3		'Human Adipose Derived Cell' (13)	
4		'Human Pluripotent Stem Cell' (11)	
5		'Induced Pluripotent Stem Cell' (iPSCS) (11)	

*Note: No keywords were found related to 3D printing techniques as the number of keywords was scarce for this APY.

'Cartilage Regeneration' (30 occurrences). In APY 2016, the number of keywords was scarce and keywords related to techniques were not present; the most frequent keywords for cell sources and tissue/organs were respectively 'Adipose Derived Stem Cells' (ADSC) (21 occurrences) and 'Organoids' (29 occurrences).

4. Conclusions

This study tracked knowledge production in bioprinting from 2000 to 2017 through scientometric analyses of the most complete scientific databases, namely, Scopus and Web of Science, as part of a CTI methodology.

A keyword network map analysis was applied to visualise the co-occurrence of terminology associated with 3D bioprinting and to identify the most frequent keywords in scientific publications. Additionally, the APY was obtained for each keyword to show its usage in recent years. These approaches offered insights into the most commonly used materials, biological elements, applications, and methods in bioprinting.

From APY 2011 to 2016, the papers analysed showed that the most frequently occurring keywords for materials, biological elements, and applications were polylactic acid (PLA) in APY 2014, mesenchymal stem cells (MSC) in APY 2013 and 2014, and bone tissue engineering and bone regeneration respectively in APY 2012 and 2014.

From a general perspective, in APY 2011–2016, the most frequent keywords were 'Treatment' and 'Bioink'. The papers analysed reflected research on cancer, regenerative medicine, and MSC analysis for the former keyword and application of multicellular spheroid deposition and the use of hydrogels like GelMA for the latter keyword.

In the last three years (2015–2017, *i.e.*, APY 2016), studies focused on bioinks, organoids, adipose tissue-derived stem cells (ADSC), and cell spheroids for fabricating complex tissues[9,30]. It should be noted that spheroids have great potential in bioprinting because a spherical shape enhances cell aggregation and promotes cell-to-cell contact[30].

Results of the research trends obtained for bioprinting techniques, cell sources, and tissue/organs (APY 2011–2016) exhibited that for techniques inkjet printing prevailed (APY 2012–2014). Considering the cell sources, two trends were identified, the first one where different types of stem cells are used including 'Mesenchymal Stem Cell' (MSC; APY 2012–2014), 'Bone Marrow Derived Mesenchymal Stem Cells' (BMSC) and 'Human Bone Marrow Derived Mesenchymal Stem Cell' (HBMSC). The second trend shows that 'Human Adipose Stem Cell' (HASC; APY 2015–2016) is applied. On the other hand, it was observed an increasing effort to study fully functional organs. 'Skeletal Muscle' and 'Bone Construct' predominated for the APY 2011, in the following APY (2012) 'Graft' leaded and 'Heart' and 'Lung' were present too. Moreover, 'Organ' leaded for the APY 2013, 'Liver' for the APY 2014, 'Neural Tissue Engineering' for the APY 2015, and 'Organoids' for the APY 2016. In particular, an increased number of studies of organoids are expected because these are small self-organized 3D structures derived from stem cells that can reproduce the functionality of organs[32].

The results of this study present insights into the main trends of scientific published research. These can be valuable to people involved in R&D activities in the 3D bioprinting field.

Conflict of Interest

No conflict of interest was reported by the authors.

References

1. Ventola C L, 2014, Medical applications for 3D printing: Current and projected uses. *P T*, 39(10): 704–711. Available from: http://www.ncbi.nlm.nih.gov/pmc/articles/PMC4189697
2. Banks J, 2013, Adding value in additive manufacturing. *IEEE Pulse*, 4(6): 22–26. http://dx.doi.org/10.1109/mpul.2013.2279617
3. Paterson A M, Bibb R, Campbell R I, *et al*., 2015, Comparing additive manufacturing technologies for customised wrist splints. *Rapid Prototyp J*, 21(3): 230–245. http://dx.doi.org/10.1108/RPJ-10-2013-0099
4. Tan X, Kok Y, Tan Y J , *et al*., 2015, Graded microstructure and mechanical properties of additive manufactured Ti-6Al-4V via electron beam melting. *Acta Materialia*, 97: 1–16. http://dx.doi.org/10.1016/j.actamat.2015.06.036
5. Kolesky D B, Truby R L, Gladman A S, *et al*., 2014, 3D bioprinting of vascularized, heterogeneous cell-laden tissue constructs. *Adv Mater*, 26(19): 3124–3130. http://dx.doi.org/10.1002/adma.201305506
6. Murphy S V, Atala A, 2014, 3D bioprinting of tissues and organs. *Nat Biotechnol*, 32(8): 773–785. http://dx.doi.org/10.1038/nbt.2958
7. Derby B, 2012, Printing and prototyping of tissue and scaffolds. *Science*, 16(338): 921–927. http://dx.doi.org/10.1126/science.1226340
8. Pati F, Jang J, Ha D H, *et al*., 2014, Printing three-dimensional tissue analogues with decellularized extracellular matrix bioink. *Nat Commun*, 5: 1–11. http://dx.doi.org/10.1038/ncomms4935

9. Chatzinikolaidou M, 2016, Cell spheroids: The new frontiers in in vitro models for cancer drug validation. *Drug Discov Today*, 21(9): 1553–1560. http://dx.doi.org/10.1016/j.drudis.2016.06.024
10. Ozbolat I T, 2016, 3D bioprinting: Fundamentals, principles and applications. Academic Press.
11. Small H, 1973, Co-citation in the scientific literature: A new measure of the relationship between two documents. *J Assoc Inf Sci Technol*, 24(4): 265–269. http://dx.doi.org/10.1002/asi.4630240406
12. He Q, 1999, Knowledge discovery through co-word analysis. *Library Trends*, 48(1): 133–159.
13. Trappey A J C, Trappey C V, Lee K L C, 2017, Tracing the evolution of biomedical 3D printing technology using ontology-based patent concept analysis. *Technol Anal Strateg Manag*, 29(4): 339–352. http://dx.doi.org/10.1080/09537325.2016.1211267
14. Rodríguez S M, Hernández de Menéndez A M, Arcos Novillo D A, 2016, Additive manufacturing: Importance and challenges for Latin America, in Anticipating future innovation pathways through large data analysis, Springer, New York, 249–271. http://dx.doi.org/10.1007/978-3-319-39056-7_14
15. Rodríguez-Salvador M, Rio-Belver R M, Garechana-Anacabe G, 2017, Scientometric and patentometric analyses to determine the knowledge landscape in innovative technologies: The case of 3D bioprinting. *PLoS One*, 12(6): e0180375. http://dx.doi.org/10.1371/journal.pone.0180375
16. Elsevier B V, 2016, Scopus: Content coverage guide, viewed 10 November 2015, Avaliable from: https://www.elsevier.com/data/assets/pdf_file/0007/69451/scopus_content_coverage_guide.pdf
17. Norotte C, Marga F S, Niklason L E, *et al*., 2009, Scaffold-free vascular tissue engineering using bioprinting. *Biomaterials*, 30(30): 5910–5917. http://dx.doi.org/10.1016/j.biomaterials.2009.06.034
18. Melchels F P W, Domingos M A N, Klein T J, *et al*., 2012, Additive manufacturing of tissues and organs. Prog Polym Sci, 37(8): 1079–1104. http://dx.doi.org/10.1016/j.progpolymsci.2011.11.007
19. Malda J, Visser J, Melchels F P, *et al*., 2013, 25th anniversary article: Engineering hydrogels for biofabrication. *Adv Mater*, 25(36): 5011–5028. http://dx.doi.org/10.1002/adma.201302042
20. Kang H W, Lee S J, Ko I K, *et al*., 2016, A 3D bioprinting system to produce human-scale tissue constructs with structural integrity. *Nat Biotechnol*, 34(3): 312–319. http://dx.doi.org/10.1038/nbt.3413
21. Jakab K, Norotte C, Marga F, *et al*., 2017, Tissue engineering by self-assembly and bio-printing of living cells. *Biofabrication*, 2(2): 022001. http://dx.doi.org/10.1088/1758-5082/2/2/022001
22. Duan B, Hockaday L A, Kang K H, *et al*., 2013, 3D bioprinting of heterogeneous aortic valve conduits with alginate/gelatin hydrogels. *J Biomed Mater Res A*, 101A(5): 1255–1264. http://dx.doi.org/10.1002/jbm.a.34420
23. Tunkelang D, 2014, Web of science quick reference manual. http://dx.doi.org/10.1145/2615569.2618145
24. Van Eck N J, Waltman L, 2017, VOSviewer manual. Avaliable from: http://www.vosviewer.com/documentation/Manual_VOSviewer_1.6.1.pdf
25. Bastian M, Heymann S, Jacomy M, 2009, Gephi: An open source software for exploring and manipulating networks. Third international AAAI conference on weblogs social media. http://dx.doi.org/10.1136/qshc.2004.010033
26. Leydesdorff L, Rafols I, 2012, Interactive overlays: A new method for generating global journal maps from Web-of-Science data. *J Informetr*, 6(2): 318–332.http://dx.doi.org/10.1016/j.joi.2011.11.003
27. Akhtar N, 2014, Social network analysis tools. in Proceedings-2014 4th International Conference on Communication Systems and Network Technologies, CSNT 2014. http://dx.doi.org/10.1109/CSNT.2014.83
28. Heymann S, Le Grand B, 2013, Visual analysis of complex networks for business intelligence with Gephi. in Proceedings of the International Conference on Information Visualisation. http://dx.doi.org/10.1109/IV.2013.39
29. Shi P, Yong T, Edgar S, *et al*., 2017, Hybrid three-dimensional (3D) bioprinting of retina equivalent for ocular research. *Int J Bioprint*, 3(2): 138–146. http://dx.doi.org/10.18063/IJB.2017.02.008
30. Sriphutkiat Y, Kasetsirikul S, Zhou Y, 2018, Formation of cell spheroids using standing surface acoustic wave (SSAW). *Int J Bioprint*, 4(1): 1–12. http://dx.doi.org/10.18063/ijb.v4i1.130
31. Nguyen D, Hgg D A, Forsman A, *et al*., 2017, Cartilage tissue engineering by the 3D bioprinting of iPS cells in a nanocellulose/alginate bioink. *Sci Rep*, 7(1): 1–10. http://dx.doi.org/10.1038/s41598-017-00690-y
32. Barbuzano J, 2017, Organoids: A new window into disease, development and discovery. viewed 6 June 2018. Avaliable from: https://hsci.harvard.edu/organoids