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Three Dimensional (3D) Printing: A Scientometric Assessment of Global Publications Output during 2007-16

B.M. Gupta[#,*] and S.M. Dhawan[$]

[#]*CSIR-NISTADS, Delhi, India*
[$]*CSIR-National Physical Laboratory, Delhi, India*
[*]*E-mail: bmgupta1@gmail.com*

ABSTRACT

The papers provides quantitative and qualitative description of three dimensional (3D) printing research based on global publications output (7309 publications) in the field as indexed in Scopus database covering the 10-year period 2007-2016. 3D printing research registered 54.61 per cent growth per annum and averaged 10.59 citations per papers in 10 years, and bulk of global output (93.79 %) in the field emanates from just top 16 countries. The papers further provides an insight into qualitative performance of 3D printing research in terms of relative citation index, citations per papers, highly cited papers, top 25 global organisations and authors in the field, most favoured subjects in the field, and most favoured materials, technologies, and applications used in the field. The study concludes that 3D printing is the next revolution in industrial manufacturing led by USA and China. Asian and Pacific countries should take initiatives to support 3D printing research through appropriate policy and funding mechanisms as well as encourage research teams to collaborate with leading international hubs in 3D printing research.

Keywords: 3D printing; Materials science; Global publications; Scientometrics; Bibliometrics

1. INTRODUCTION

Three dimensional (3D) printing is about building 3D objects of virtually any shape from a digital model or file by successively creating layers of material on top of each other. 3D printing is also known as rapid prototyping or additive manufacturing. 3D printing is a disruptive technology that has transformed prototype manufacturing in a major way, offering the industry new and inexpensive avenues to convert 3D CAD design to a real life functional objects, and creating complex three dimensional shapes in a smart and cost effective way. 3D printing technologies replaces traditional machine tool based subtractive processes such as molding, casting, and cutting, used earlier in creating prototypes. 3D printing finds applications across various industries such as architecture, construction, industrial design, automotive, aerospace, military, engineering, civil engineering, dental and medical industries, biotech (human tissue replacement), fashion, footwear, jewelry, eyewear, education, geographical information systems, food and many other fields[1].

3D printing offers compelling business opportunities for companies to grow. Innovative designing, high adaptability levels, less time to market, the ability to manufacture parts without expensive tooling, and reduced turnaround time for making a prototype are some of the factors that are driving industry for early adoption of 3D printing. Instead of outsourcing prototyping process, which in the past used to result in additional costs and increased turnaround time, original equipment manufacturers can now print a prototype overnight and at one fourth of the cost using 3D printing. Polymers are the most preferred 3D print materials because of their flexibility and strength. Metals are expected to be adopted as 3D print material in the future, as components that need to withstand high temperature and pressure can be manufactured using 3D printers with metals as print material. However, 3D printers cannot be used for mass manufacturing, owing to the size constraint. A 3D printer will not be able to print more than one object at a time[2].

The 3D printing market is segmented on the basis of technology, material, application, and region. The 3D printing technology segment includes technologies such as stereo-lithography (SLA), laser sintering, electron beam melting (EBM), fused disposition modelling (FDM), laminated object manufacturing (LOM), three dimensional inkjet printing (3IDP), and other technologies. The material segment includes materials such as polymers, metals/alloys, and others (glass, ceramics, wood, and composites). The application segment includes prototyping and tooling, R&D and innovation, manufacturing complex components, and others (customisation, personalisation, and aftermarket)[2].

1.1 Literature Review

Very few quantitative studies are so far available in the literature on bibliometric/scientometric analysis of 3D printing research covering publications and patents. Zhao[3], *et*

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al. in their study on 3D printing based on publications data sourced from WoS database covering the period 1984-2014 described growth of publications, their distribution by sub-fields and identification of most productive organisations, etc. Another publication from *Technology Insight*[1] analysed patent activity covering 3D printing research (since 1990), focusing on identifying research trends in processes patented and their applications from various perspectives. Similarly a report from UK Intellectual Property Office[4] analysed 9145 global published patents from over 4000 patent families from 1980 to 2013, it identified patent issuing countries, top inventor countries, top patent assignees, application type, top international patent classification sub-groups, patents with high citations, patent landscaped with areas of interest of countries and top applicants, collaboration between top patent assignees, etc. It also analysed 1066 records from non-patent literature covering the period 2008-13. Hornick[5] analysed 3D printing related patents issued since 1995, and patent applications published since 2001. It reported their distribution by sector, technology, inventor and company name. Xu[6], *et al.* studied both Chinese patents and publications in 3D printing during 1981-2015. It observed that China ranked top as the most productive countries accounting for 39 per cent global publications and patents share, and 2nd top with 32 per cent global research and innovations share. Singh[7], *et al.* reviewed recent advances in materials and technological innovations in 3D printing and discussed patents filed in 3D printing sub-fields, such as materials, and their applications along with industry-wise patent trends. Besides 3D printing, bibliometric studies analysing publication output in sub-fields of materials science such as meta-materials[8], graphene[9], nano-materials[10] and rare earths[11].

2. OBJECTIVES

The main aim of this study is to describe the qualitative and qualitative performance of 3D printing research based on publications as indexed in Scopus database during 2007-16. The study in particular, focuses on objectives such as – publication analysis in terms of annual global output, annual and absolute growth, citation analysis in terms of citation impact of research output, analysis in terms of global share of top 16 most productive countries, their citations share, citation impact, analysis in terms of distribution of publication output by broad sub-fields, distribution by materials used, technologies used, and applications, analysis in terms of productivity and citation impact of top 25 most productive organisations and authors, analysis in terms of media of research communications, and characteristic bibliographic features of top 114 highly cited papers.

3. METHODOLOGY

The data for the present study in 3D printing research was retrieved and downloaded from the Scopus database (http://www.scopus.com) covering 10 year period 2007-16. Keywords for search included such as "3D printing'' and "Three Dimensional Printing''. These keywords were suffixed to "keyword tag", "source title tag", and the search output refined by period '2007-16' using "date range tag". This main search strategy was further refined by country to identify top 16 most productive countries in 3D printing research. The global search output was distributed by subject, collaborating countries, author-wise, organisation-wise and journal-wise, etc. by using analytical provisions of Scopus database such as "subject area tag", "country tag", "source title tag", "journal title name" and "affiliation tag". For citation data, citations to publications were counted from date of their publication till 11 February 2018. Separate search strategies were formulated to get data on 3D technologies, materials used and applications in different fields. The study analysed the publications data across a series of raw and relative bibliometric indicators with a view to understand the dynamics of 3D printing research. A complete counting method, wherein every contributing author or organisation covered in multiple authorship papers was fully counted was used. All authors or organisations to multi-authored papers have received equal credit in data counting and analysis. The data for the study was derived on 11-12 February 2018.

(((KEY("3D Printing'') OR TITLE("3D Printing'')) AND PUBYEAR > 2006 AND PUBYEAR < 2017) or ((KEY("Three Dimensional Printing'') OR TITLE("Three Dimensional Printing'')) AND PUBYEAR > 2006 AND PUBYEAR < 2017))

4. ANALYSIS

The global research output in field of 3D printing cumulated to 7309 publication in 10 year during 2007-16. 3D printing research registered 54.61 per cent growth per annum, up from 80 in 2007 to 2792 publication in 2016, and averaged 10.5924 citations per papers in years. Five-year absolute growth by 675.33 per cent in the field reaffirms that 3D printing research followed a growing trend during five-year period 2007-11 to 2012-16, up from 835 in 2007-11 to 6474 publication in 2012-16 as shown in Table 1.

Of the total publications, 54.28 per cent appeared as articles, 33.90 per cent as conference papers, 4.88 per cent as reviews, 1.93 per cent as notes, 1.74 per cent as book chapters, 1.12 per cent as short notes and others as editorials (72), letters (41), articles in press (20), book (14) and erratum (10) as shown in Table 1.

4.1 Top 16 Most Productive Countries in 3D Printing

3D printing research has been found to have spread to as many as 90 countries, of which 43 countries published 1-10 papers, 23 country 11-50 papers, 8 country 51-100 papers, 13 country 101-500 papers and 3 country 501-2200 papers. However bulk of research output (93.79 %) in the field still comes from just 16 most productive countries. The USA leads the ranking with 32.03 per cent global publications share, followed distantly by China (13.85 % share). All others are single digit growth countries including UK and Germany (7.94 % and 7.51 %), Japan and South Korea (4.79 % and 4.49 %), Canada (3.32 %), Australia, Singapore, Italy, France and Taiwan (from 2.27 % to 2.90 %) during 2007-16 as shown in Table 2. Except for China and Taiwan, the remaining top 14 country scored relative citation index above average. Compared to the world average impact of 10.59 citations per papers, these top

16 countries averaged their citation impact 13.1 citations per papers, demonstrating thereby that these top 16 countries play major role in making quantitative and qualitative contributions to 3D printing research. Further, these top 16 countries publish 18 per cent to 48 per cent share of their country output as international collaborative papers.

Table 1. World publication output and citations count in 3D printing research, 2007-16

Publication period	World		
	TP	TC	CPP
2007	80	141	1.76
2008	141	3664	25.99
2009	209	4762	22.78
2010	188	4936	26.26
2011	217	4060	18.71
2012	270	6269	23.22
2013	419	7208	17.20
2014	1099	15574	14.17
2015	1894	17942	9.47
2016	2792	12855	4.60
2007-11	835	17563	21.03
2012-16	6474	59848	9.24
2007-16	7309	77411	10.59

TP=Total Papers; TC=Total Citations; CPP=Citations Per Papers

4.2 Subject-Wise Distribution of Research Output

Engineering is the most favoured subject in 3D printing research (with 53.76 % publications share), followed distantly by materials science (29.44 %), computer science (22.44 %), medicine (19.17 %), physics and astronomy (15.64 %), biochemistry, genetics and molecular biology (11.15 %), chemical engineering (9.67 %), etc. during the period as shown in Fig. 1 and Table 3.

These 14 sub-field of 3D printing research (as identified in Scopus database classification) witnessed fluctuations in their activity index during 2007-11 to 2012-16 compared to world average index of 100. In most sub-fields their activity index changed above and below to world average in 2012-16 compared to their corresponding status in 2007-11. Chemical engineering recorded the highest citation impact per papers of 25.86, followed by biochemistry, genetics & molecular biology (23.22), chemistry (22.54), materials science (15.75), etc. as shown in Fig. 1 and Table 3.

4.3 Distribution of Publications by Applications Type, Technology Type and Material Used

Medical application is the most favoured topic in 3D printing research accounting for the highest number of publications (1401), followed by mechanical (1175), tissue engineering (974), scaffolding (864), prosthesis (482), robotics (347), construction (313), mobile or phone (150), printed circuit board (143), aerospace (120), automobile (100), food industry (97), Defense (73), clothing (66), aircraft (50), Hand tool (40), shoe (14), Jewelry (12), furniture (10), etc. during 2007-16.

Fused deposition modeling is the most used technology in

Table 2. Global publication output and share of top 16 most productive country in 3D printing during 2007-16

Country	Number of Papers			Share of Papers			TC	CPP	ICP	%ICP	RCI
	2007-11	2012-16	2007-16	2007-11	2012-16	2007-16	2007-16				
USA	240	2101	2341	28.74	32.45	32.03	36018	15.39	515	22.00	1.45
China	116	896	1012	13.89	13.84	13.85	7511	7.42	274	27.08	0.70
UK	62	518	580	7.43	8.00	7.94	6408	11.05	221	38.10	1.04
Germany	93	456	549	11.14	7.04	7.51	6899	12.57	194	35.34	1.19
Japan	63	287	350	7.54	4.43	4.79	3884	11.10	65	18.57	1.05
South Korea	43	285	328	5.15	4.40	4.49	5397	16.45	91	27.74	1.55
Canada	19	224	243	2.28	3.46	3.32	2683	11.04	75	30.86	1.04
Australia	13	199	212	1.56	3.07	2.90	3594	16.95	88	41.51	1.60
Singapore	14	195	209	1.68	3.01	2.86	3931	18.81	73	34.93	1.78
Italy	12	188	200	1.44	2.90	2.74	2441	12.21	96	48.00	1.15
France	19	147	166	2.28	2.27	2.27	1893	11.40	75	45.18	1.08
Taiwan	29	126	155	3.47	1.95	2.12	826	5.33	30	19.35	0.50
Netherlands	21	118	139	2.51	1.82	1.90	3310	23.81	67	48.20	2.25
Switzerland	20	112	132	2.40	1.73	1.81	2381	18.04	58	43.94	1.70
Spain	8	113	121	0.96	1.75	1.66	1296	10.71	46	38.02	1.01
India	26	92	118	3.11	1.42	1.61	1316	11.15	32	27.12	1.05
Total	798	6057	6855	95.57	93.56	93.79	89788	13.10	2000	29.18	1.24
World	**835**	**6474**	**7309**				**77411**	**10.59**			

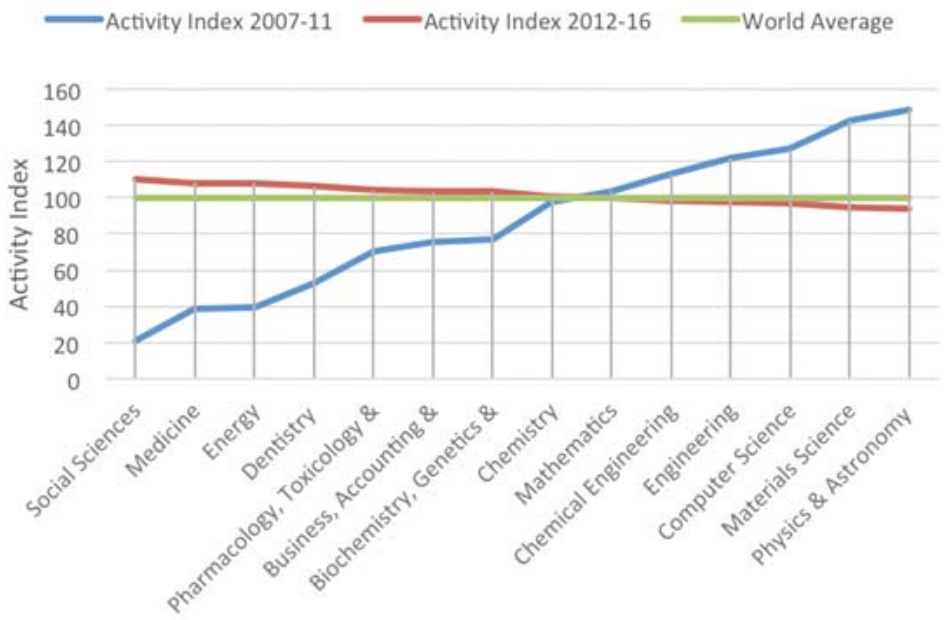

Figure 1. Changes in activity index of subjects under 3D printing research during 2007-16

3D printing accounting for the highest of publications (393), followed by direct manufacturing (239), photo-lithography (98), micro-fabrication (92), stereo-lithography (75), digital light processing (61), laser ablation (51), laser powder forming (42), direct laser forming (37), computer numerical control (32), laser metal forming (30), plastic based 3D printing (20), laminated object manufacturing (17), cladding (13), contour crafting (9), multi-photon lithography and robo-casting (7 each), electrophoretic deposition(6), etc.

'Plastic as a material' is the most used material in 3D printing research accounting for highest number of 575 publications, followed by ceramic (281), titanium (218), thermoplastic (176), aluminum (167), steel (141), photo-polymers (140), (134), silver (133), elastomers (129), polyethylene (118), stainless steel (76), epoxy (63), carbon fiber (49), nickel (46), rubber (45), nylon and polyamide (37 each), fiber glass (36), polypropylene (33), clay (21), polyethylene terephthalate (18), etc.

4.4 Top 25 Most Productive Global Organisations

About 2803 organisations participated in 3D printing research during 2007-16, of which 2027 published 1-5 papers each, 458 organisations 6-10 papers each, 241 organisations 11-20 papers each, 63 organisations 31-50 papers each, 13 organisations 51-100 papers each and 1 organisation more than 100 papers during 2007-16. The productivity of top 25 most productive organisations varied from 40 to 133 publications per organisation; together they contributed 19.58 per cent (1431) global publications share and 36.20 per cent (28022) global citations share during 2007-16. Their scientometric profile is presented in Table 4.

Twelve organisations registered their international collaborative publications share (ICP) above the group average (33.26 %) of all organisations : CNRS Centre National de la Recherche Scientifique, France (54.55 %), Brigham and Women's Hospital, USA (48.94 %), National University of Singapore (48.94 %), Tsinghua University, China (45.31 %), Georgia Institute of Technology, USA (44.44 %), Harvard Medical School, USA (43.84 %), Massachusetts Institute of Technology, USA (42.39 %), Zhejiang University, China (41.67 %), University College of London, UK (38.60 %), Harvard University, USA (38.10 %), ETH, Zurich, Switzerland (36.36 %) and Technical University Munchen, Germany (33.33 %) during 2007-16.

Table 3. Subject-Wise Breakup of Global Publications in 3D Printing during 2007-16

Subject*	Number of Papers (TP)			Activity Index		TC	CPP	%TP
	2007-11	2012-16	2007-16	2007-11	2012-16		2007-16	
Engineering	546	3383	3929	121.64	97.21	43599	11.10	53.76
Materials Science	349	1803	2152	141.96	94.59	33902	15.75	29.44
Computer Science	237	1403	1640	126.50	96.58	9297	5.67	22.44
Medicine	61	1340	1401	38.11	107.98	13881	9.91	19.17
Physics & Astronomy	194	949	1143	148.57	93.74	11723	10.26	15.64
Biochemistry, Genetics & Molecular Biology	78	810	888	76.89	102.98	20620	23.22	12.15
Chemical Engineering	91	616	707	112.67	98.37	18284	25.86	9.67
Chemistry	59	471	530	97.44	100.33	11946	22.54	7.25
Mathematics	55	410	465	103.53	99.54	2133	4.59	6.36
Social Sciences	5	210	215	20.36	110.27	1065	4.95	2.94
Business, Accounting & Management	16	170	186	75.30	103.19	1017	5.47	2.54
Pharmacology, Toxicology & Pharmaceutics	14	161	175	70.03	103.87	2600	14.86	2.39
Dentistry	9	141	150	52.52	106.12	2083	13.89	2.05
Energy	6	129	135	38.90	107.88	983	7.28	1.85
World Output	835	6474	7309					

Table 4. Scientometric profile of top 25 most productive global organisations in 3D printing research during 2007-16

Organisation	TP	TC	CPP	ICP	%ICP	RCI
Nanyang Technological University, Singapore	133	2754	20.71	31	23.31	1.96
Massachusetts Institute of Technology, USA	92	2413	26.23	39	42.39	2.48
Georgia Institute of Technology, USA	81	1097	13.54	36	44.44	1.28
Harvard Medical School, USA	73	2197	30.10	32	43.84	2.84
Tsinghua University, China	64	1003	15.67	29	45.31	1.48
Harvard University, USA	63	2570	40.79	24	38.10	3.85
Zhejiang University, China	60	999	16.65	25	41.67	1.57
Huazhong University of Science & Technology, China	58	558	9.62	19	32.76	0.91
University College of London, UK	57	877	15.39	22	38.60	1.45
Ministry of Education, China	56	520	9.29	13	23.21	0.88
University of Texas at El Paso, USA	56	1169	20.88	5	8.93	1.97
Pohang University of Science & Technology, South Korea	54	1565	28.98	16	29.63	2.74
Cornell University, USA	54	897	16.61	13	24.07	1.57
Brigham and Women's Hospital, USA	47	1611	34.28	23	48.94	3.24
National University of Singapore	47	590	12.55	23	48.94	1.19
Loughborough University, UK	46	250	5.43	11	23.91	0.51
Virginia Polytechnic Institute & State University, USA	46	676	14.70	6	13.04	1.39
Technical University Munchen, Germany	45	519	11.53	15	33.33	1.09
CNRS Centre National de la Recherche Scientifique, France	44	461	10.48	24	54.55	0.99
Xian Jiatong University , China	44	1330	30.23	9	20.45	2.85
ETH, Zurich, Switzerland	44	1196	27.18	16	36.36	2.57
Peking University, China	43	315	7.33	8	18.60	0.69
University of Washington, Seattle, USA	43	1018	23.67	12	27.91	2.24
University of California, San Diego, USA	41	1036	25.27	13	31.71	2.39
Shanghai Jiao Tong University, China	40	401	10.03	12	30.00	0.95
Total of 25 organisations	1431	28022	19.58	476	33.26	1.85
Total of World	7309	77411	10.59			
Share of top 25 organisations in World total output	19.58	36.20				

Eleven organisations registered their relative citation index above the group average (1.85) of all organisations: Harvard University, USA (3.85), Brigham and Women's Hospital, USA (3.24), Xian Jiatong University , China (2.85), Harvard Medical School, USA(2.84), Pohang University of Science & Technology, South Korea (2.74), ETH, Zurich, Switzerland (2.57), Massachusetts Institute of Technology, USA (2.48), University of California, San Diego, USA (2.39), University of Washington, Seattle, USA (2.24), University of Texas at El Paso, USA (1.97), Nanyang Technological University, Singapore (1.96) during 2007-16

4.5 Top 25 Most Productive Authors

About 3644 authors participated in 3D printing research during 2007-16, of which 3214 author published 1-5 papers each, 367 author 6-10 papers each, 59 author 11-30 papers each and 4 author 31-50 papers each. The research productivity of top 25 most productive author varied from 15 to 45 publication per author. Together they contributed 7.74 per cent (566) global publications share and 18.98 per cent (14695) global citations share during 2007-16. Their detailed scientometric profile is presented in Table 5.

Eight of top 25 author registered their publications output above the group average of 22.64: C.K. Chua (Singapore)(45 papers), D.W. Cho (S. Korea) (42 papers), M.M. Tentzeris (USA)(33 papers), W.Y. Yeong (Singapore) (31 papers), C.B. Williams (USA) and R.B. Wicker (USA)(29 papers each), J.A. Lewis (USA) (27 papers) and D. Li (China) (23 papers) during 2007-16.

Nine of top 25 author contributed their share of international collaborative publications above the group average of 22.44 per cent of all authors: W. Sun (China)(76.47 %), E. Vorndran (Germany) (62.5 %), U.Gbureck (Germany) (60.0 %), M.M. Tentzeris (USA) (57.58 %), A. Khademhosseini (USA) (50.0 %), P. Greil (Germany) (46.67 %), D.W. Cho (S.Korea) (26.19 %), J. He (China) (25.0 %) and S. Chen (USA) (23.53 %) during 2007-16.

Ten of top 25 author registered their relative citation index above the group average (2.45) of all authors: J.A. Lewis(USA) (8.94), J.H. Shim (South Korea) (4.59), U. Gbureck (Germany) (3.92), S. Chen (USA) (3.59), A. Khademhosseini (USA) (3.56), J. Jang (South Korea) (3.54), J.M. Pearce (USA) (3.29), C.K. Chua (Singapore) (3.18), D.W. Cho (South Korea) (2.89) and E. Vorndran (Germany) (2.64) during 2007-16. Eight of top 25 organisations registered their publications output greater than the group average of 57.24: Nanyang Technological University, Singapore (133 papers), Massachusetts Institute of Technology, USA (92 papers), Georgia Institute of Technology, USA (81 papers), Harvard Medical School, USA (73 papers), Tsinghua University, China (64 papers), Harvard University, USA (63

Table 5. Scientometric profile of top 25 most productive authors in 3D printing research during 2007-16

Author	Affiliation of the Author	TP	TC	CPP	HI	ICP	% ICP	RCI
C.K. Chua	Nanyang Technological University, Singapore	45	1515	33.67	15	10	22.22	3.18
D.W. Cho	Pohang University of Science & Technology, South Korea	42	1284	30.57	18	11	26.19	2.89
M.M. Tentzeris	Georgia Institute of Technology, USA	33	168	5.09	8	19	57.58	0.48
W.Y. Yeong	Nanyang Technological University, Singapore	31	509	16.42	12	1	3.23	1.55
C.B. Williams	Virginia Tech, USA	29	596	20.55	11	4	13.79	1.94
R.B. Wicker	University of Texas at El Paso, USA	29	711	24.52	15	2	6.90	2.32
J.A. Lewis	Harvard University, USA	27	2557	94.70	21	2	7.41	8.94
D. Li	Xian Jiatong University, China	23	134	5.83	7	5	21.74	0.55
A. Khademhosseini	Brigham & Women's Medical Hospital, USA	22	829	37.68	12	11	50.00	3.56
H. Lipson	Cornell University, USA	22	508	23.09	11	0	0.00	2.18
J. Suwanprateeb	National Science & Technology Development Agency, Thailand	22	267	12.14	8	0	0.00	1.15
U. Gbureck	Abteilung fur Funktionwerkstoffe, Germany	20	830	41.50	15	12	60.00	3.92
J.H. Shim	Korea Polytechnic University, South Korea	19	924	48.63	13	3	15.79	4.59
R. Singh	Guru Nanak Dev Engineering College, Ludhiana, India	19	154	8.11	7	0	0.00	0.77
J. Straub	University of North Dakota, USA	19	70	3.68	15	0	0.00	0.35
L.G. Zhang	George Washington University, USA	18	217	12.06	8	1	5.56	1.14
S. Chen	University of California, San Diego, USA	17	646	38.00	11	4	23.53	3.59
J.M. Pearce	Michigan Technological University, USA	17	593	34.88	11	1	5.88	3.29
W. Sun	Tsinghua University, China	17	302	17.76	9	13	76.47	1.68
J. He	Xian Jiatong University, China	16	79	4.94	5	4	25.00	0.47
D. Huson	University of West of Bristol, UK	16	25	1.56	4	2	12.50	0.15
J. Jang	Pohang University of Science & Technology, South Korea	16	599	37.44	10	2	12.50	3.54
E. Vorndran	University of Wurzburg, Germany	16	448	28.00	11	10	62.50	2.64
W. Zhu	University of California, San Diego, USA	16	406	25.38	10	3	18.75	2.40
P. Greil	University of Erlangen-Nuremberg, Germany	15	324	21.60	10	7	46.67	2.04
Total		566	14695	25.96	11.08	127	22.44	2.45
Total of World		7309	77411	10.59				
Share of 25 Authors in World Total Output		7.74	18.98					

papers), Zhejiang University, China (60 papers) and Huazhong University of Science & Technology, China (58 papers) during 2007-16.

4.6 Medium of Research Communication

Of the total world output in 3D printing research, 62.98 per cent (4603) appeared in journals, 28.96 per cent (2117) in conference proceedings, 3.98 per cent (291) in book series, 2.27 per cent (166) in trade publications and 1.79 per cent (131) as book. Of the 1034 journal which reported 4603 article, 884 published 1-5 papers each, 85 published 6-10 papers each, 39 published 11-20 papers each, 21 published 21-50 papers each and 5 published 51-100 papers each during 2007-16. The top 20 most productive journal accounted for 16.58 per cent share of total 3D printing output that appeared in journal medium during 2007-16, which increased from 15.38 per cent to 16.70 per cent between 2007-11 and 2012-16. The top most productive journal (with 99 papers) was *Biofabrication*, followed by *Rapid Prototyping Journal* (70 papers), *Advanced Materials* (70 papers), *ACS Applied Materials & Interfaces* (58 papers), etc. during 2007-16 as shown in Table 6.

4.7 Highly Cited Papers

Of the total world output in 3D printing research (7309 publications), only 114 (1.56 % share) cumulated 101 to 973 citations per papers (cumulative total 21996 citations) since their publication during 2007-16, averaging to 192.95 citations per papers. The distribution of 114 highly cited papers is skewed. Eighty nine papers cumulated citations in the range 101-200 per papers, 18 papers were in citation range 201-400, 4 papers in citation range 401-600 and 3 papers were in citation range 701-973.

Of the 114 highly cited papers, 36 resulted from contribution by single organisations per papers (non-collaborative papers) and 78 from two or more organisations per papers (42 national collaborative and 36 international collaborative papers).

Among highly cited papers, USA collaborated in the largest number of papers (67 papers), followed by Germany (11 papers), South Korea (10 papers), Australia and Netherland (9 papers each), Singapore and UK (7 papers each), Japan (6 papers), China (5 papers), Canada (4 papers), Belgium, France, India, Italy and Switzerland (3 papers each), Brazil, Finland and Israel (2 papers each), etc.

The 114 highly cited papers belonged to 656 authors and

Table 6. Top 20 most productive journals in 3D printing research during 2007-16

Journal	Number of Papers		
	2007-11	2012-16	2007-16
Bio-fabrication	7	92	99
Rapid Prototyping Journal	16	54	70
Advanced Materials	13	57	70
ACS Applied Materials & Interfaces	2	56	58
Lab on a Chip	0	55	55
Biomaterials	14	31	45
PLOS One	0	43	43
Acta Biomaterialia	3	36	39
Chinese Journal of Tissue Engineering	0	36	36
Virtual & Physical Prototyping	3	28	31
ACM Transactions on Graphics	0	30	30
International Journal of Advanced Manufacturing	7	23	30
Journal of Craniofacial Surgery	1	27	28
Chinese Journal of Reparative & Reconstructive Surgery	0	27	27
ACS Biomaterials Science & Engineering	0	26	26
Nature	0	26	26
3D Printing & Additive Manufacturing	0	25	25
Scientific Reports	0	25	25
Advanced Functional Materials	6	19	25
Journal of Micro-mechanics & Micro-engineering	5	19	24
Total of 20 journals	66	697	763
Total global journal output	429	4174	4603
Share of top 20 journals in global journal output	15.38	16.70	16.58

278 organisations. The leading organisations participating in highly cited papers were: Harvard Medical School, USA (8 papers), Massachusetts Institute of Technology, USA (7 papers), Harvard University, USA, Brigham & Women's Hospital, USA and University of Illinois at Urbana-Champaign (6 papers each), University of Texas at El Paso, USA (4 papers), Georgia Institute of Technology, USA, Pohang University of Science & Technology, South Korea and ETH, Zurich, Switzerland eth (3 papers), etc.

The leading authors participating in highly cited papers were: J.A. Lewis (USA) (9 papers), A. Khademhosseini (USA), R.B. Wicker (USA) and J.A. Rogers (USA) (3 papers each), C.K. Chua (Singapore), D.W. Cho (South Korea), H. Gbureck (Germany), J.H. Shim (South Korea), J.M. Pearce (USA) (2 papers each), etc.

Of the 114 highly cited papers, 92 were published as articles, 15 as review papers, 3 each as book and conference papers and 1 as short survey.

These 114 highly cited papers appeared across 56 journals, of which 15 papers were published in *Biomaterials* (IF=5.51), 14 in *Advanced Materials* (IF=15.78), 5 papers each in *Bio-fabrication* (IF=4.67) and ACM Transactions on Graphics (IF=4.99), 4 papers each in *Nature Communication* (IF=11.329) and *Science* (IF-34.661) (4 papers each), 3 papers each in *Analytical Chemistry* (IF=5.886), *Tissue Engineering-Part C* (IF=2.58) and *Biotechnology and Bioengineering* (IF=4.243), 2 papers each in *Lab on a Chip* (6.045), *Materials and Design* (IF=4.364), *Nature Biotechnology* (IF=43.113) and *Dental Materials* (IF=4.07) and 1 papers each in 40 other journal.

5. CONCLUSION

Conclusively, 3D printing is the next revolution in industrial manufacturing led by USA and China. USA, China, UK, Germany, and Japan which dominate the field with two-third of the world output, 66.12 per cent global publications share. The remaining top 11 countries account for less than one-third, 27.88 per cent global publications share. Interestingly, countries like Netherland, USA, Singapore, Australia and South Korea dominate 3D printing research more in qualitative terms compared to the rest of the world. In order that Asian and Pacific countries including South Korea, Australia, Singapore, Taiwan and India are able to become more competitive and perform better in future, stakeholders across such nations should support 3D printing research through appropriate policy and funding mechanisms as well as encourage research teams to collaborate with leading international hubs in 3D printing research. India in particular should take initiative to come up with a national action plan for advancement of 3D printing in the country. At present its global publications share is just 1.61 per cent.

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CONTRIBUTORS

Dr B.M. Gupta received his BLibSci, Associateship in Documentation and PhD from Karnataka University. He is a recipient of the Fullbright Professional Fellowship in Library and Information Science (1999) and Fellow of the Society for Information Science (2007). Retired Scientist G and Emeritus Scientist from CSIR- NISTADS, Delhi in 2013. He has published more than 200 research paperss mainly in the area of scientometrics in journals and conferences.
Contribution in the current study : Data collection, analysis and jointly writing the paper with co-author.

Dr S.M. Dhawan received his MSc (Physics) from Sardar Patel University, MLIS from University of New York, USA, and PhD in Library Science. He superannuated as Scientist 'F' from CSIR-National Physical Laboratory, Delhi in 2005. He has worked for innovation supporting library transformation into digital era and in addition has successfully completed several biliometric/scientometric projects. He has authored several research paperss, research reports covering several areas of library science, library management systems and scientometrics.
Contribution in the current study, Jointly writing the paper with co-author.