Quantum Sensing Research: A Scientometric Assessment of Global Publications during 1991-2020

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ABSTRACT

The study presents a global research scenario in the domain of quantum sensing in quantitative and qualitative terms. The study is based on an analysis of 588 global publications in the field, sourced from the Scopus database for the period 1991-2020. The study identified key countries, organizations and authors, network collaborative linkages at national, institutional, and author level. In addition, it identified broad subject areas intersecting quantum sensing research, key journals for research communications, and broad characteristics of highly-cited papers. The study finds that the USA and Germany lead the world ranking in quantum sensing research with a combined share of 50% to the global output. The USA, Germany, and Italy are the home countries to 13 of the top 15 most productive organizations, and also the home countries to 14 of the top 15 most productive authors in the subject. The top journals publishing most research publications are Physical Review A, Physical Review Letters and New Journal of Physics. However, in the most cited journals list in the subject, Agriculture & Forest Meterology, Science and Physical Review A tops the list.

1. Introduction

Quantum sensing deals with quantum measurement, exploring the use of quantum properties in single particles to measure a broad range of physical quantities, and to set higher levels of measurement accuracy, far beyond what was the limit previously perceived by uncertainty principle (Degen, Reinhard & Cappellaro, 2017). Quantum sensing uses quantum technologies to design and engineer drastically improved sensors and measuring devices (Pirandola et al., 2018). Quantum sensors promise far more accuracy in measurements than conventional sensors. Quantum sensors promise new detection capabilities, detecting even the tiniest electrical signals in the human body, monitoring brain activity on the go, and detecting underground signals that will have applications in civil engineering and resource extraction including oil and gas. It will now be possible to have ultra-accurate navigation,

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even underwater, and sense changes in gravity thereby revealing potential earthquakes or volcanic activity, climate change. Above all, it will be possible to measure physical quantities against atomic properties, so there is no drift or need to calibrate (CNRS, 2021; NATO, 2020; Tetienne & Hall, 2021). In brief, quantum sensing finds innovative applications in as diverse fields as metrological standards, biological imaging, navigation systems, detailed underground mapping, next generation detectors, and autonomous cars (Fuentes & Bouyer, 2021). Quantum sensing not only have important commercial applications, they have potential to improve our everyday life and will also deepen our understanding of nature. Given the disruptive role that quantum sensing technologies are going to play in the near future, it will be worthwhile that a bibliometric study be undertaken to analyze and evaluate the global literature in quantum science research with the aim to identify the key players in this research at global, national, institutional, and individual scientist level.

2. Literature Review

As seen from the literature, no bibliometric study has been published till date on the topic assessment and evaluation of national and global research on quantum sensing. However, quite a few studies on similar topics have already been undertaken, such as quantum technologies, quantum computing (4703 global publications during 2007-16) quantum machine learning (1374 global publications during 1999-20), quantum neural networks (546 global records during 1990-19), quantum cryptography (10801 publications during 1992-20), quantum electronics (10115 records since 2008), quantum information processing (2000-17), quantum robotics (650 global records during 1993-20) and quantum dots (Dhawan, Gupta & Mamdapur, 2018; Dhawan, Gupta & Mamdapur, 2021; Gupta & Dhawan, 2020a; Dhawan, Gupta & Mamdapur, 2021; Ibrahim, Julius & Choudhury, 2021; Terekhov, 2020; Gupta & Dhawan, 2020b; Gupta, Dhawan & Mamdapur, 2021; Seskir & Aydinoglu, 2021; Tolcheev, 2018). Given the fact that no study has been undertaken till date in quantum sensing, the authors thought it appropriate to fill the gap and accordingly undertake this study to assess and evaluate global literature in the subject on metrics.

3. Objectives

The study seeks to understand the status and performance of global research in the domain of quantum sensing at global, national, institutional, and individual author level based on select indicators derived from publications and citation data in the subject. The data for the study has been sourced from the Scopus international database for the period 1991-2020. For research evaluation, the publicatio ns data on quantum sensing will be analyzed on a number of parameters (i) distribution of publications by type and source, (ii) publication growth rate- annual and cumulative, (iii) quantify citation impact of publications in terms of citations per paper, relative citation index, and share of highly-cited papers (iv) identify the most productive countries in the world, (v) distribution of publications by broad subjects and significant keywords, (vi) identify and profile of most productive organizations and the most productive authors in the world, (vii) identify top channels for research communication, and (viii) describe the bibliographic characteristics of highly-cited papers in the subject.

4. Methodology

The Scopus database (https://www.scopus.com) is used in this study for sourcing publication and citation data on the topic of quantum sensing research. A comprehensive search strategy was developed for identifying, retrieving, and downloading publications metadata. The keywords "quantum sensing" and "quantum sensors" were clubbed to field tags "Keyword" and "Title" (Article Title). The search output was confined to global search limited to the publication period '1991-20'. Subsequentl y, the search output was refined by the publication country name, one by one, to identify and generate a list of top 10 most productive countries of the world in this subject. The search yielded 588 global records, which were downloaded in csv file format to be further analyzed using statistical methods. The analytical provisions of the Scopus database were used to generate statistics on the publications output by broad subject areas, collaborating countries, contributing authors, affiliating organizations, and source journals, etc. The citations to each publication were counted from the date of their publication till 27.2.2021. The study examined the performance of the most productive countries, organizations, authors and journals on select bibliometric indicators. The VOS viewer and biblioshiny app for bibliometrix were used to evaluate and visualize the interactions among most productive countries/territories, organizations, authors and keywords. (TITLE ("quantum sensor*" or "quantum sensing") OR KEY ("quantum sensor*" or "quantum sensing")) AND (EXCLUDE (PUBYEAR, 2021)).

5. Analysis and Results

5.1 Publication and Citation Analysis

The global research in the domain of quantum sensing accumulated a total of 588 publications, an average of 19.6 publications per year during 1991-2020. The research in the subject: (i) registered a 14.85% annual average growth, (ii) its annual output increased in publication volume from just 1 to 121 during 1991-2020 and (iii) its 15-year cumulative output increased by 16.37.5% from 32 in 1991-05 to 556 in 2006-20. Of the total output, the largest share appeared as articles and conference papers (55.27% and 35.54%), respectively. The remaining output appeared as reviews (3.74%), conference reviews (2.55%), book chapters (1.19%), letters and short surveys (0.51% each) and book, editorial, note and erratum (0.17% each). The quantum sensing research registered a citation impact of 12.04 citations per paper (CPP) since publication during 1991-2020. Its citation impact in a 15 year window since publication was the highest, at 18.63 CPP in 1991-2005, which slipped to 11.66 CPP in 2006-2020 (**Table 1**).

Of the total 588 publications, 253 (43.03%) had resulted from sponsored research projects funded by 100+ national and international funding agencies. The number of funded papers increased in publication volume from 3 in 1991-2005 to 250 in 2006-20. The bulk of the funded papers, 73.52% share, appeared during the last 3 years.

The sponsored research papers received a total of 3640 citations since their publication, registering a citation impact of 14.39 citations per paper, marginally above the world average of 12.04 CPP. The leading funding agencies in quantum sensing research were: National Science Foundation (45 papers), European Research Council (32 papers), Deutsche Forschungsgemeinschaft and European Commission (24 papers each), Horizon 2020 Framework Program (21 papers), National Natural Science Foundation of China (20 papers), Japanese Society for Promotion of Science (18 papers), etc.

Table 1. Quantum sensing research: global publications output and citations 1991-2020

Publication Period	TP	TC	CPP	FP	Publication Period	TP	TC	CPP	FP
1991	1	12	12.00		2010	10	34	3.40	1
1992	1	9	9.00		2011	14	541	38.64	3
1993	3	240	80.00		2012	17	245	14.41	3
1997	1	9	9.00		2013	16	155	9.69	6
1998	2	5	2.50		2014	20	635	31.75	1
1999	1	5	5.00		2015	26	435	16.73	7
2000	2	120	60.00	2	2016	30	697	23.23	10
2001	3	24	8.00		2017	61	1337	21.92	31
2002	1	58	58.00		2018	88	941	10.69	56
2003	7	78	11.14	1	2019	120	462	3.85	61
2004	6	18	3.00		2020	121	194	1.60	69
2005	4	18	4.50		1991-2005	32	596	18.63	3
2006	5	32	6.40		2006-2020	556	6483	11.66	250
2007	9	84	9.33		1991-2020	588	7079	12.04	253
2008	8	492	61.50	1					
2009	11	199	18.09	1					

TP=Total Papers; TC=Total Citations; CPP=Citations Per Paper; FP=Funded Papers

5.2 Top 10 most productive countries

The global research in the domain of quantum sensing witnessed the participation of 48 countries across the world. The distribution of research by country of publication is skewed: 31 countries contributed 1-10 papers each, 14 countries 11-50 papers each and 2 countries 108-206 papers each.

The USA and Germany lead the global ranking with 35.03% and 18.37% global share respectively, followed by the U.K., China, Italy, Japan, France and Australia (from 5.27% to 9.86%), Russia Federation and Switzerland (4.76% and 3.91%). Five of the top 10 countries registered their relative citation index above the group average (1.23): Switzerland (6.02), Australia (1.46), U.K. (1.41), USA (1.39) and Germany (1.27). The international collaborative papers (ICP) as a share of national output of top 10 countries varied from 27.18% to 72.41%, with an average of 47.62% (**Table 2**).

Table 2. Quantum sensing research: top 10 most productive countries 1991-2020

S. No	Name of the Country	TP	TC	CPP	HI	ICP	%ICP	%TP	RCI	TCL
1	USA	206	3442	16.71	28	56	27.18	35.03	1.39	73
2	Germany	108	1657	15.34	17	62	57.41	18.37	1.27	108
3	U.K.	58	982	16.93	15	42	72.41	9.86	1.41	70
4	China	50	188	3.76	8	18	36.00	8.50	0.31	25
5	Italy	47	351	7.47	9	22	46.81	7.99	0.62	32
6	Japan	38	199	5.24	9	19	50.00	6.46	0.43	27
7	France	36	163	4.53	9	21	58.33	6.12	0.38	45
8	Australia	31	545	17.58	10	18	58.06	5.27	1.46	26
9	Russia Federation	28	87	3.11	5	8	28.57	4.76	0.26	14
10	Switzerland	23	1666	72.43	11	14	60.87	3.91	6.02	21
	Total of 10 countries	625	9280	14.85	12.1	280	47.62	106.29	1.23	441
	World total	588	7079	12.04			27.18	100.00		

TP=Total Publications; TC=Total Citations; CPP=Citations per Paper; HI= Herch Index; TCL=Total Collaborative Linkages; ICP=International Collaborative Publications; RCI=Relative Citation Index

5.2.1 Collaborative linkages among top 10 countries

All of the top 10 most productive countries collaborated in quantum sensing research; their one-to-many collaborative linkages count varied from 17 to 330. Their one-to-one collaborative linkages, between two countries constitute a total of 441 linkages and these varied from 14 to 108. Germany, the USA and the U.K. registered the largest number of collaborative linkages (108, 73 and 70) with other countries. Similarly, Russia Federation, Switzerland and China registered the lowest number of collaborative linkages (14, 21 and 25) with other countries. Among the leading country-to-country collaborations, the Germany-France topped the list, registered the highest number of collaborative linkages (14), followed by the USA-Germany (13 linkages), Germany-U.K. (12 linkages), USA-U.K. (9 linkages), Germany-China (7 linkages), USA-Italy, Germany-Italy, Germany-Japan, Germany-Switzerland, U.K.-France, U.K.-Australia and Italy-France (6 linkages each), etc (**Table 3**). A total 47 countries were engaged in Quantum Sensing research. A visual map network interactions among top ten countries was created using VOS viewer tool. The collaborative linkages for Germany were the maximum 71 (9 nodes), followed by the USA 47 (9 nodes) and the U.K. 43 (8 nodes). These top 10 collaborating countries appear in two clusters as shown in **Fig. 1**. The thickness of links between the countries coupled with the distance between them represents the degree of their collaboratio n in research. The bigger the diameter of a network country node and its font size, the bigger its weight in research collaboration.

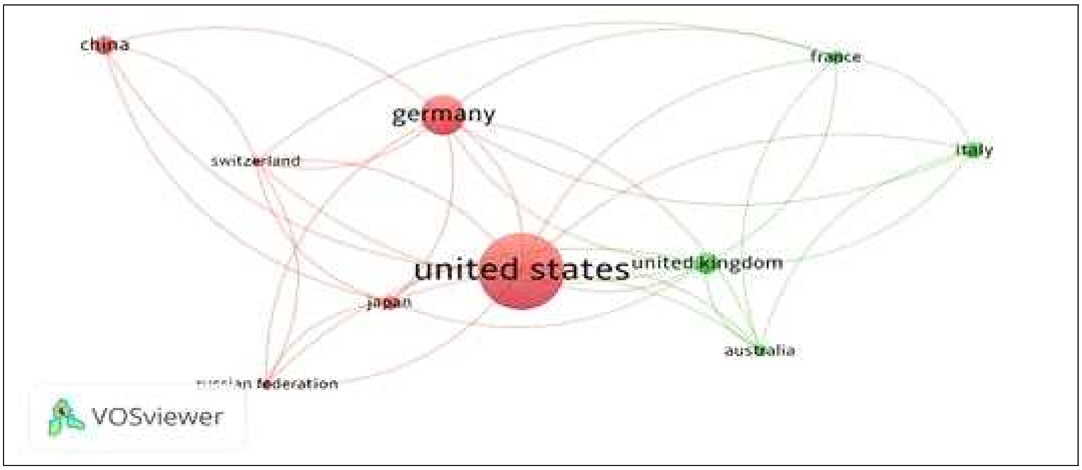

Fig. 1. Country-wise collaboration network visualization

Table 3. Quantum sensing research: collaborative linkages among most productive countries 1991-2020

S. No	Name of the Country	Collaborative linkages with other countries	TCL(NOC)
1	USA	2(13), 3(9), 4(1), 5(6), 6(4), 7(2), 8(4), 9(4), 10(4)	47(9)
2	Germany	1(13), 3(12), 4(7), 5(6), 6(5), 7(14), 8(4), 9(4), 10(6)	71(9)
3	U.K.	1(9), 2(12), 5(4), 6(3), 7(6), 8(6), 9(2), 10(1)	43(8)
4	China	1(1), 2(7), 6(1), 10(1)	10(4)
5	Italy	1(6), 2(6), 3(4), 7(6), 8(2)	24(5)
6	Japan	1(4), 2(5), 3(3), 4(1), 5(4), 8(2), 9(1), 10(2)	20(8)
7	France	1(2), 2(14), 3(6), 5(6), 8(2), 10(2)	32(6)
8	Australia	1(4), 2(4), 3(6). 5(2), 6(4), 7(2),	22(6)
9	Russia Federation	1(4), 2(4), 3(2), 6(1), 10(1)	12(5)
10	Switzerland	1(4), 2(6), 3(1), 4(1), 6(2), 7(2), 9(1)	17(7)

TCL=Total Collaborative Linkages; NOC=Number of Countries

5.3 Subject-wise distribution

The Scopus database classified the global output on the topic of quantum sensing in 7 broad disciplines (**Table 3**). Physics & Astronomy, Engineering and Materials Science are the top subject areas intersecting with quantum sensing research. They accounted for 76.02%, 45.07% and 42.52% for global share respectively in the subject, followed by Computer Science and Mathematics (21.43% and 17.18%), Chemistry and Biochemistry, Genetics & Microbiology (8.67% and 7.65%) during 1992-2020. In terms of research activity index between 1991-2005 and 2006-2020, the subjects which showed a jump in their research activity in 11 years were: Physics & Astronomy, Engineering Materials Science, Chemistry and Biochemistry, Genetics & Microbiology. Besides, Computer Science and Mathematics showed a decline in research activity during the period. Of the top ten subjects, Chemistry registered the highest citation impact per paper (25.9 CPP) and Biochemistry, Genetics & Molecular Biology subject the lowest (1.48 CPP) (**Table 4**).

Table 4. Quantum sensing research: subject-wise breakup of global publications 1999-2020

S.No	Subject	Number of Papers			Activity Index		TC	CPP	%TP
		1991-05	2006-20	1991-2020	1991-05	2006-20	1999-2020		
1	Physics & Astronomy	14	433	447	57.55	102.44	5051	11.30	76.02
2	Engineering	14	251	265	97.08	100.17	1185	4.47	45.07
3	Materials Science	12	238	250	88.20	100.68	1323	5.29	42.52
4	Computer Science	11	115	126	160.42	96.52	394	3.13	21.43
5	Mathematics	11	90	101	200.12	94.24	359	3.55	17.18
6	Chemistry	0	51	51	0.00	105.76	1321	25.90	8.67
7	Biochemistry, Genetics & Molecular Biology	2	343	45	10.65	105.14	510	1.48	7.65
	Total	32	556	588	100.00	100.00	7079	12.04	100.00

TP=Total Publications; TC=Total Citations; CPP=Citations per Paper

5.3.1 Significant keywords

The top 43 keywords (assumed to be significant) were identified from the global literature (588) on quantum sensing research (**Table 4**). These keywords, considered as research hot-spots, provide a secondary approach to identify research trends in the domain of quantum sensing. The frequency of keyword occurrence in the quantum sensing literature for 1991-2020 was the maximum (250) for ‘Quantum Sensors’, followed by ‘Quantum Sensing’ (132), ‘Quantum Optics’ (110), ‘Quantum Theory’ (90), ‘Quantum Entanglement’ (81), ‘Photons’ (62), ‘Nitrogen Vacancy Center’ (55), ‘Nitrogen Vacancies’ (51), etc (**Table 5**). A co-occurrence relationship chart of top keywords is shown in **Fig. 2**. The size of each node (associated to a keyword) is proportional to the number of documents where the keyword appears. Keywords co-occurrence chart created using VOS viewer software formed four clusters. Red and green colour clusters with 15 items each, blue colour with 11 items and yellow colour with 2 items as shown in **Fig. 2**.

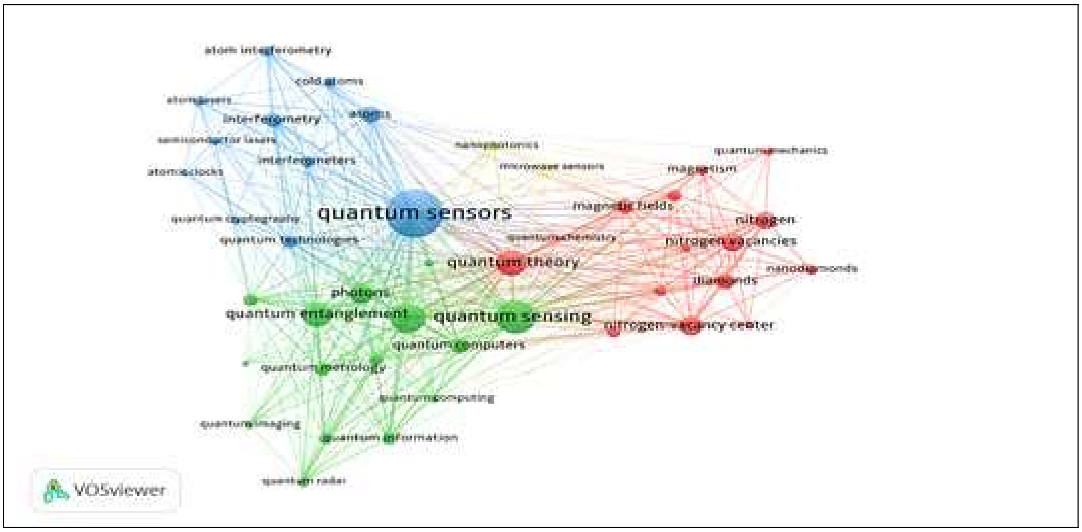

Fig. 2. Keywords Co-occurrence Networks chart on Quantum Sensing research from 1991 to 2020.

Table 5. List of top 43 significant keywords appearing in global quantum sensing literature

S.No	Name of the Keyword	Frequency	S.No	Name of the Keyword	Frequency	S.No	Name of the Keyword	Frequency
1	Quantum Sensors	250	16	Quantum Technologies	29	31	Quantum Mechanics	15
2	Quantum Sensing	132	17	Magnetometry	28	32	Semiconductors Lasers	15
3	Quantum Optics	110	18	Quantum Information	28	33	Quantum Electronics	14
4	Quantum Theory	90	19	Quantum Communication	26	34	Sensing Applications	14
5	Quantum Entanglement	81	20	Sensors	25	35	Nanophotonics	13
6	Photons	62	21	Dynamical Decoupling	24	36	Quantum Imaging	13
7	Nitrogen Vacancy Center	55	22	Interferometers	24	37	Nanomagnetics	12
8	Nitrogen Vacancies	51	23	Spin Dynamics	22	38	Quantum Computing	12
9	Nitrogen	50	24	Radar	21	39	Quantum Cryptography	12
10	Atoms	45	25	Atom Inferometry	20	40	Atomic Clocks	12
11	Diamonds	45	26	Cold Atoms	20	41	Microwave Sensors	11
12	Interferometry	36	27	Magnetism	20	42	Quantum Chemistry	11

13	Quantum Computers	36	28	Nano-Diamonds	20	43	Semiconductor Quantum Dots	9
14	Magnetic Fields	33	29	Atom Lasers	17			
15	Quantum Meterology	32	30	Quantum Radar	17			

5.4 Top 15 most productive organizations

In all, a total of 293 organizations were found to have participated in quantum sensing research during 1991-2020. Of these, 231 organizations published 1-5 papers each, 40 organizations 6-10 papers each, 18 organizations 11-20 papers each and 5 organizations 21-36 papers each. Of the top 15 most productive global organizations in quantum sensing research, 4 each were from the USA, Germany and Italy and 3 from France. The research productivity of top 15 most productive organizations in the subject varied from 12 to 36 publications per organization; together they contributed a 35.52% (488) global publications share and a 76.62% (17190) global citations share during the period. The scientometric profile of top 15 most productive organizations is presented in (**Table 6**). On further analysis, it was observed that (i) Five of the 15 organizations contributed publications above average productivity (18.13) of all 15 organizations: Naval Research Lab., USA (36 papers), Massachusetts Institute of Technology, USA (34 papers), University of Ulm, Germany (30 papers), Gottfried Wilhelm Leibniz Universitat Hannover, Germany (27 papers) and Humboldt-Universitat zu Berlin, Germany (21 papers); and (ii) Two of the top 15 organizations performed, in terms of citation per paper and relative citation index, above their group average (12.82 and 1.06 respectively): Massachusetts Institute of Technology, USA (38.76 and 3.22) and University of Ulm, Germany (19.4 and 1.61).

Table 6. Scientometric profile of 15 most productive organizations in quantum sensing research 1991-2020

S.No	Name of the Organization	TP	TC	CPP	HI	ICP	ICP (%)	RCI	TCL
1	Naval Research Lab., USA	36	273	7.58	10	10	27.78	0.63	31
2	Massachusetts Institute of Technology, USA	34	1318	38.76	14	11	32.35	3.22	49
3	University of Ulm, Germany	30	582	19.40	11	23	76.67	1.61	107
4	Gottfried Wilhelm Leibniz Universitat Hannover, Germany	27	294	10.89	7	13	48.15	0.90	104
5	Humboldt-Universitat zu Berlin, Germany	21	174	8.29	5	8	38.10	0.69	95
6	CNRS, France	17	196	11.53	7	9	52.94	0.96	111
7	Consiglio Nazionale delle Ricerche, Italy	16	72	4.50	5	7	43.75	0.37	74
8	National Institute of Standards & Technology, USA	15	121	8.07	6	3	20.00	0.67	38
9	Ferdinand-Braun Institut Leibniz-Institut fur Ho Hochstfrequenztechnik, Germany	14	79	5.64	3	1	7.14	0.47	35

10	LENS European Lab for Non-Linear Spectroscopy, Italy	14	138	9.86	6	10	71.43	0.82	74
11	L'Observatoires de Paris, France	13	113	8.69	6	7	53.85	0.72	97
12	Systemes de Reference Temps-Espace, France	13	113	8.69	6	7	53.85	0.72	91
13	Universersita degli Studi di Firenze, Italy	13	94	7.23	5	9	69.23	0.60	75
14	University of Missouri, USA	12	39	3.25	4	8	66.67	0.27	26
15	CNR-Instituto Nazionale di Ottica, Italy	12	73	6.08	6	4	33.33	0.51	38
	Total of 15 organizations	287	3679	12.82	6.73	130	45.30	1.06	1045
	Global total	588	7079	12.04					
Share of top 15 organizations in global total		48.81	51.97						

TP=Total Publications; TC=Total Citations; CPP=Citations per Paper; HI= Herch Index; TCL=Total Collaborative Linkages; ICP=International Collaborative Publications; RCI=Relative Citation Index

5.4.1 Institutional collaboration linkages among top 15 organizations

The top 15 most productive organizations collaborated in quantum sensing research. Their combined collaborative linkages strength is 145 and it varied from 26 to 111 linkages per organization. The strength of collaborative linkages between one-to-one organizations varied from 1 to 13 (**Table 7**). CNRS, France, University of Ulm, Germany and Gottfried Wilhelm Leibniz Universitat Hannover, Germany registered the highest number of collaborative linkages (111, 107 and 104). Similarly, University of Missouri, USA, Ferdinand-Braun Institut Leibniz-Institut fur Ho Hochstfrequenztechnik, Germany and Naval Research Lab., USA registered the lowest linkages (26, 31 and 36). In terms of one-to-many organizations links, -- Humboldt-Universitat zu Berlin, Germany and Ferdinand-Braun Institut Leibniz-Institut fur Ho Hochstfrequenztechnik, Germany and L'Observatoires de Paris, France and Systemes de Reference Temps-Espace, France -- registered the highest number of collaborative linkages (13 each), followed by Naval Research Lab., USA and University of Missouri, USA and LENS European Lab for Non-Linear Spectroscopy, Italy and Universersita degli Studi di Firenze, Italy (12 linkages each), Gottfried Wilhelm Leibniz Universitat Hannover, Germany and Humboldt-Universitat zu Berlin, Germany and Gottfried Wilhelm Leibniz Universitat Hannover, Germany and Humboldt-Universitat zu Berlin, Germany (11 linkages each), CNRS, France and L'Observatoires de Paris, France and CNRS, France and Systemes de Reference Temps-Espace, France (9 linkages each), etc. The collaborative networks between 15 top institutes were mapped through biblioshiny tool and represented in **Fig. 3**. The box represents each note and its size depends upon the number of its publications and the lines indicates the links between collaborating institutions. The various colors in the visualization networks represent the cooperation clusters. The largest cluster (in green) represents the University of Ulm, Germany, Gottfried Wilhelm Leibniz Universitat Hannover, Germany, Humboldt-Universitat zu Berlin, Germany and Ferdinand-Braun Institut Leibniz-Institut fur Ho Hochstfrequenztechnik, Germany.

Table 7. Quantum sensing research: collaborative linkages among most productive organiztions 1991-2020

S. No	Name of the Organization	Number of Collaborative linkages with other organizations	TCL(NOC)
1	Naval Research Lab., USA	14(12)	12(1)
2	Massachusetts Institute of Technology, USA	7(2), 10(3), 13(3)	8(3)
3	University of Ulm, Germany	4(7), 5(5), 10(1), 12(1)	14(4)
4	Gottfried Wilhelm Leibniz Universitat Hannover, Germany	3(7), 5(11), 6(4),7(1), 8(1), 9(3), 11(4), 12(4)	35(8)
5	Humboldt-Universitat zu Berlin, Germany	3(5), 4(11), 6(2), 7(1), 9(13), 10(4), 11(4), 12(4), 13(4)	48(9)
6	CNRS, France	3(2), 4(4), 5(2), 7(1), 9(1), 10(2), 11(9), 12(9), 13(2),	32(9)
7	Consiglio Nazionale delle Ricerche, Italy	2(2), 4(1), 5(1), 6(1), 9(1), 10(3), 11(1), 12(1), 13(4), 15(8)	23(10)
8	National Institute of Standards & Technology, USA	4(1), 10(1), 13(1)	3(3)
9	Ferdinand-Braun Institut Leibniz-Institut fur Ho Hochstfrequenztechnik, Germany	4(3), 5(13), 6(1), 7(1), 10(1), 11(1), 13(1)	21(7)
10	LENS European Lab for Non-Linear Spectroscopy, Italy	2(3), 4(4), 5(4), 6(2), 7(3), 8(1), 9(1), 11(4), 13(12), 15(4)	38(10)
11	L'Observatoires de Paris, France	4(4), 5(4), 6(9), 7(1), 9(1), 10(4), 12(13), 13(4)	40(8)
12	Systemes de Reference Temps-Espace, France	3(1), 4(4), 6(9), 5(4), 7(1), 9(1), 10(4), 11(13), 13(4)	41(9)
13	Universersita degli Studi di Firenze, Italy	2(3), 3(1), 4(4), 5(4), 6(2), 7(4), 8(1), 10(12), 11(4), 12(4), 15(4)	43(11)
14	University of Missouri, USA	1(12)	12(1)
15	CNR-Institute Nazionale di Ottica, Italy	2(3), 7(8), 10(4), 13(4)	19(4)

TCL=Total Collaborative Linkages; NOO=Number of Organizations

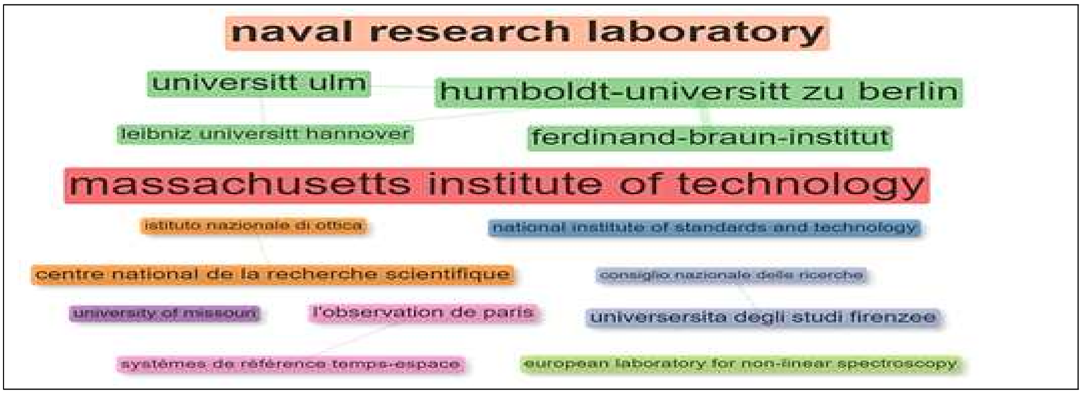

Fig. 3. Institutional collaboration networks chart on quantum sensing research

5.5 Top 15 most productive authors

In all, a total of 389 authors contributed to global research in the domain of quantum sensing during 1991-2020. Of these, 342 authors published 1-5 papers each,34 authors 6-10 papers each, 12 authors 11-20 papers each and 1 author 21 papers. Of the top 25 authors, 6 were from Germany, 4 each from Italy and USA and 1 from Israel. The research productivity of the top 15 most productive authors varied from 9 to 21 publications per author. Together they accounted for a 34.18% (201) global publications share and a 40.26% (2850) global citations share. The scientometric profile of top 15 most productive organizations is presented in (**Table 8**).

On further analysis, it was observed that: (i) Six of top 15 authors contributed publications above the average productivity (13.4) of all 15 organizations: A. Peters (21 papers), M. Lanzagorta (20 papers), J.F. Smith (16 papers), F. Jelezko and A. Wicht (15 papers each) and P. Cappellars (14 papers); (ii) Five authors registered citation per paper and relative citation index above their group average (14.18 and 1.18): P. Cappellars (61.79 and 5.13), F. Jelezko (26.47 and 2.20), A. Retzker (19.73 and 1.64), G.M.Tino (19.40 and 1.61) and M.B. Plenio(16.75 and 1.39).

Table 8. Scientometirc profile of top 15 most productive in quantum sensing research 1991-2020

S.No	Name of the Author	Affiliation of the Author	TP	TC	CPP	HI	ICP	ICP (%)	RCI	TCL
1	A. Peters	Humboldt-Universitat zu Berlin, Germany	21	174	8.29	5	8	38.10	0.69	303
2	M. Lanzagorta	Naval Research Lab, USA	20	121	6.05	6	10	50.00	0.50	33
3	J. F. Smith	Naval Research Lab., USA	16	152	9.50	8	0	0.00	0.79	0
4	F. Jelezko	University of Ulm, Germany	15	397	26.47	7	13	86.67	2.20	82
5	A. Wicht	Ferdinand-Braun-Institut, Leibniz-Institut Fur Hochsfreqienzrecnik, Germany	15	88	5.87	4	1	6.67	0.49	125
6	P. Cappellars	Massachusetts Institute of Technology, USA	14	865	61.79	9	7	50.00	5.13	46
7	J. Uhlmann	Naval Research Lab, USA	13	39	3.00	4	8	61.54	0.25	29
8	W. Ertmer	Gottfried Wilhelm Leibniz Universitat Hannover, Germany	12	113	9.42	4	8	66.67	0.78	198
9	M. B. Plenio	University of Ulm, Germany	12	201	16.75	6	5	41.67	1.39	58
10	M. Barbieri	Universitat degli Studi Roma Tre, Italy	11	52	4.73	4	1	9.09	0.39	76
11	I. Gianani	Universitat degli Studi Roma Tre, Italy	11	52	4.73	4	1	9.09	0.39	76
12	E. M. Rasel	Gottfried Wilhelm Leibniz Universitat Hannover,	11	146	13.27	5	10	90.91	1.10	215

		Germany								
13	A. Retzker	Hebrew University of Jerusalem, Israel	11	217	19.73	7	8	72.73	1.64	45
14	G. M. Tino	LENS European Lab for Non-Linear Spectroscopy, Italy	10	194	19.40	5	6	60.00	1.61	104
15	V. Cimini	Universitat degli Studi Roma Tre, Italy	9	39	4.33	4	6	66.67	0.36	71
			201	2850	14.18	5.47	92	45.77	1.18	1461
			588	7079	12.04					
			34.18	40.26						

TP=Total Publications; TC=Total Citations; CPP=Citations per Paper; HI= Herch Index; TCL=Total Collaborative Linkages; ICP=International Collaborative Publications; RCI=Relative Citation Index

5.5.1 Collaborative linkages among top 15 authors

All of the top 15 most productive authors, except two, collaborated in quantum sensing research. Their combined collaborative linkages strength is 1461 links and it varied from 17-72 links per author. The number of collaborative linkages between one-to-one authors varied from 4 to 13 (**Table 9**). A. Peters, E. M. Rasel and W. Ertmer registered the highest number of collaborative linkages (303, 215 and 198. J. Uhlmann, M. Lanzagorta and A. Retzker registered the lowest collaborative linkages (29, 33 and 45) among top 15 authors. Among the author to author collaboration linkages, A. Peters and A. Wicht and M. Lanzagorta and J. Uhlmann registered the highest number of collaborative linkages (13 each), followed by A. Peters – E. M. Rasel, W. Ertmer – E. M. Rasel, M. Barbieri – I. Gianani and A. Peters – E. M. Rasel (11 linkages each), each. As seen from collaborative network of top 15 authors was mapped by using the biblioshiny tool (**Fig. 4**). The thickness of the box (node) is proportional to its number of collaborative publications. The bigger the box size and the text font size, the more the number of collaborative publications. The map suggested that there has been active collaboration amongst the most productive authors.

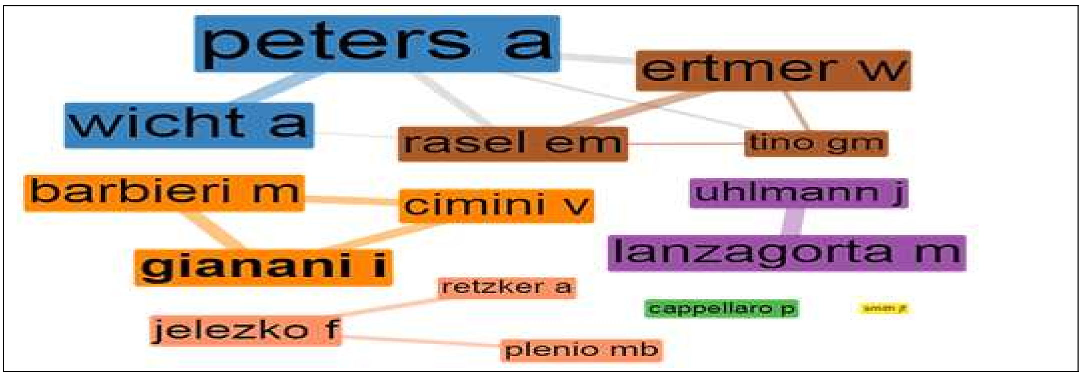

Fig. 4. Collaborative linkages network of top authors on Quantum Sensing research from 1991 to 2020.

Table 9. Quantum sensing research: collaborative linkages among top 15 most productive authors

S. No	Name of the Author	Number of collaborative linkages with other authors	Total Collaborative linkages
1	A. Peters	5(13), 8(9), 12(11), 14(4)	37(4)
2	M.Lanzagorta	7(13)	13(1)
3	J.F.Smith	Nil	Nil
4	F.Jelezko	9(5), 13(6)	11(2)
5	A.Wicht	1(13)	13(1)
6	P.Cappellars	Nil	Nil
7	J.Uhlmann	2(13)	13(1)
8	W.Ertmer	1(9), 12(11), 14(4)	24(3)
9	M.B.Plenio	4(5)	5(1)
10	M.Barbieri	11(11), 15(9)	20(2)
11	I.Gianani	10(11), 15(9)	20(2)
12	E.M.Rasel	1(11), 8(11)	22(2)
13	A.Retzker	4(6)	6(1)
14	G.M.Tino	1(4), 8(4)	8(2)
15	V.Cimini	11(9)	9(1)

5.6 Channels of research communication

Of the total world output in quantum sensing research, 59.52% (350) appeared in 141 journals, 36.73% (216) in conference proceedings, 1.87% (11) in book series, 1.02% (6) as books and 0.85% (5) in trade journals. Of the 141 journals, 130 published 1-5 papers each, 5 published 6-10 papers each, 4 published 11-20 papers each and 2 journals published 21-28 papers each during 1991-2020.

The top 15 most productive journals accounted for a 48.0% share of the global output in quantum sensing research during the period. The top 5 most productive journals were: Physical Review A (30 papers), Physical Review Letters (28 papers), New Journal of Physics (23 papers), Physical Review Applied (17 papers) and Nano Letters (11 papers). The top 5 most impactful journals were: Agriculture & Forest Meterology (69.67), Science (42.17), Physical Review A (34.0), Nature Communic ation (30.56) and Physical Review Letters (25.07). A list of top 15 most productive journals is shown in **Table 10**.

Table 10. List of top 15 most productive journals in quantum sensing

Agriculture & Forest Meteorology, Physical Review Letters and Science and 1 paper each in *Angewandte Chimie-International Edition, Annual Review of Physical Chemistry, Contemporary Physics, Nature Photonics., New Journal of Physics, Physical Review A and Review of Modern Physics*

S. No	Name of the Journal	TP	TC	CPP
1	Physical Review A	30	579	19.30
2	Physical Review Letters	28	702	25.07
3	New Journal of Physics	23	285	12.39
4	Physical Review Applied	17	70	4.12
5	Nano Letters	11	247	22.45
6	Nature Communication	9	275	30.56
7	Quantum Science & Technology	8	11	1.38
8	ACS Photonics	6	77	12.83
9	Agriculture & Forest Meteorology	6	418	69.67
10	Science	6	253	42.17
11	Applied Physics Letters	5	59	11.80
12	Journal of Physics B	5	26	5.20
13	Physical Review X	5	96	19.20
14	Scientific Reports	5	23	4.60
15	EPJ Quantum Technology	4	27	6.75
	Total of 15 top journals	168	3148	18.74
	Global total papers in journals	350		
	Share of top 15 journals in global total	48.0		

TP=Total Publications; TC=Total Citations; CPP=Citations Per Paper

5.7 Highly-cited papers

Of the total 588 global publications on quantum sensing research during 1991-2020, only 13 (2.21% share) registered 102 to 604 citations per paper (assumed here as highly-cited papers). These 13 highly cited papers received a total of 2891 citations, since their publication, an average of 222.38 citations per paper. The distribution of citations across 13 highly cited papers is highly skewed: 9 papers each registered citations in the range 102-149 and 4 papers in citation range 203-604. Among the 13 highly cited papers (11 articles and 2 reviews), 4 involved zero collaboration and 1 resulted from national collaboration and 8 from international collaboration. Among 13 highly cited papers, USA contributed the highest number of papers (6), followed by Germany, Switzerland and U.K. (4 papers each), Australia (2 papers), Canada, Costa Rica, Denmark, Estonia, France, Netherland, Singapore and Spain (1 paper each). Among 13 highly-cited papers, 3 papers each have been contributed by MIT, USA, University of Ulm, Germany and ETH, Zurich. 10 journals account for 13 highly cited papers. Of these, the largest number of papers 2 each) has been published in *Agriculture & Forest Meteorology, Physical Review Letters and Science* and 1 paper each in *Angewandte Chimie-International Edition, Annual Review of Physical Chemistry, Contemporary Physics, Nature Photonics., New Journal of Physics, Physical Review A and Review of Modern Physics.*

6. Summary and Conclusion

The study analyses the global output in quantum sensing research on metrics with the aim to understand its status and performance at national, institutional, and author level. The study identified key players in quantum sensing research such as key countries, key institutions, key authors, and key areas of research. The study also presented a visual view of network collaborative relationships between key players. The global research on this theme comprised a total of 588 publications in the 30-year period 1991-2020. The global research registered a 14.85% annual average growth, its 15-year cumulative output increased by 16.37%, and its research received an average of 12.04 citations per paper (CPP) since publication during the period. A 43.03% share of global output appeared as sponsored research papers. Although participation in quantum sensing research is global (with a participation of 48 countries), but only the top two countries (the USA and Germany) account for a 50% share. The other productive countries in the list of top-10 are the U.K., China, Italy, Japan, France and Australia but their global share is comparatively small ranging from 5.27% to 9.86% share of world output. Although a total of 389 authors from 293 organizations had participated in global quantum sensing research, but a significant share (35.52% and 34.18%) of global output is dominated by the top 15 most productive organizations and top 15 most productive authors respectively. Among the top 15 participating organizations, 4 each come from the USA, Germany and Italy and 3 from France). Among top 15 most productive authors, 6 come from Germany, 4 each from Italy and USA and 1 from Israel. The journals such as Physical Review A (30 papers), Physical Review Letters (28 papers), New Journal of Physics (23 papers) and Physical Review Applied (17 papers) lead in global publication productivity. In addition, in terms of most cited journals, Agriculture & Forest Meteorology (69.67), Science (42.17), Physical Review A (34.0) and Nature Communication (30.56) top the most cited journals list. The global research in the field of quantum sensors is distributed across seven disciplines. Of these, Physics & Astronomy, Engineering and Materials Science accounted for a major share (76.02%, 45.07% and 42.52% respectively) to the global output.

The research in the field of quantum sensing is still at a nascent stage of its development. Even after 30-year research into quantum sensing area the body of literature in the subject is still very small, standing just at a total of 588 publications, nearly 19.6 publications globally per year. The USA, Germany, and Italy are the top three countries that have come to dominate the domain of quantum sensing research at a global level. This conclusion is based on country-wise research productivit y, organization-wise productivity, and publication of research output that appeared mainly in research journals that have country of their publication in western countries. Further, this study finds that Massachusetts Institute of Technology, USA and University of Ulm, Germany have emerged both as most productive organizations and the most cited organizations. In addition, ETH, Zurich, though it is not ranking the list of top 15 most productive organizations, but it emerged as one of top three highly cited organizations. This confirms the view that there is very little correlation between most cited organizations and most productive organizations. The contribution of Asian countries in the growth and development of research in the subject is marginal. The findings in this study should be of interest to researchers, policy formulators and other actors, especially those from the developing countries. The findings in this study should be of interest to stakeholders in the country in planning R&D investments for strengthening research infrastructure, initiating new programmes aimed at international collaboration, and in undertaking fresh programmes for manpower development in the domain of quantum sensing research.

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