Quantum Machine Learning: A Scientometric Assessment of Global Publications during 1999-2020

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ABSTRACT

The study provides a quantitative and qualitative description of global research in the domain of quantum machine learning (QML) as a way to understand the status of global research in the subject at the global, national, institutional, and individual author level. The data for the study was sourced from the Scopus database for the period 1999-2020. The study analyzed global research output (1374 publications) and global citations (22434 citations) to measure research productivity and performance on metrics. In addition, the study carried out bibliometric mapping of the literature to visually represent network relationship between key countries, institutions, authors, and significant keyword in QML research. The study finds that the USA and China lead the world ranking in QML research, accounting for 32.46% and 22.56% share respectively in the global output. The top 25 global organizations and authors lead with 35.52% and 16.59% global share respectively. The study also tracks key research areas, key global players, most significant keywords, and most productive source journals. The study observes that QML research is gradually emerging as an interdisciplinary area of research in computer science, but the body of its literature that has appeared so far is very small and insignificant even though 22 years have passed since the appearance of its first publication. Certainly, QML as a research subject at present is at a nascent stage of its development.

1. Introduction

Quantum machine learning (QML) is a fascinating new technology that combines classical machine learning and quantum computers in a way that it eventually accelerates the computing process in machine learning (Some, 2020). Basically machine learning is all about how classical computers learn patterns in data. But given the fact that classical computers have hit their own computational limits, at times it is out of their reach to run many machine learning algorithms faster (Louriz,

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2019). On the other hand, quantum computers that are packed with incredible computational power and speed, can accelerate a number of machine learning algorithms, make data pattern learning process faster, and even compute and run many a complex machine learning operations that were otherwise out of the reach of classical computers (TensorFlow, 2020). Quantum computing relies on quantum mechanics phenomena of superposition and entanglement to do things faster, more efficiently. It is now possible to do many such things that we couldn't have even dreamed of without quantum computers. Having recognized that the increased computational power, increased data availability, and algorithmic advances have all influenced QML techniques to provide good results in deep learning, optimization, kernel evaluation, cryptography, and quantum simulation tasks (Ciliberto et al., 2018). Currently, IBM, Google, NASA, and Microsoft are some of the global enterprises that are spearheading their R&D efforts and making significant advances in QML research.

2. Literature Review

There is only a single study by (Pande & Mulay, 2020) in the body of bibliometric literature that deals per se on the topic of quantitative assessment of QML research. In addition, there are quite a few other studies related to broader topics such as 'quantum technologies' (quantum computing) research and 'machine learning' research. Pande & Mulay in their study examined QML research and identified the trends in research during 2014-19, focusing mainly on growth parameters, identification of major countries, organizations, authors and journals involved in QML research.

In the area of quantum technologies, (Dhawan, Gupta, & Bhusan, 2018) examined 4703 global publications on quantum computing during 2007-16, with focus on identification of the top 10 countries, top 30 most productive organizations and authors, top 20 journals and 124 highly cited papers. (Tolcheev, 2018) highlighted the bibliometric characteristics of the quantum technologies literature during 2000-16 and identified and evaluated the key areas of research and the publication activities of different countries. (Gupta & Dhawan, 2020) examined global research (546 publications) in the domain of "Quantum Neural Networks" (QNN) on metrics such as publication output, document type, country, collaboration patterns, institutional and author affiliation, subjects, journal name, and citation patterns during 1990-2019, using Scopus database.

In the area of machine learning, (Dhawan, Gupta, & Singh, 2020) examined 48,455 global publications on machine learning during 2009-18, by focusing on growth rate, citations per paper, international collaborative papers, relative citation index, activity index, top productive countries, organizations, authors, journals, and highly-cited papers. (Rincon-Patino et al., 2018) studied machine learning research output during 2007-17 and identified the most notable authors, institutions, keywords, countries, categories, and journals. (Gupta & Dhawan, 2019b) examined 3960 Indian machine learning publications during 2006-17 using bibliometric techniques. It studies aspects such growth rate, global publications share, share of international collaborative papers, analyses of top 10 countries, top 20 organizations and authors, core source journals and subject areas. (Gupta & Dhawan, 2019a) examined global deep learning research using bibliometric indicators during 2004-17. (Cova & Pais, 2019) examined 5,279 publications (receiving 81,248 citations) on machine learning (ML) applications in different sub-fields of chemistry during 2008 - 2019.

The topics such as machine learning, quantum technologies and now quantum machine learning, of late, have been receiving national attention by various countries (including India) in terms of R&D investments and dedicated budgets. It is observed that QML as a subfield has been growing in terms of its applications especially in the last few years. It was, therefore, felt that there is a need to undertake a bibliometric study of the literature in the field, covering publications data since its beginning (1999) till date. Even as Pandey & Mulay have published recently in 2020 a study on this topic, but the fact is that their study is based on a limited publications dataset (276 and 154 publications from two separate databases), on a limited publication period span, covering just 6-year period 2014-19, and analyzed on a set of limited parameters. Given this rationale, the authors thought it prudent to carry out a comprehensive study in QML research that is based on a larger dataset, on a larger set of metrics, with the aim to describe the contemporary status of QML research at global, national, institutional, and individual author level. In addition to providing a window to key productive countries, key research organizations, key contributing authors and journals, such a study is also going to carry out a bibliometric mapping of QML literature to visually represent network relations between key authors, institutions, and countries involved in QML research.

3. Objectives of the Study

The present study seeks to examine global publications output in the domain of quantum machine learning (QML) research with the purpose to understand the status of QML research at global, national, institutional, and individual author level, using quantitative and qualitative metrics. The data for the study has been sourced from the Scopus database covering the period 1999-2020. The study seek to evaluate the publications data in terms of (i) distribution of publications by type and source, (ii) annual and cumulative publications growth, (iii) the citation impact registered by the publications (iv) the publication profile of the top 10 most productive countries, (v) the distribution of publications by broad subjects and significant keywords, (vi) the publications profile of top 25 organizations and authors of publications, (vii) the top communications channels in the research, and (viii) the bibliographic characteristics of highly-cited papers in the subject.

4. Methodology

The study sourced data on the topic of quantum machine learning from the Scopus database (http://www.scopus.com). The search strategy that this study used in order to identify, retrieve, and download publications metadata included using search keywords “quantum machine learning” tagged to field tags “Keyword” and “Title” (Article Title), and subsequently confined the global search output to the period ‘1999-2020’. In the subsequent rounds of data search, the global output was refined by the country name, one by one, to identify and generate a list of top 15 most productive countries in the subject. The study noted that the global output in the field of quantum machine learning for the period 1999-2020 was 1374 publications. The data was downloaded in csv file format, which was subsequently analyzed using statistical methods. In addition, the authors used analytical provisions of the Scopus database as a means to distribute the publications output by broad subject areas, collaborating countries, contributing authors, affiliating organizations, and source journals, etc. The citations to publications were counted from date of their publication till 9.2.2021. The study used bibliometric techniques and indicators as a method to quantify and evaluate the performance of the most productive countries, organizations, authors and journals. The VOSviewer and biblioshiny app for bibliometrix were used to evaluate and visualize the interaction among most productive countries/territories, organizations, authors and keywords.

(KEY (quantum machine learning) or TITLE (quantum machine learning)) and PUBYEAR > 1998 AND PUBYEAR < 2021

5. Analysis and Results

5.1 Publication and Citation Analysis

The global research in the domain of quantum machine learning accumulated a total of 1374 publications in 22-year during 1999-2020, an average of 62.45 publications per year. The annual research output in the subject registered a 40.1% growth, from just 1 in the beginning year 1999 to 471 publications in the year 2020. In 11 years, research output in QML had increased by 2128.81% from 59 in 1999-2009 to 1315 publications in 2010-2020. This implies that research activity in quantum machine learning has witnessed a rapid growth during the latter part of the 11-year study period in 2010-2020.

The global quantum machine learning research registered a citation impact of 16.33 citations per paper (CPP) since publication in 1999-2020. Its citation impact was the highest, a 32.54 CPP, in 1999-2009, and it slipped to 15.60 CPP in 2010-2020. The apparent drop in citation rate is in large part due to the shorter citation window to publications that appeared in 2010-2020 (**Table 1**).

Of the total output, a majority of publications appeared as article and conference papers (66.30% and 21.76%), respectively. The remaining output appeared as reviews (6.40%), book chapters (1.67%), editorials (1.38%), notes (0.73%), short surveys (0.58%), books, conference reviews and erratum (0.22% each) and letters, data paper and undefined (0.15% each).

Of the total 1374 publications, 687 (50.0%) had resulted from research funded by 100+ national and international funding agencies. The number of funded papers increased from 6 during 1999-2009 to 681 during 2010-20. 82.68% of the funded papers were published during the last 3 years.

These 687 publications received 12844 citations since their publication, registered a citation impact of 18.70 citations per paper, marginally above the world average, a 16.33 CPP. The leading funding agencies in quantum machine learning research were: National Natural Science Foundation of China (166 papers), National Science Foundation, USA (119 papers), U.S. Department of Energy (68 papers), European Research Council (51 papers), etc.

Table 1. QML Research: Global Publications Output and Citations 1999-2020

Publication Period	TP	TC	CPP	FP	Publication Period	TP	TC	CPP	FP
1999	1	30	30.0		2012	17	550	32.4	2
2000	1	1	1.0		2013	20	648	32.4	7
2001	1	0	0		2014	33	766	23.2	14
2002	2	71	35.5		2015	48	2636	54.9	16
2003	3	18	6.0		2016	59	1757	29.8	23
2004	2	29	14.5		2017	105	4749	45.2	48
2005	4	94	23.5		2018	194	4176	21.5	114
2006	7	427	61.0	1	2019	342	3569	10.4	192
2007	9	106	11.8		2020	471	969	2.06	262
2008	16	258	16.1	2	1999-09	59	1920	32.5	6
2009	13	886	68.2	3	2010-20	1315	20514	15.6	681
2010	14	498	35.6	2	1999-2020	1374	22434	16.3	687
2011	12	196	16.3	1					

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

5.2 Top 15 Most Productive Countries

The distribution of global research in the domain of QML was highly skewed by country of publication. In all, 72 countries participated in global research on QML research. Of these, top 15 most productive countries account more than 100.0% global publication and citation share. The USA and China leads the ranking with global publication share of 32.46% and 22.56%, followed by U.K. and Germany (10.84% and 10.04%), Canada, Switzerland, India, Italy, Japan, and Australia (from 3.64% to 6.04%), etc during 1999-2020. The global publication share of 11 of the top 15 countries (USA, U.K., Switzerland, China, India, South Korea, Italy, Russia Fed., Australia and Canada) increased by 0.89% to 17.98% in 11 years between 1999-2020 and 2010-2020. During the same period the global share of Japan, Spain, Germany and Austria decreased by 0.67% to 4.57%. Eight of the top 15 countries registered their relative citation index above the group average (1.33), Switzerland (2.73), South Korea (2.66), Germany (1.93), Russia Federation (1.68), Canada (1.66), Spain (1.65), USA (1.56) and U.K. (1.40). The international collaborative papers as a share of top 10 countries varied from 17.39% to 69.30%, with an average of 49.62%. The funded research papers as a share of the top 15 countries varied from 8.96% to 77.50%, with an average of 56.85%. The international collaborative papers (ICP) as a share of national output of top 15 countries varied from 22.39% to 74.29%, with an average of 50.93% (**Table 2**).

Table 2. QML Research: Top 15 Most Productive Countries 1999-2020

S.No	Name of the Country	Number of Papers			Share of Papers			TCP	CPP	ICP	%ICP	RCI	TCL	FP	%FP
		1999-09	2010-20	1999-2020	1999-09	2010-20	1999-2020	1999-2020							
1	USA	9	437	446	15.25	33.23	32.46	11328	25.4	206	46.2	1.6	330	255	57.2
2	China	11	299	310	18.64	22.74	22.56	3434	11.1	115	37.1	0.7	178	201	64.8
3	U.K.	2	147	149	3.39	11.18	10.84	3402	22.8	102	68.5	1.4	181	93	62.4
4	Germany	8	130	138	13.56	9.89	10.04	4360	31.6	93	67.4	1.9	189	75	54.4
5	Canada	3	80	83	5.08	6.08	6.04	2251	27.1	45	54.2	1.7	45	43	51.8
6	Switzerland	0	75	75	0	5.7	5.46	3344	44.6	52	69.3	2.7	163	53	70.7
7	India	1	66	67	1.69	5.02	4.88	223	3.33	15	22.4	0.2	17	6	8.96
8	Italy	1	62	63	1.69	4.71	4.59	947	15	37	58.7	0.9	67	27	42.9
9	Japan	3	58	61	5.08	4.41	4.44	686	11.3	20	32.8	0.7	55	37	60.7
10	Australia	1	49	50	1.69	3.73	3.64	547	10.9	29	58	0.7	62	22	44
11	South Korea	0	40	40	0	3.04	2.91	1736	43.4	24	60	2.7	63	31	77.5
12	Russia Fed.	0	36	36	0	2.74	2.62	989	27.5	20	55.6	1.7	35	23	63.9
13	France	1	34	35	1.69	2.59	2.55	454	13	26	74.3	0.8	55	15	42.9
14	Spain	3	31	34	5.08	2.36	2.47	916	26.9	20	58.8	1.7	48	19	55.9
15	Austria	4	29	33	6.78	2.21	2.4	690	20.9	21	63.6	1.3	31	21	63.6
	Total of 15 countries	47	1573	1620	79.66	119.62	117.9	35307	21.8	825	50.9	1.3	1519	921	56.9
	World total	59	1315	1374				22434	16.3						

TCP=Total Paper; CPP=Citations Per Paper; ICP=International Collaborative Papers; RCI=Relative Citation Index; TCl=Total Collaborative Publications; FP=Funded Papers

*Note: There is overlapping in the total output of top 15 countries due to international collaborative papers being common to more than one country. As a result sum of their individual output (1620) in QML research exceeds the global output (1374).

5.2.1 Collaborative Linkages among Top 15 Countries

All of the top 15 most productive countries collaborated in QML research; their one-to-many collaborative linkages count varied from 17 to 330, and their one-to-one collaborative linkages varied from 1 to 64. Among the collaborations at country-to-country level, the USA - China topped the list, registered the highest number of collaborative linkages (64), followed by the USA - the U.K. (49), the USA - Germany (32), USA - Canada (26), USA - Switzerland (22), Germany - Switzerland (20), U.K. - Switzerland (19), U.K. - Italy (16), U.K. - Germany (15), Germany - South Korea (15), China - Australia (13), USA - Australia (12), USA - Italy (11), Germany - Italy (10), USA - France (10). A collaborative network chart covering top 15 countries is presented in Fig. 1. The countries with same colour belong to a single cluster. The thickness of links between the countries and the distance between them represents the degree of their research collaboration. The bigger the diameter of a network node and its font size, the bigger its weight in research collaboration. The USA dominates in QML collaborative research, followed by China, Germany, the UK, and others.

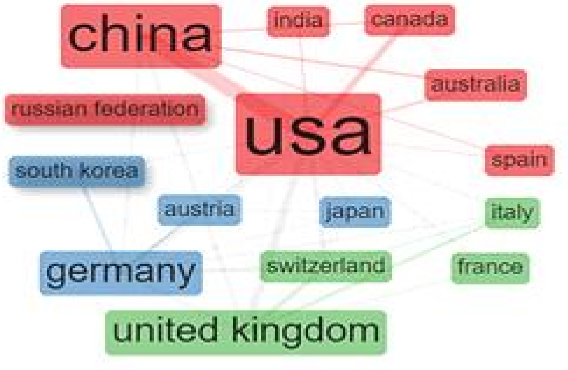

Fig. 1. Country collaboration networks chart

5.3 Subject-Wise Distribution

Physics & Astronomy and Computer Science are the top subject areas that contributed the largest share (42.43% and 36.32% respectively) to the global output in QML research, followed by Chemistry and Engineering (24.75% and 22.34%), Materials Science (20.31%), Biochemistry, Genetics & Molecul ar Biology (7.79%), and other six subjects contributing 1.60% to 4.66% during 1999-2020. In terms of activity index between 1999-2020 and 2010-20, the subjects who showed a jump in their research activity in 11 years were: Physics & Astronomy, Chemistry, Materials Science, Neuroscience, Energy and Medicine, as against decrease in 6 other subjects from 1999-09 to 2010-20. Amongst twelve subjects, Neuroscience registered the highest citation impact per paper (29.67 CPP) and Engineering subject the least (7.66 CPP) (**Table 3**).

Table 3. QML Research: Top 15 Most Productive Countries 1999-2020

S.No	Subject	Number of Papers			Activity Index		TC	CPP	%TP
		1999-09	2010-20	1999-2020	1999-09	2010-20	1999-2020		
1	Physics & Astronomy	9	574	583	35.95	102.87	10786	18.5	42.4
2	Computer Science	37	462	499	172.68	96.74	5218	10.5	36.3
3	Chemistry	9	331	340	61.65	101.72	8178	24.1	24.8
4	Engineering	21	286	307	159.3	97.34	2353	7.66	22.3
5	Materials	3	276	279	25.04	103.36	3544	12.7	20.3

	Science								
6	Biochemistry, Genetics & Molecular Biology	8	99	107	174.12	96.67	2256	21.1	7.79
7	Chemical Engineering	8	56	64	291.1	91.43	732	11.4	4.66
8	Pharmacology, Toxicology & Pharmaceutics	5	55	60	194.07	95.78	1225	20.4	4.37
9	Neuroscience	1	38	39	59.71	101.81	1157	29.7	2.84
10	Energy	0	37	37	0	104.49	566	15.3	2.69
11	Medicine	0	25	25	0	104.49	299	12	1.82
12	Environment Science	1	21	22	105.86	99.74	499	22.7	1.6
	Total	59	1315	1374			22434	16.3	

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

5.3.1 Significant Keywords

In all, 60 keywords (assumed to be significant) were identified from the global literature on quantum machine learning research. These keywords are considered as research hot-spots and as a secondary support to understand the trends in the domain of quantum machine learning research. The frequency of keyword occurrence in the QML literature for 1999-2020 was the maximum (893) for Machine Learning, followed by Learning Systems (487), Quantum Theory (370), Quantum Chemistry (286), and Learning Algorithms (219), artificial intelligence (209), quantum computers (191), quantum optics (183), neural networks (150), quantum computing (137), quantum mechanics (122), quantum machines (111), quantum machine learning (105), density functional theory (104), machine learning techniques (101), deep learning (93), computation theory (85), machine learning methods (78), support vector machines (75), machine learning models (72), etc. A co-occurrence relationship chart of top 60 keywords is shown in Fig. 2. Each node is associated to a keyword and its size is proportional to the number of documents where the keyword appears. Machine learning in the keyword co-occurrence network is the largest node in diameter and its font size. The same colour nodes belong a single cluster. Learning systems and quantum theory are the second and the third ranking keywords, but both are in same colour cluster. Links between nodes relate keywords which usually appear together in the same documents. The top 60 keywords were divided into 4 clusters. Cluster 1 with blue color has 23 keywords, followed by cluster 2 with red color and 17 keywords, and cluster 3 (green) & 4 (yellow) with 13 and 7 keywords respectively.

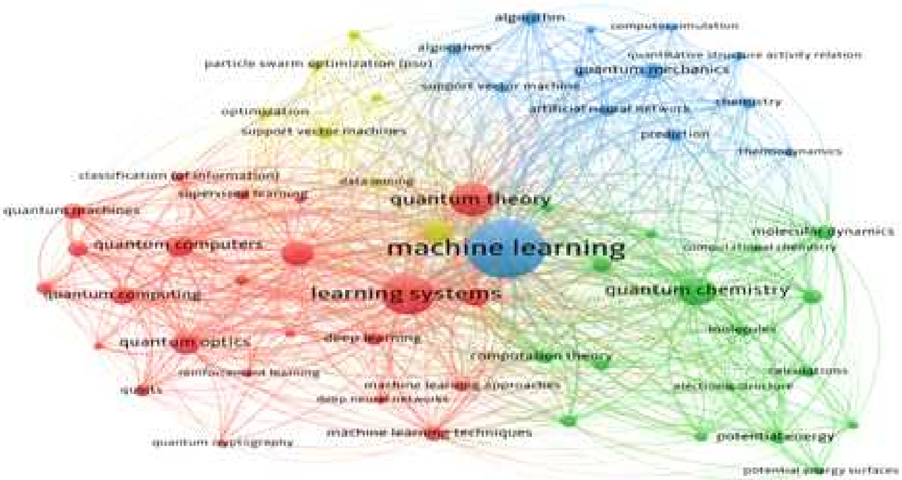

Fig. 2. Keyword co-occurrence network visualization

5.4 Top 25 Most Productive Organizations

In all, a total of 344 organizations were found to have participated in QML research during 1999-2020. Of these, 211 organizations published 1-5 papers each, 91 organizations 6-10 papers each, 32 organizations 11-20 papers each and 10 organizations 21-32 papers each. Of the top 25 most productive global organizations in QML research, 5 each were from USA and U.K, 4 from China, 3 each from Canada and Switzerland, 2 from Germany and 1 each from Austria, France and Singapore.

The research productivity of top 25 most productive organizations in the subject varied from 13 to 32 publications per organization; together they contributed 35.52% (488) global publications share and 76.62% (17190), global citations share during the period. The scientometric profile of top 8 most productive and 8 most impactful organizations is presented in **Table 4.**

Table 4. Scientometric profile of top 8 most productive and impactful organizations in QML during 1999-2021

S.No	Name of the Organization	TP	TC	CPP	HI	ICP	ICP(%)	RCI	TCL
	Top 8 Most Productive Organizations								
1	Tsinghua University, China	32	414	12.94	13	18	5.98	0.79	74
2	University of Bassel, Switzerland	27	1374	50.89	16	18	5.98	3.12	40
3	Massachusetts Institute of Technology, USA	26	1735	66.73	11	10	3.32	4.09	51
4	University of S&T of China	25	514	20.56	12	12	3.99	3.78	55
5	ETH, Zurich, Switzerland	25	1543	61.72	13	20	6.64	2.49	89
6	Harvard University, USA	23	934	40.61	14	14	4.65	3.25	59
7	Univ. of Waterloo, Canada	23	1219	53.00	11	15	4.98	1.01	62

8	Ministry of Education, China	22	363	16.50	8	9	2.99	1.01	94
	Top 8 Most Impactful Organizations								
1	Microsoft Research, USA	17	1401	82.41	11	15	4.98	5.05	50
2	Argonne Nat. Lab., USA	16	1163	72.69	10	9	2.99	4.45	39
3	Massachusetts Institute of Technology, USA	26	1735	66.73	11	10	3.32	4.09	51
4	ETH, Zurich, Switzerland	25	1543	61.72	13	20	6.64	3.78	89
5	Tech. Univ. of Berlin, Germany	17	904	53.18	12	15	4.98	3.26	77
6	Univ. of Waterloo, Canada	23	1219	53.00	11	15	4.98	3.25	62
7	University of Bassel, Switzerland	27	1374	50.89	16	18	5.98	3.12	40
8	University College, London, U.K.	22	1085	49.32	12	14	4.65	3.02	70

TP=Total Publications; TC=Total Citations; CPP=Citations Per Paper; ICP=International Collaborative Papers; RCI=Relative Citation Index; HI=H-Index

5.4.1 Institutional Collaboration Linkages among Top 25 Organizations

The top 25 most productive organizations collaborated in QML research; their collaborative linkages varied from 23 to 101. The collaborative linkages between one-to-one organizations varied from 1 to 25. University of Waterloo, Canada and Perimeter Institute of Theoretical Physics, Canada both registered the highest number of collaborative linkages (14 each), followed by Argonne National Lab., USA, and University of Basel, Switzerland (6 each), Tsinghua Univ. China - Southern University of China, China and Harvard University, USA - University of Toronto, Canada (5 each), ETH, Zurich - Univ. of Oxford, U.K. (4 each), etc. A collaborative networks chart of top 25 organizations is presented in Fig. 3. The node indicates the number of publications, the more the number of publications the larger the node size. Tsinghua University tops in the list with most collaborative publications, followed by University of Cambridge.

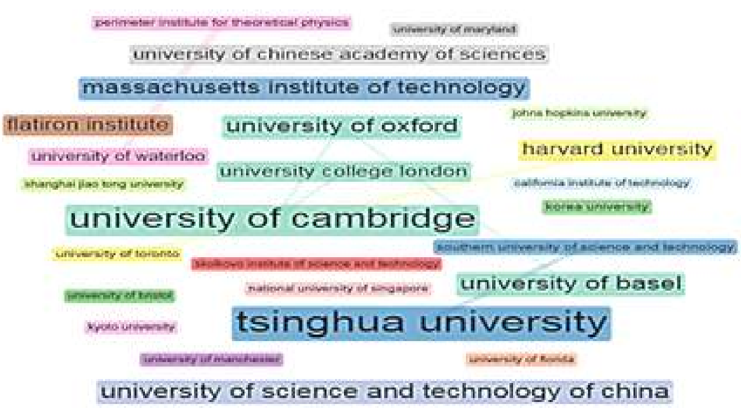

Fig. 3. Institutional collaboration network

5.5 Top 25 Most Productive Authors

In all, a total of 534 authors were found to have contributed to global QML research during 1999-2020. Of these, 499 authors published 1-5 papers each, 31 authors 6-10 papers each and 4 authors 11-18 papers each. Of the top 25 authors, 3 each were from USA, U.K and Germany, 2 each from Austria, Canada, China, Italy and South Africa and 1 each from India, Luxembourg, Russia Federation and South Korea. The research productivity of top 25 most productive authors varied from 6 to 18 publications per author. Together they contributed 16.59% (228) global publications share and 47.37% (10,627) global citations share during 1999-2020. The scientometric profile of top 8 most productive and 8 most impactful authors is presented in **Table 5.**

Table 5. Scientometric profile of top 8 most productive and impactful authors in QML during 1999-2020

S.No	Name of the Authors	Affiliation of the Author	TP	TC	CPP	HI	ICP	ICP(%)	RCI	TCL
	Top 8 Most Productive Authors									
1	P.L.A. Popelier	University of Manchester, U.K.	18	489	27.17	10	3	2.11	1.66	52
2	N. Wiebe	Microsoft Research, USA	17	720	42.35	9	4	2.82	2.59	72
3	A. Aspuru-Guzik	Harvard University, USA	13	755	58.08	9	8	5.63	3.56	53
4	O.A. Von Lilienfeld	University of Basel, Switzerland	13	1097	84.38	12	8	5.63	5.17	38
5	G. Csanyi	University of Cambridge, U.K.	10	607	60.70	7	6	4.23	3.72	39
6	A. Tkatchenko	University of Luxembourg	10	1202	120.20	9	9	6.34	7.36	42
7	H.J. Briegel	Univ. of Innsbruck, Austria	9	315	35.00	6	5	3.52	2.14	31
8	M. Ceriotti	Swiss Federal Institute of Technology in Lausanne, Switzerland	9	324	36.00	7	7	4.93	2.20	36
	Top 8 Most Impactful Authors									
1	K.R. Muller	Tech. Univ of Berlin, Germany	9	1197	133.00	9	9	6.34	8.14	42
2	A.Tkatchenko	University of Luxembourg	10	1202	120.20	9	9	6.34	7.36	42
3	M. Rupp	Fritz Haber Inst. Of Max Planck Soc., Germany	9	980	108.89	9	8	5.63	6.67	33
4	O.A. Von Lilienfeld	University of Basel, Switzerland	13	1097	84.38	12	8	5.63	5.17	38
5	M. Schuld	Univ. of KwaZulu Natal, S.Africa	8	490	61.25	6	4	2.82	3.75	17
6	G. Csanyi	University of Cambridge, U.K.	10	607	60.70	7	6	4.23	3.72	39
7	A. Aspuru-Guzik	Harvard University, USA	13	755	58.08	9	8	5.63	3.56	53
8	R.G. Melko	Univ. of Waterloo, Canada	8	361	45.13	6	5	3.52	2.76	22

TP=Total Publications; TC=Total Citations; CPP=Citations Per Paper; ICP=International Collaborative Papers; RCI=Relative Citation Index; HI=H-Index

5.5.1 Collaborative Linkages among Top 25 Authors

Most of the top 25 most productive authors, except few, collaborated in QML research, and their collaborative linkages varied from 17-72. The number of collaborative linkages between one-to-one authors varied from 1 to 9. Among the individual author to author collaboration linkages, A. Tkatchenko and K.R. Muller registered the highest number of collaborative linkages (9), followed by F. Sciarrino - N. Spagnolo (7), H.J. Briegel - V. Dunjko (6), B. Jiang - H. Guo (6), N. Wiebe - F. Sciarrino (4), N. Wiebe - N. Spagnolo (4), O.A. Von Lilienfeld - M. Rupp (4), F. Petruccione - M. Schuld (3 linkages), etc. A collaborative networks chart of top 25 authors is presented in Fig. 4. The thickness of the box is proportional to its number of collaborative publications. The bigger the box size and its font size, the more the number of collaborative publications. The chart suggests there has been active collaboration amongst the most productive authors.

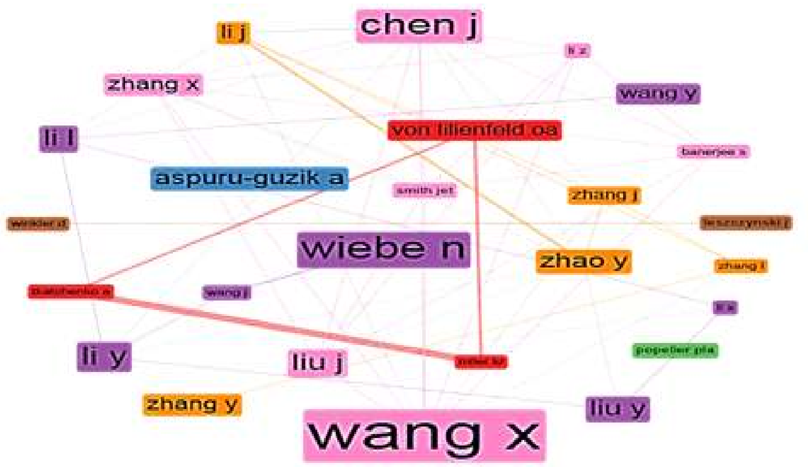

Fig. 4. Co-Author Collaboration networks chart

5.6 Channels of Research Communication

Of the total world output in QML research, 75.69% (1040) appeared in journals, 18.63% (256) in conference proceedings, and the remaining 4.37% (54) appeared as book series, 0.87% (12) as books and 0.44% (6) in trade journals during 1999-2020. Of the 345 journals that had reported 1040 articles, 306 published 1-5 papers each, 19 published 6-10 papers each, 10 published 11-20 papers each and 10 journals published 21-55 papers each during 1999-2020.

The top 20 most productive journals accounted for a 49.71% share of the global output in QML research during the period. The top 6 most productive journals were: Physical Review A (55 papers), Journal of Chemical Physics (42 papers), Physical Review B (40 papers each), New Journal of

Physics (34 papers) and Physical Review Letters (32 papers), Quantum Information Processing (26 papers each), Nature Communication (24 papers) and Journal of Physical Chemistry A (23 papers). The top 6 most impactful journals were: Chemical Science (56.88), Physical Review X (54.10), International Journal of Quantum Chemistry (47.92), Physical Review Letters (42.14), Nature (38.440 and Nature Communications (37.94).

5.7 Highly-Cited Papers

Of the total 1374 global publications on QML research during 1999-2020, only 43 (3.13% share) registered 100+ citations per paper since their publication (assumed here as highly-cited papers). Together these 43 papers received a total of 9206 citations, since their publication, an average of 214.09 citations per paper. The distribution of 43 highly cited papers is highly skewed: 25 papers each registered citations in the range 107-194, 10 papers in citation range 210-297 and 7 papers in citation range 328-674. Among the 43 highly cited papers (35 articles and 8 reviews), 9 involved zero collaboration and 13 national and 21 international collaboration. Among 43 highly cited papers, USA contributed the highest number of papers (29), followed by Germany (10), Switzerland (9), China (6), Canada and U.K. (5 each), South Korea (4), Austria, Russia Federation and Spain (2 papers), France, Italy and Japan (1 each). Among 43 high-cited papers, University of Basel, Switzerland contributed 5 papers, followed by MIT, USA, ETH, Zurich, University of Waterloo, and Argonne National Lab, USA (4 papers each), Perimeter Institute of Theoretical Physics (3 papers), University of Cambridge and Technical University of Berlin (2 papers each), etc. Among 43 high-cited papers, O.A. Von Lilienfeld and M. Rupp contributed 4 papers each, K.R. Muller and A. Tkatchenko (3 each), G. Csanyi, R.G. Melko and M. Schuld (2 each), etc. 32 journals participated in 43 high cited papers published in journals. Of these, the largest number of papers (4 each) has been published in International Journal of Quantum Chemistry, followed by Physical Review Letters (3 papers), Chemical Science, Nature Communications, Nature Physics and Physical Review X (2 papers each) and 1 paper each by 26 other journals.

6. Summary and Conclusion

This study used bibliometric methods to analyze the global research in the domain of QML (1374 publications) published during 1999-2020. The study provides an overview of the status of research in quantum machine learning on a series of quantitative and qualitative metrics, and presents a visual view of network relationship between leading authors, research institutions, and collaborative countries. In addition, the study identifies the global players in QML research including as key countries, key institutions, key authors, and key subject areas of research.

The study concludes that the QML research is gradually emerging as an interdisciplinary area of research in the field of computer science. But, despite its growing importance in the academia and industry, the body of the global literature in the subject is still very small, limited to just 1374 publications which appeared in a long period 22 years during 1999-2020, with an average output of 62 publications per year. The study finds that QML as a research field is still at a nascent stage of its development. Even as participation in QML research is global, but only a select few countries dominate in global productivity in the field. For instance, the USA, China, the UK, and Germany accounted for a significantly high 75.90% share of the global output, In contrast, global share of 11 of 15 most productive countries is in single digits, it is just small and insignificant. Besides, most of top 25 centres of excellence in QML research come from such leading countries as the USA, China, UK, and Germany that dominate global productivity in the subject. The study observes that most countries in the top 15 list -- including India, Italy, Japan, Australia, South Korea, Russia Fed., France, Spain, and Austria will -- are peripheral players in global QML research. The policy makers and other stakeholders in such countries need to initiate national programmes and make fresh R&D investments aimed at strengthening research infrastructure, international collaboration, capacity building and manpower development in the domain of quantum machine learning research and thereby lead their country to come to the top the global research in the subject.

7. Limitations of the Study

We used Scopus database for sourcing publications data for our bibliometric study. Whereas Scopus is a universally recognized international bibliographic and citation database for the purpose of undertaking bibliometric studies, the quantity and quality of data used for the present study is as good as are the Scopus search tools. In our search strategy, we used Keyword and Article title tags for high recall in search output.

References

Ciliberto, C., Herbster, M., Ialongo, A. D., Pontil, M., Rocchetto, A., Severini, S., & Wossnig, L. (2018). Quantum Machine Learning: A classical Perspective. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *474*(2209), 20170551. https://doi.org/10.1098/rspa.2017.0551

Cova, T. F. G. G., & Pais, A. A. C. C. (2019). Deep Learning for Deep Chemistry: Optimizing the Prediction of Chemical Patterns. *Frontiers in Chemistry*, *7*, 809. https://doi.org/10.3389/fchem.2019.00809

Dhawan, S. M., Gupta, B. M., & Bhusan, S. (2018). Global Publications Output in Quantum Computing Research: A Scientometric Assessment during 2007-16. *Emerging Science Journal, 2*(4). https://doi.org/10.28991/esj-2018-01147

Dhawan, S. M., Gupta, B. M., & Singh, N. K. (2020). Global Machine-learning Research: A Scientometric Assessment of Global Literature during 2009-18. *World Digital Libraries-An International Journal*, *13*(2), 105-120. https://doi.org/10.18329/09757597/2020/13209

Gupta, B. M., & Dhawan, S. M. (2019a). Deep Learning Research: Scientometric Assessment of Global Publications Output during 2004-17. *Emerging Science Journal*, *3*(1), 23.

https://doi.org/10.28991/esj-2019-01165

Gupta, B. M., & Dhawan, S. M. (2019b). Machine Learning Research in India: A Scientometric Assessment of Papers During 2006-17. *World Digital Libraries - An International Journal*, *12*(1), 19-32. https://doi.org/10.18329/09757597/2019/12102

Gupta, B. M., & Dhawan, S. M. (2020). Quantum neural network (QNN) research a scientometrics assessment of global publications during 1990-2019. *International Journal of Information Dissemination and Technology*, *10*(3), 168-174. https://doi.org/10.5958/2249-5576.2020.00030.8

Louriz, R. (2019). *Highlighting Quantum Computing for Machine Learning.* https://medium.com/meetech/highlighting-quantum-computing-for-machine-learning-1f1abd41cb59

Pande, M., & Mulay, P. (2020). Bibliometric Survey of Quantum Machine Learning. *Science & Technology Libraries*, *39*(4), 369-382. https://doi.org/10.1080/0194262X.2020.1776193

Rincon-Patino, J., Ramirez-Gonzalez, G., & Corrales, J. C. (2018). Exploring Machine Learning: A Bibliometric General Approach Using CiteSpace. *F1000Research*, *7*, 1240. https://doi.org/10.12688/f1000research.15619.1

Some, K. (2020, June 22). Understanding Quantum Computing for Machine Learning. *Analytics Insight.* https://www.analyticsinsight.net/understanding-quantum-computing-machine-learning/

TensorFlow. (2020). *Quantum Machine Learning Concepts.* https://www.tensorflow.org/quantum/concepts

Tolcheev, V. O. (2018). Scientometric Analysis of the Current State and Prospects of the Development of Quantum Technologies. *Automatic Documentation and Mathematical Linguistics*, *52*(3), 121-133. https://doi.org/10.3103/S000510551803007X

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