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Perspective Paper

A Scientometric Analysis of Catalysis Research

Rosaria Ciriminna[1], Irina L Simakova[2], Mario Pagliaro[1,*], Dmitry Yu Murzin[3]

[1]Istituto per lo Studio dei Materiali Nanostrutturati, CNR, via U. La Malfa, Palermo, ITALY.
[2]Boreskov Institute of Catalysis, Lavrentieva 5, Novosibirsk, RUSSIA.
[3]Industrial Chemistry and Reaction Engineering, Abo Akademi University, Biskopsgatan, Turku, FINLAND.

ABSTRACT
The outcomes of the present scientometric analysis of research in catalysis provide chemistry and catalysis scholars with a closer bibliometric knowledge of an old and central field of chemical research. The field nowadays is being reshaped by fundamental and technological advances spanning from single-atom heterogeneous catalysis to flow chemistry. Improving and widening research and education in catalysis is a strategic need for national economies. Four research policy guidelines aimed at fostering progress in catalysis research and education conclude the study.

Keywords: Scientometric analysis, Catalysis, Bibliometric indicators, Catalysis research, Catalysis journals.

Correspondence
Mario Pagliaro
Istituto per lo Studio dei Materiali Nanostrutturati, CNR, via U. La Malfa 153, 90146 Palermo, ITALY.
Email: mario.pagliaro@cnr.it

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INTRODUCTION

Almost as old as chemistry as a modern science based on the principles formulated by Lavoisier in the late 1700s, catalysis entered chemistry research in 1835. At that time Berzelius introduced the term "catalysis" to indicate "the decomposition of bodies by this force in the same way that one calls by the name analysis the decomposition of bodies by chemical affinity".[1]

According to Berzelius the catalytic force in question, "very different from chemical affinity", was exerted by "simple and compound bodies" on other bodies.[1]

In simple terms, catalysis is a phenomenon related to acceleration of the rates of chemical reactions in the presence of substances (catalysts), which remain formally unchanged during the reaction. In reality, the catalysts are involved in forming chemical bonds with the reactants during so-called catalytic cycles.

An instructive account on the historic development of the catalysis concept and its explanation was published by Wisniak in 2009.[2] The study goes from Berzelius until the first two Nobel prizes awarded in 1909 to Oswald and in 1912 to Sabatier. The latter was awarded for his work on hydrogenation of organic compounds in the presence of metals, namely the catalytic hydrogenation of unsaturated organic molecules using "finely divided" Ni obtained by reducing nickel hydroxide with H_2 at 250°C.

A brief, but still very interesting history of catalysis dividing its historical development into five distinct periods was published by scholars in Sweden in 2013.[3]

Only a few scientometric study on catalysis have been published so far. In 2014, Zibareva and co-workers published two bibliometric analyses. The first was aimed to identify "hot topics" in catalysis research, namely photocatalysis, electrocatalysis, stereoselective catalysis, biocatalysis, catalytic functionalization of organic compounds, nanocatalysis via graphene-based materials, biofuel catalytic production and catalysis in new energy technology.[4] The second one was aimed specifically at a bibliometric analysis of publications including the term "nanocatalysis". It was concluded that "nanocatalysis" was a new research subject pertaining both to nanotechnology and to catalysis science.[5]

Though focused on a scientometric assessment of Indian publications in catalysis between 2006 and 2015, the first comprehensive study on catalysis was reported by Siddaiah and co-workers in 2016 in an open access journal aimed primarily at librarians.[6]

According to Dhawan *et al*. the overall number of research articles in catalysis was found to have grown at 5.78% annual growth rate, going from 6,907 publications in 2006 to 11,303 in 2015.[6]

These findings are consistent with the rapid growth in knowledge production in chemistry between 1990 and 2009. Moreover, during this period because of profound changes in the chemical research process there was a clear shift towards multidisciplinary and collaborative research carried out by scholars from other disciplines and from different countries.[7]

Catalysis is at the core of chemical manufacturing, incorporating not only production of hydrocarbon fuels in various oil refineries around the globe but also of virtually all chemicals, including both bulk and fine chemicals. Apart from few exceptions catalytic technologies employed in industry comprising both catalyst manufacture and application in chemical reactors are proprietary.

Once the patents have been filed, similar to scientists from academia, industrial researchers also publish in chemistry and catalysis journals. The justification for such policy was recently formulated in the following way: "publication becomes… a valuable tool to profile the expertise of a company to the scientific community and find partners, in order to initiate bilateral collaborations or other publicly funded projects with university. In a similar way, the innovation potential of a company becomes visible via publications, increasing its prestige".[8]

The paucity of scientometric studies in catalysis science and technology is accompanied by a similar low number of studies devoted to contemporary catalysis education. This is somewhat surprising considering a widespread need perceived in many countries for better education in catalysis.[9,10]

This study critically presents the outcomes of a scientometric analysis of research in catalysis. Discussion is put in context of scientific publishing in the modern digital era. A particular feature of contemporary research is an increase in the number of preprints, which became rather popular in the fields adjacent to chemistry. This slowly but inexorably impacts the dissemination of chemical knowledge.[11] Moreover, chemical manufacturing is experiencing some sort of renaissance related to emerging fields of green and sustainable process chemistry technology, compliant with circular economy.

Researchers in chemistry, including those involved in catalysis, need knowledge of scientometric tools like the *h*-index[12]and scientometry in general. Indeed, regardless of thoughtful pleas for quality and scientific impact, often researchers are evaluated based on examining the journal impact factor of the published papers only.[13] Subsequently different metrics (e.g. *h*-index) are regularly used by universities and research agencies as a "decision-making tool" to evaluate both single researchers and entire university departments. In the latter case it can be done via the mean *h*-index of the researchers working there.[14]

We agree with Barnes: the scholarly debate on science metrics currently confined to highly technical discussions in specialized journals[13] needs to shift from the latter journals to the main scientific journals and preprint servers regularly used by researchers active in that field. This study serves to this scope in the important chemistry research field of catalysis.

The research policy guidelines concluding the study are aimed at fostering progress in catalysis research, education and industrial uptake in economically developed and developing countries.

RESEARCH AND PUBLISHING IN CATALYSIS

Ending his "On Catalysis" Nobel lecture given on December 12, 1909, Ostwald noted how the scientific field of catalysis was "in the first stages of its development. At present the main task is still essentially to discover and scientifically to establish the various cases of catalysis".[15]

Sabatier followed suit publishing in 1913 *La Catalyse en Chimie Organique*,[16] a book so rich of valuable information about the fundamentals of catalysis that the English. The English translation of that book published in 1922 is still read and commented at advanced catalysis courses more than a century later.[17]

The first catalytic use of gold, up to that time and many decades after considered chemically unreactive, was reported in 1913 by Fokin. He used asbestos as a support of the finely divided gold nanoparticles in a industrially important reaction of methanol oxidative dehydrogenation to formaldehyde[18] (today carried out in industry using either silver or iron catalysts).

Fokin also discovered that Au and Ag powders were more active than supported Pt. Sabatier referred to Fokin's work in *La Catalyse en Chimie Organique*. Eventually, the latter book in 1922 was translated into English,[19] but these published findings were forgotten until Haruta and co-workers in 1987 reported the high catalytic activity of gold nanoparticles in low-temperature CO oxidation.[20]

In the times of Sabatier and many decades thereafter the most important achievements in catalysis were published in general chemistry journals.

The first international catalysis journal specifically devoted to catalysis was *Kinetics and Catalysis*, namely the English translation of the Russian journal *Kinetika i Kataliz* founded in 1960 by Boreskov, Balandin and other prominent scientists at the Academy of Sciences of the USSR. Two years later the *Journal of Catalysis* was established by the Academic Press.

In the preface to the first issue of *Catalysis Reviews* launched in 1968 Heinemann wrote "catalysis is involved in one or the other step of manufacture of almost one-half of our industrial and agricultural product, yet it is less structured, less understood, still less of a science and more of an art than many other fields of smaller importance to our daily lives".[21]

Elsevier started to publish *Journal of Molecular Catalysis* in 1975, followed in 1981 by *Applied Catalysis*. The latter journal was split in two sections in 1988, shortly after the 1987 launch by the same publisher of *Catalysis Today*. At approximately the same time another publisher, Springer, had started two journals in the field, namely *Catalysis Letters*, introduced in 1988 and *Topics in Catalysis*, which started in 1994.

Reflecting the rapid rise of publications in the field which occurred since the early 2000s,[6] several scientific publishers established new catalysis journals (Table 1).

Table 1: Catalysis journals launched since the early 2000s.

Journal	Year of launch	Publisher
Advanced Synthesis & Catalysis	2001	Wiley-VCH
ChemCatChem	2008	Wiley-VCH
Catalysis Science & Technology	2010	RSC Publishing
ACS Catalysis	2011	ACS Publishing
Catalysts	2011	MDPI
Modern Research in Catalysis	2012	SCIRP
Current Catalysis	2012	Bentham Science
Nature Catalysis	2018	SpringerNature

All these and related catalysis journals today publish research articles and reviews from all types of catalysis including heterogeneous catalysis, homogeneous catalysis, biocatalysis, electrocatalysis, photocatalysis, nanocatalysis and organocatalysis.

Following the 1950-1977 development of organometallic catalysis,[22] for which in 1963 the Nobel prize in chemistry was awarded to Natta and Ziegler for olefin polymerization and in 1973 to Fisher and Wilkinson for new olefin hydroformylation catalysts, the prestige of catalysis as an academic discipline increased again since the early 2000s.

In 2001 Noyori and Knowles became Nobel laureates for their work on chirally catalysed hydrogenation reactions and Sharpless for his work on chirally catalysed oxidation reactions. In 2005, Chauvin, Grubbs and Schrock were recognized for the development of the metathesis method in organic synthesis. In 2007, Ertl was awarded the Nobel prize for his studies of chemical processes on solid surfaces. His research included a seminal work on nitrogen fixation relevant for the Haber–Bosch ammonia synthesis process. Lately research in catalysis was once again in the spotlight after the Nobel prizes in 2010 were awarded to Heck, Negishi and Suzuki for cross-coupling catalytic reactions and in 2018 to Arnold for the directed evolution of enzymes.

Similarly to chiral ferrocenylphosphine ligands for asymmetric catalytic hydrosilylation of ketones introduced in 1974,[23] the catalysts developed by the Nobel laureates mentioned above and by several other chemists are widely used nowadays in manufacturing of fine and specialty chemicals, vitamins and other active pharmaceutical ingredients.

The almost contemporary emergence, in the early 1990s, of nanochemistry and green chemistry oriented to waste-prevention rather than waste control, drove a second wave of progress in catalysis science and technology.

A number of developed bottom-up material synthetic routes appeared such as the sol-gel and hydrothermal ones often "assisted" by microemulsion templates. These routes along with new surface chemical functionalization strategies enabled reproducible and robust preparation of nanostructured catalytic materials of high activity, selectivity and stability.[24] These materials are suitable for use in various application areas of catalysis, including less conventional ones, such as producing pharmaceutical "generics" with dramatically reduced reaction times, solvent utilization and waste production.[25]

Note that conventional, so-called stoichiometric production routes, used in manufacturing fine chemicals (10,000 t/a demand) and pharmaceuticals (1,000 t/a demand) generate substantial amounts of waste in general, reaching in the worst cases 100 kg of waste per kg of the manufactured product.[26]

SCIENTOMETRIC ANALYSIS

The scientometric assessment of research in catalysis referring to the 2006-2015 period shows that China led the ranking with 28.1% of the global share of research articles in the field, followed by the USA with 14.9% of the share.[5] The other countries in the ranking were Japan, India, Germany, France, South Korea, Iran, Spain and Great Britain. Together these first 10 countries accounted for 82.5% of the global publication share in the catalysis research output.

Following the same approach a scientometric assessment of research articles in catalysis published in indexed scientific journals between 2015 and November 13, 2020 (Table 2) was obtained in this work by carrying out a search in Scopus using the words "catalysis" or "catalyst" present in the title, abstract or keywords.

Limited to documents published in English in the form of research articles or reviews (excluding book chapters, conference papers and *erratum* communications), the search returned 279,829 documents. Of these, 279,042 were published in scientific journals, 623 in book series, 149 in trade journals, 12 in books and 3 in conference proceedings.

Interestingly the share of the leading countries (top 20 in Table 2) even increased in the last five years amounting to 83.9% of all papers in English published in journals indexed by Scopus, with China (28.8%) dominating even further. Germany surpassed Japan and Iran managed to remain amid the world's top 10 countries for research in catalysis regardless economic sanctions that, for example, slow down or even impede purchase of chemical reactants from academic laboratories in that country.

Other countries worth mentioning are Italy (12th in the global ranking) and Russia (11th in the ranking list). Russia, for example, hosts since 1958 the world's largest academic centre in the field of catalysis, the renowned Boreskov Institute of Catalysis, which is nowadays incorporated in the Russian Academy of Sciences.[27]

In Russia, since the 2006 new science policy allocates funds and grants depending on the research assessment based on publications in the international literature. Since then, the number of research papers published in English in all scientific fields including chemistry dramatically increased. The current policy in Russia also drives institutions outside of three main scientific cities (Moscow, St. Petersburg and Novosibirsk) to enter the international arena in a way similar to that followed by China in the last three decades with several leading universities and research centres today located well beyond China's two main cities (Beijing and Shanghai).

Indeed, amid the first twenty institutions including umbrella organizations (e.g. academies of sciences and national research councils) only few are not Chinese (Table 3), representing France, Russia and Spain.

As can be seen from Table 4 globally not chemical companies, but rather public funding organizations are responsible for financial support of scholars working in the field of catalysis. Contrary to Table 3 there is more diversity in top funding organizations representing not only China, but other Asian countries, Europe, including European Research Council and both North and South America.

It is instructive to analyze the top chemical journals which publish papers in the field of catalysis (Table 5). Among the top 10 two journals specialize only in catalysis (*ACS Catalysis* and *Applied Catalysis B: Environmental*), two specialize in materials and organic chemistry while the remaining ones are

Table 2: Top 20 most productive countries in catalysis research 2015- 2020 (Source: Scopus, November 13, 2020).

Ranking	Country	Number of papers	Share of papers (%)
1	China	104,148	28.8
2	United States	41,101	11.4
3	India	23,170	6.4
4	Germany	15,777	4.4
5	Japan	14,882	4.1
6	Iran	12,108	3.4
7	Great Britain	11,551	3.2
8	South Korea	11,440	3.2
9	France	9,463	2.6
10	Spain	9,304	2.6
11	Russian Federation	7,965	2.2
12	Italy	6,879	1.9
13	Canada	6,546	1.8
14	Australia	5,901	1.6
15	Brazil	4,895	1.4
16	Saudi Arabia	4,445	1.2
17	Taiwan	3,603	1.0
18	Poland	3,416	1.0
19	Netherlands	3,388	0.9
20	Switzerland	3,374	0.9

Table 3: Top 20 institutions in scientific output in catalysis in 2015-2020 (Source: Scopus, November 13, 2020).

Ranking	Country	Institution	Papers
1	China	Chinese Academy of Sciences	17,146
2	China	Ministry of Education China	14,950
3	China	University of Chinese Academy of Sciences	6,519
4	France	CNRS Centre National de la Recherche Scientifique	4,942
5	China	University of Science and Technology of China	3,156
6	China	Tianjin University	2,946
7	China	Tsinghua University	2,937
8	China	Zhejiang University	2,679
9	Russia	Russian Academy of Sciences	2,603
10	China	East China University of Science and Technology	2,535
11	China	Nanjing University	2,359
12	China	South China University of Technology	2,321
13	China	Dalian Institute of Chemical Physics Chinese Academy of Sciences	2,300
14	China	Dalian University of Technology	2,195
15	China	Sichuan University	2,056
16	China	Nankai University	2,032
17	China	Beijing University of Chemical Technology	1,995
18	China	Jilin University	1,890
19	Spain	Consejo Superior de Investigaciones Científicas	1,872
20	China	Nanyang Technological University	1,751

Table 4: Top 41 organizations funding catalysis research 2015-2020 (Source: Scopus, November 13, 2020).

Rank	Country	Funder	Papers
1	China	National Natural Science Foundation of China	68,168
2	China	Fundamental Research Funds for the Central Universities	10,530
3	USA	National Science Foundation	9,730
4	China	National Basic Research Program of China (973 Program)	7,111
5	Japan	Japan Society for the Promotion of Science	6,075
6	USA	National Institutes of Health	5,930
7	USA	U.S. Department of Energy	5,731
8	Korea	National Research Foundation of Korea	4,917
9	China	Chinese Academy of Sciences	4,810
10	China	China Postdoctoral Science Foundation	4,576
11	Germany	Deutsche Forschungsgemeinschaft	4,074
12	USA	Office of Science	3,514
13	UK	Engineering and Physical Sciences Research Council	3,095
14	China	Priority Academic Program Development of Jiangsu Higher Education Institutions	3,038
15	China	China Scholarship Council	2,929
16	EU	European Regional Development Fund	2,882
17	Canada	Natural Sciences and Engineering Research Council of Canada	2,815
18	EU	European Research Council	2,810
19	China	Natural Science Foundation of Jiangsu Province	2,794
20	Spain	Ministerio de economía y competitividad	2,433
21	EU	European Commission	2,418
22	Korea	Ministry of Science, ICT and Future Planning	2,332
23	Japan	Ministry of Education, Culture, Sports, Science and Technology	2,257
24	Brazil	Conselho Nacional de Desenvolvimento Científico e Tecnológico	2,180
25	China	Natural Science Foundation of Shandong Province	2,043
26	Australia	Australian Research Council	1,966
27	India	Science and Engineering Research Board	1,902
28	India	Department of Science and Technology, Government of Kerala	1,799
29	Brazil	Coordenação de Aperfeiçoamento de Pessoal de Nível Superior	1,777
30	India	Council of Scientific and Industrial Research	1,766
31	India	Department of Science and Technology, Ministry of Science and Technology	1,701
32	USA	National Institute of General Medical Sciences	1,625
33	China, Hong Kong	University Grants Committee	1,579
34	Russia	Russian Foundation for Basic Research	1,529
35	India	University Grants Commission	1,481
36	Russia	Russian Science Foundation	1,391
37	China	Ministry of Education of the People's Republic of China	1,388
38	China	Science and Technology Commission of Shanghai Municipality	1,376
39	China	Natural Science Foundation of Guangdong Province	1,367
40	France	Centre National de la Recherche Scientifique	1,280
41	EU	Seventh Framework Programme	1,218

Table 5: Top 80 (from 160) journals publishing catalysis research 2015-2020 (Source: Scopus, November 13, 2020).

Rank	Journal	CiteScore* (2016-2019)	Papers
1	*RSC Advances*	6.5	7,178
2	*AngewandteChemie International Edition*	20.8	5,326
3	*Chemical Communications*	9.8	5,274
4	*ACS Catalysis*	19.6	5,269
5	*Journal of the American Chemical Society*	24.8	4,916
6	*International Journal of Hydrogen Energy*	8.0	4,596
7	*Journal of Organic Chemistry*	7.8	3,925
8	*Applied Catalysis B: Environmental*	25.3	3,608
9	*Chemistry A European Journal*	9.0	3,480
10	*Journal of Materials Chemistry A*	17.1	3,235
11	*Catalysis Today*	9.5	3,123
12	*Chemical Engineering Journal*	15.2	3,116
13	*Catalysis Science and Technology*	10.2	3,074
14	*ChemCatChem*	7.4	3,045
15	*ACS Applied Materials & Interfaces*	13.6	3,043
16	*Organic Letters*	10.4	2,901
17	*Applied Surface Science*	8.7	2,599
18	*New Journal of Chemistry*	4.7	2,566
19	*Tetrahedron Letters*	4.5	2,488
20	*Journal of Physical Chemistry C*	7.3	2,463
21	*Catalysts*	3.7	2,424
22	*Applied Catalysis A General*	8.5	2,301
23	*ACS Sustainable Chemistry & Engineering*	9.7	2,234
24	*ChemistrySelect*	2.6	2,219
25	*ElectrochimicaActa*	10.0	2,218
26	*Organic & Biomolecular Chemistry*	6.1	2,027

27	*Industrial & Engineering Chemistry Research*	5.3	1,968
28	*Journal of Catalysis*	11.9	1,944
29	*Dalton Transactions*	6.8	1,941
30	*Nature Communications*	18.1	1,812
31	*Catalysis Letters*	4.1	1,739
32	*Tetrahedron*	4.3	1,700
33	*Fuel*	9.1	1,697
34	*Catalysis Communications*	6.7	1,688
35	*Green Chemistry*	15.8	1,680
36	*Nanoscale*	11.3	1,621
37	*Advanced Synthesis & Catalysis*	9.3	1,593
38	*ChemSusChem*	12.5	1,511
39	*Chemical Science*	15.5	1,503
40	*Applied Organometallic Chemistry*	3.6	1,486
41	*European Journal of Organic Chemistry*	4.9	1,472
42	*Journal of Colloid and Interface Science*	11.0	1,413
43	*Synlett*	4.4	1,391
44	*Synthesis*	4.9	1,369
45	*Physical Chemistry Chemical Physics*	6.3	1,340
46	*Journal of Hazardous Materials*	13.1	1,330
47	*Journal of Power Sources*	14.4	1,319
48	*Molecular Catalysis*	7.5	1,308
49	*Research on Chemical Intermediates*	3.9	1,279
50	*Scientific Reports*	7.2	1,216
51	*Organometallics*	6.9	1,199
52	*Molecules*	4.1	1,151
53	*Inorganic Chemistry*	7.9	1,091
54	*Microporous and Mesoporous Materials*	7.7	1,079
55	*Journal of Alloys and Compounds*	7.6	1,078
56	*Journal of The Electrochemical Society*	5.8	1,065
57	*Journal of Biological Chemistry*	7.4	1,028
58	*Chemosphere*	8.8	1,007
59	*Organic Chemistry Frontiers*	7.7	1,006
60	*Energy and Fuels*	5.7	958
61	*ACS Omega*	2.7	942
62	*Bioresource Technology*	12.8	929
63	*Reaction Kinetics, Mechanisms and Catalysis*	2.5	889
64	*Journal of Organometallic Chemistry*	3.8	878
65	*Environmental Science and Pollution Research*	4.9	869
66	*Chemistry - an Asian Journal*	6.3	798
67	*Advanced Materials*	41.3	794
68	*Carbon*	14.1	785
69	*Biochemistry*	5.3	775
70	*Biosensors and Bioelectronics*	17.6	775
71	*International Journal of Biological Macromolecules*	6.9	773
72	*Synthetic Communications*	2.6	760
73	*Fuel Processing Technology*	9.5	754
74	*Sensors and Actuators B Chemical*	11.8	740
75	*ChemElectroChem*	5.6	737
76	*Topics in Catalysis*	4.4	727
77	*Chinese Journal of Catalysis*	8.7	723
78	*Ceramics International*	6.1	722
79	*Nano Energy*	23.1	719
80	*Journal of Environmental Chemical Engineering*	6.7	718

*CiteScore 2019 reflects the number of citations in 2016-2019 to papers, reviews, etc published in those years divided by the total number of publications in the same period.

multidisciplinary chemistry journals. In fact among 80 journals publishing in the field, many possess such multidisciplinary flavor and only less than 20% publish exclusively papers devoted to catalysis.

Pointing to slow but increasing acceptance of the open access (OA) publishing model also among chemists, out of 279,829 articles published in 2015–2020 OA was opted in 18.0% of the cumulative number of papers published.

The graph in Figure 1 shows that the yearly number of studies is constantly increasing reflecting the steady attention to the field of catalysis in industry and academia.

To understand the scope of the growth of research in catalysis science and technology it is enough to learn that a similar search for original research and review articles published in English limited to year 2000 returned 16,339 documents. In

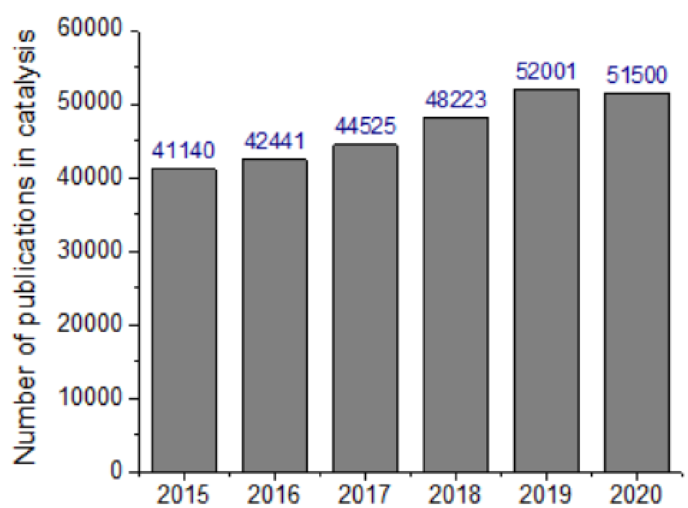

Figure 1: Yearly number of publications in catalysis science and technology, 2015-2020 (November 17, 2020). [Source: Scopus].

other words, the scientific output in catalysis has more than tripled, largely due to contributions of scholars based in Asia, predominantly in China and India, but also in South Korea and in Iran. An old research field historically dominated by researchers based in USA, Europe and Japan is now largely dominated by China. With over 1.35 billion inhabitants growing at a fast pace and a vibrant chemistry and chemical engineering school growing rapidly in terms of quality, quantity, funding and international collaborations,[28] India is likely to surpass contributions from the USA within the next decade.

EXPANDED SCOPE OF CATALYSIS RESEARCH

From the economic viewpoint research in catalysis is particularly important because, through further organic process development, it enables the production of virtually all chemical substances, including value-added fine and specialty chemicals and active pharmaceutical ingredients (APIs).

Certainly, utilization of continuous production technologies is a common place in production of fuels and bulk chemicals, However, utilization of the same practices in manufacturing of fine chemicals is reshaping the industry at the global level. Until the advent of flow chemistry production processes, manufacturing fine chemicals and APIs, requiring significant capital and operational expenses (CAPEX and OPEX, respectively), was limited to developed countries with long chemical traditions. Different European countries including those formerly belonging to the Soviet block, as well as countries in North America can be mentioned in this context. In other places (e.g. China and India) production was outsourced to companies identified in the chemical business jargon as "custom manufacturing organizations" (CMOs).[29]

Coupled to the new generation heterogeneous catalysts, flow chemistry dramatically lowers both CAPEX and OPEX costs. The former costs are dramatically reduced because large batch reactors equipped with complex temperature, mixing and pressure control tools are replaced by one or more small flow reactors. This enables far better controlled, safer and milder reaction conditions.

The latter costs fall because as already noted by Pollak in 2011 in the preface to his reference book devoted to the fine chemical industry the "most progressive companies adopt lean production principles originally developed for the automotive industry".[29]

Continuous production in small and modular flow reactors with new generation solid catalysts prevents the formation of unwanted by-products, eliminates the need for separation of catalysts and products and shortens time to market. Production becomes truly driven by customer demand preventing overproduction. In this way operating a fine chemicals plant resembles the same lean production mode used by the most advanced manufacturing industries.[30] This shift in the paradigm requires new skills and much broader utilization of chemical engineering practices, which were often in the periphery of process development focusing otherwise on chemistry.

The increasing shortage of APIs, especially of generics, in many developed and developing countries culminated with shortage of hydroxychloroquine (HCQ) used to treat COVID-19 patients. Such situation, which in early 2020 led India to dramatically scale up production for donating the drug to more than 50 countries,[31] has made it clear that countries cannot rely any longer on API and fine chemical imports.

The creation from scratch of a national fine chemical and pharmaceutical industry in African, Asian, Latin American and European countries is now possible. Followed by South Africa with 1,859 publications in the field of catalysis in 2015-2020 (November 13, 2020) period, with 2,258 publications Egypt leads the rank of African countries. Algeria (788), Tunisia (581) and Morocco (429) rank third, fourth and fifth. The impact of COVID-19 epidemics in North African countries was very limited. In Morocco the government acquired all HCQ-containing drugs locally manufactured by a foreign company on March 2020.[32] Algeria took similar initiative at the same time negotiating with two pharmaceutical groups the purchase of large quantities of drugs using hydroxychloroquine as API both produced in Algeria and imported.[33] Tunisia begun manufacturing hydroxychloroquine locally.[34]

The latter non-steroidal drug with anti-inflammatory activity, a generic widely used also for the treatment of rheumatoid arthritis, can be manufactured under flow conditions with an yield improvement of 52% compared to the commercial process. The technology combines two packed bed reactors with one batch reactor used for heterogeneously catalyzed reductive amination and hydrogenation steps, affording direct conversion of the starting materials to HCQ.[35]

The example can be generalized. Most synthetic routes for the production of fine chemicals and APIs can now be carried out under flow using heterogeneous catalysts. These routes utilizing also single-atom catalysts,[36] are approaching commercialization at a fraction of the cost of conventional routes in much smaller chemical factories scattered across countries. Under these conditions, chemistry professionals specializing in catalysis and contemporary process chemistry should be in strong demand for all countries willing to become at least partly self-sufficient in the production of life-saving drugs.

OUTLOOK AND CONCLUSION

The field of catalysis is growing and changing its geography. This becomes apparently evident from the analysis of the top organizations, funding agencies and number of papers published by scholars representing different countries. The field is also expanding beyond its conventional borders comprising classical areas of oil refining, chemicals manufacturing and pollution control, to include also production of pharmaceuticals.

In this context, improving and broadening research and education in catalysis becomes a strategic need for governments and national economies. Four main guidelines, two for governments and two aimed at chemical companies, emerge from the present scientometric analysis and related studies on the global reshaping of the chemical industry.[37]

First, aware that catalysis and process chemistry are the key enabling technologies of the chemical industry, governments should support the creation of dedicated research centres as done for example in Russia with the Boreskov Institute of catalysis.[27] We are already witnessing such initiatives across the globe which in fact allow different research and educational institutions achieve the required critical mass to act as purposeful partners of the chemical industry.

Second, in most countries education in catalysis at the undergraduate level is generally not adequate, lacking uniformity[9] and suffering from a still fragmented approach to its sub-disciplines.[10] To overcome such situation, the example of Germany should be followed, where a national curriculum (*Lehrprofil Katalyse*) was created in 1993 being since then constantly updated.

Third, aware of the unique economic relevance of catalysis, chemical companies should start effective collaboration with public research centres thereby increasing the research and development (R&D) capacity of local firms and entrepreneurs and innovation capacity of young researchers. There are many ways to do that. Among examples known to the authors Germany, France, Finland and Switzerland should be mentioned. Worth emulating is, for instance, Switzerland where regular professional workshops between industry's and academic researchers are organized.[38]

Fourth, chemical companies should learn from what happened to manufacturers of gas-powered turbines whose market shrank from 60 GW in 2014 to 31 GW in 2018,[39] due to completely unforeseen and rapid global uptake of wind and photovoltaic power generation across the world.[40] Considering that renewable power coupled with the demand and development of Li-ion batteries is cheaper than the gas generation even without subsidies,[41] it is highly unlikely that the market for gas-powered turbines will ever recover.

The same will shortly happen with flow chemistry and new catalytic technology in chemical manufacturing. After more than two decades in which green chemistry remained mostly confined to academic research papers and conferences,[42] the falling costs of flow chemistry reactors coupled to the increasing availability of completely new heterogeneous catalysts provides a highly profitable business opportunity for all new fine chemical manufacturers. For example, using novel green technologies new or existing companies might start producing the APIs of generic medicines in increasing shortage[43] at a fraction of the cost of competitors utilizing old production technology in batch reactors.

Now that regulatory agencies in most countries allow the use of flow chemistry for manufacturing APIs and fine chemicals, it is enough to analyze the sales of industrial flow reactors to learn that the process has already started.[44]

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CONFLICT OF INTEREST

The authors declare no competing interest.

ABBREVIATIONS

ACS: American Chemical Society; **APIs:** Active pharmaceutical ingredients; **CAPEX:** Capital expenses; **CMOs:** Custom manufacturing organizations; **GW:** Gigawatts; **HCQ:** Hydroxychloroquine; **OA:** Open access; **OPEX:** Operational expenses; **R&D:** Research and development.

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