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Short Communication

The most frequently cited adsorption research articles in the Science Citation Index (Expanded)

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ABSTRACT

The 126 most frequently cited articles published in the adsorption field between 1900 and 2011 were identified and characterized using the Science Citation Index (Expanded). The data analyzed cover a range of publication years, journals, Web of Science categories, authors, institutions, countries/territories, life citation cycle curves, and characteristics of frequently cited articles. The 126 most-frequently-cited articles were each cited an average of 1014 times, ranging from 502 to 9922 citations per article from 1918 to 2006; 80% of these articles were published after 1970. Fifty-five journals were represented, led by the *Journal of the American Chemical Society*, and followed by *Science* and *Nature*. Three categories out of the 35 Web of Science categories constituted 60% of the citations. The three categories were: physical chemistry, multidisciplinary chemistry, and multidisciplinary sciences. Thirteen of the authors contributed three or more articles. Harvard University, the Massachusetts Institute of Technology, and the University of Washington led the list of 107 institutions, while the United States led the list of 17 countries/territories, comprising more than half of the articles. Collaboration among the top authors was a frequent occurrence, while inter-institutional collaboration and national collaboration was not obvious among the topmost articles. Moreover, the citation patterns as a function of time varied widely among the topmost articles. As evidenced by citation life cycles, the well known BET and Langmuir isotherms have received considerable attention during the study period, and will probably continue to be popular in the adsorption field. Some emerging hotspots are likely to receive particular attention in the near future; these include the new family of "M41S" materials, pseudo-second-order kinetic models, and the nudged elastic band method.

1. Introduction

At the beginning of the 19th century, the adsorption of gases onto glass powders was reported in *Annalen der Physik* [1] according to the Science Citation Index (Expanded). As early as the 18th century, Boedeker first presented an isotherm for adsorption of both basic and acidic radicals onto soils [2]. However, since the isotherm was employed for adsorption from solutions in 1906 [3], it has been called the Freundlich isotherm and is now considered to be one of the most frequently applied isotherms in the adsorption field. Many studies have contributed to the long term development of the absorption field [4,5]. Moreover, the number of citations received by an article reflects its scientific impact [6], and also provides an objective methodology for "ranking" articles [7]. Therefore, highly cited articles on adsorption were retrieved for investigation in this study to directly and efficiently characterize the impact of publications dealing with adsorption.

Similarly, in prior years, efforts were made to identify and analyze the most frequently cited articles in various fields, such as for example the medical fields, the leading dermatologic journals [8], the *Journal of Molecular Biology* [7], journals dedicated to anesthesia and pain [9], and the ophthalmology journals [10]. In these earlier studies, the number of articles cited was often used as an indicator of scientific performance, for instance in subject categories such as anesthesia and pain [9], ophthalmology [10], and obstetrics and gynecology [11]. Topmost articles were commonly listed to provide a basic source of information [12,13]. The topmost articles were categorized according to publication year [10,11,14], journal [10,11,13–15], authors [10–13,15], countries and institutions [12–14]. Of course, the number of citations of a paper is probably not sufficient to characterize the impact of a paper. Indicators such as numbers of authors cited, numbers of institutions cited, numbers of countries cited, numbers of subject areas cited, citations per year, and total number of citations of a paper to date have been applied to the high-impact papers on the subject of water

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resources [16]. Citation life cycles of highly cited articles were also considered to be important [17–19]. The citation history of papers gives more details of the impact character of articles [20].

The articles analyzed in the present work were those in the field of adsorption having more than 500 citations during the past 110 years. This study identified and examined the characteristics covering publication year, journals, Web of Science categories, authors, institutions, countries/territories, life citation cycles, and characteristics of the topmost articles.

2. Methodology

The methodology used in this study was based on the Science Citation Index (SCI-Expanded) database of Web of Science from Thomson Reuters (updated on 19 January 2012). The schematic for searching topmost articles is shown in Fig. 1. There were 305,174 documents from 1900 to 2011 with keywords "adsorption", "sorption", and "biosorption", in titles, abstracts, keywords, and "KeyWordsPlus" found using search tools in the Web of Science. The total annual citations for each article were also downloaded. Secondly, regular articles and proceedings papers (282,208) were the only document types considered. Other document types, such as meeting abstracts, notes, reviews, letters, editorial materials, corrections, book chapters, correction additions, discussions, book reviews, abstracts of published items, reprints, news items, bibliographies, items about an individual, software reviews, biographical items, and hardware reviews were excluded. Thirdly, TC2011 $\geqslant$ 500 were used as a filter to extract the most highly cited articles (154). "TC2011" denotes the total citations since publication of the article up to the end of 2011 [16]. "C2011" denotes the total citations in 2011. The advantage of this indicator is that it is an invariant parameter, thus ensuring repeatability, in comparison with the index of citation from Web of Science which has been updated from time to time. The final filter is the "front page," by which is meant that only those 126 articles containing the search keywords on their front page, article title, abstract, and author keywords were searched. Therefore, 0.0413% of the total articles are regarded as the top topmost articles. The top 126 articles having the keywords "adsorption", "sorption," or "biosorption" in the front page and having TC2011 $\geqslant$ 500 were retrieved for further analysis.

All results were analyzed using Microsoft Excel 2007. In subsequent analysis, articles originating from England, Scotland, Northern Ireland, and Wales were classified as being from the United Kingdom (UK) [21]. Articles originating from the Federal Republic of Germany (Fed Rep Ger), West Germany, and Germany were classified as being from Germany. Articles from Hong Kong before 1997 were included with China. The contributions from institutions and countries/territories were identified by the appearance of at least one author in the publications. Collaboration type was determined from the addresses of the authors. The articles were classified into four types based on the country/territory and institution: (1) "single country article," if the researchers' addresses were from the same country; "single institution article," if the researchers' addresses were from the same institution; (2) "internationally collaborative article," if the articles were coauthored by researchers from multiple countries [21]; "inter-institutionally collaborative article," if authors were from different institutions; (3) "first author article," if the first author was from the country/territory or institution for analysis; and, (4) "corresponding author article," if the corresponding author was from the country/territory or institution for analysis. TP, SP, CP, FP, and RP are the number of total articles, "single country articles" or "single institution articles", "internationally collaborative articles" or "inter-institutionally collaborative articles", "first author articles", and "corresponding author articles" for a country/territory or institution, respectively.

3. Results and discussion

3.1. Publication year

The 126 topmost articles (TC2011 $\geqslant$ 500) were published in the past 89 years from 1918 to 2006. Fig. 2 illustrates the distribution of these 126 articles over the years, and their citations per publication (CPP). The publication output by decade increased from the 1910s to the 1970s, but fell temporarily in the 1980s, and rocketed to a high of 50 articles in the 1990s, and finally dropped during the most recent decade. The decade with the most articles was the 1990s, which had 50 articles (40%), followed by the decade of the 2000s with 24 articles (19%), and the decade of the 1980s with 17 articles (13%). The three most productive years were in the 1990s, namely 1999 (11 articles), 1991 (8 articles), and 1997 (7 articles). No topmost articles have been found in the decade of the 1920s, and no topmost articles have yet emerged in the most recent 5 years (2007–2011). Obviously, the recent articles need time to accumulate citations [7].

Only six of the topmost articles were published prior to 1950, while four fifths of the topmost articles appeared after 1970. It seems that with increasing time since publication there is an increasing chance of the paper being forgotten [7]. In addition, as time passes, even "true classics" are gradually less often cited, probably because their substance is being absorbed by the current knowledge, a phenomenon that has been termed "obliteration by incorporation" [22]. In particular, the decade of the 1930s, with two articles, and the 1910s, with one article, had much higher CPP's, 5215 and 3576, which can be attributed to the article by Brunauer et al., in 1938, with a TC2011 of 9922, and Langmuir, in 1918, with a TC2011 of 3576. The CPP's of the 1940s and the 1990s were 1248 and 1138 respectively, while the CPP's of the other five decades ranged from 710 to 880.

The 126 topmost articles during 1918–2006 are shown in Figs. 3-1–3-3, in three stages: 1918–1991, 1991–1997, and 1997–2006, respectively. The 126 articles received a total of 127,769 citations. In terms of TC2011, 65 articles (52%) received 500–700 citations each and totaled 37,513 citations (29%); 33 (26%) of the articles received 701–1000 citations each and totaled 26,591 citations (21%); 15 articles (12%) received 1001–1500 citations each and totaled 18,034 citations (14%); 7 articles (5.6%) received 1501–2000 citations each and totaled 12,255 citations (10%); 4 articles (3.2%) received 2001–4000 citations each and totaled 14,214 citations (11%); and 2 articles (1.6%) received more than

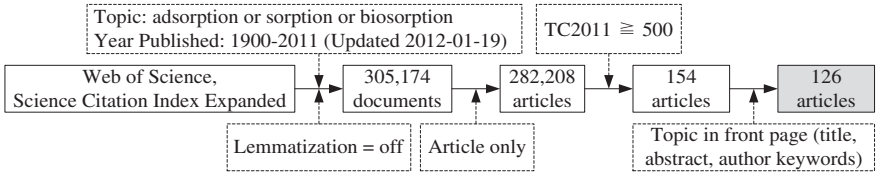

Fig. 1. Schematic for searching the topmost articles.

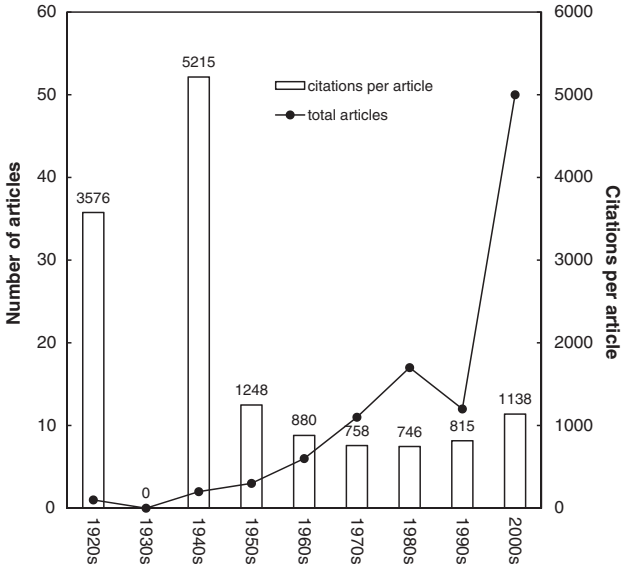

Fig. 2. Number of articles and citations per article by decade.

9000 citations each and totaled 19,162 citations (15%). The mean number of CPP was 1014, which was much higher than the value of 100 classic citations in some medical fields, such as 405 in general surgical journals [15], 447 in orthopaedic surgery [14], 629 in urology [13], 283 in anesthetic journals [12], and 318 in ophthalmology journals [10].

The most frequently cited article (TC2011 = 9922) was titled "adsorption of gases in multimolecular layers" by Brunauer et al. in the *Journal of the American Chemical Society* in 1938. This is the well known multi-layer adsorption isotherm, the so-called BET (Brunauer, Emmett, and Teller) isotherm [5]. Langmuir published the earliest topmost adsorption article "the adsorption of gases on plane surfaces of glass, mica and platinum" in the *Journal of the American Chemical Society* in 1918 (TC2011 = 3576). This is the first theoretical adsorption isotherm, named the Langmuir isotherm [4]. The most recent topmost article was titled "effects of functionalization, catenation, and variation of the metal oxide and organic linking units on the low-pressure hydrogen adsorption" published in the *Journal of the American Chemical Society* by Rowsell and Yaghi in 2006 (TC2011 = 516). The peak period of topmost articles was an 89 year period from 1918 to 2006; the TC2011 has a high mean number of CPP of articles ranging from 502 to 9922.

3.2. Journal and Web of Science category

The Journal Citation Reports (JCRs), indexes 8073 journals with citation references across 174 scientific disciplines in 2010. The impact factor of a journal according to JCR for the year 2010 was determined based on top articles reported in that year. The topmost articles were published by 55 journals among the 35 Web of Science categories issued by six countries including 30 journals from the USA, UK (13), Netherlands (6), Switzerland (4), and one each from Germany and France. The classic articles on adsorption were distributed in more journals than were the topmost articles in some medical fields, such as, for example, the eleven journals cited in the top 100 cited articles in obstetrics and gynecology [11], 10 journals cited in the top 100, from general surgical citations classics [15], seven journals cited in the top 100 from classic papers of orthopaedic surgery [14], 15 journals cited in the top 100 cited articles, from urology [13], five journals cited in the top 10 cited articles, from anesthetic citation classics [12], and 13 journals in 100 from ophthalmology class citations [10]. Of these 55 journals, 35 (64%) journals contained only one article; 15 (27%) journals contained 2–4 articles; 5 (9%) journals contained more than five articles, and accounted for 39% of the total articles. Eight journals had impact factors higher than 10 in 2010; nine journals with impact factors between 5 and 10; 15 were between 3 and 5; 12 were between 1 and 3; and 11 journals had no impact factors in JCR in 2010. The *Journal of the American Chemical Society* published the most "top-cited articles" with 21 articles (17%), followed by *Science* with 9 articles, and *Nature* with 8 articles, while their impact factors were 9.023, 31.777, and 36.104 respectively (Table 1). As expected, the topmost articles were published in journals with

(1) TC2010 and authors of the top-cited articles according to the order of their publication years (1918-1991).

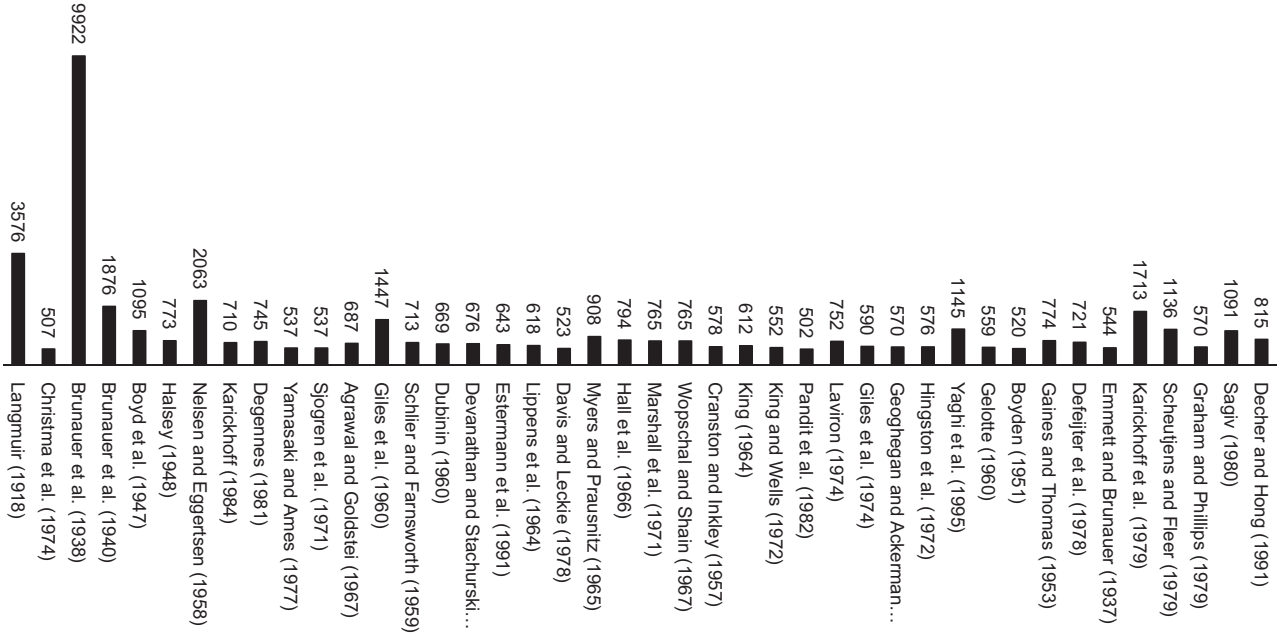

Fig. 3.1. TC2010 and authors of the top-cited articles according to the order of their publication years (1918–1991).

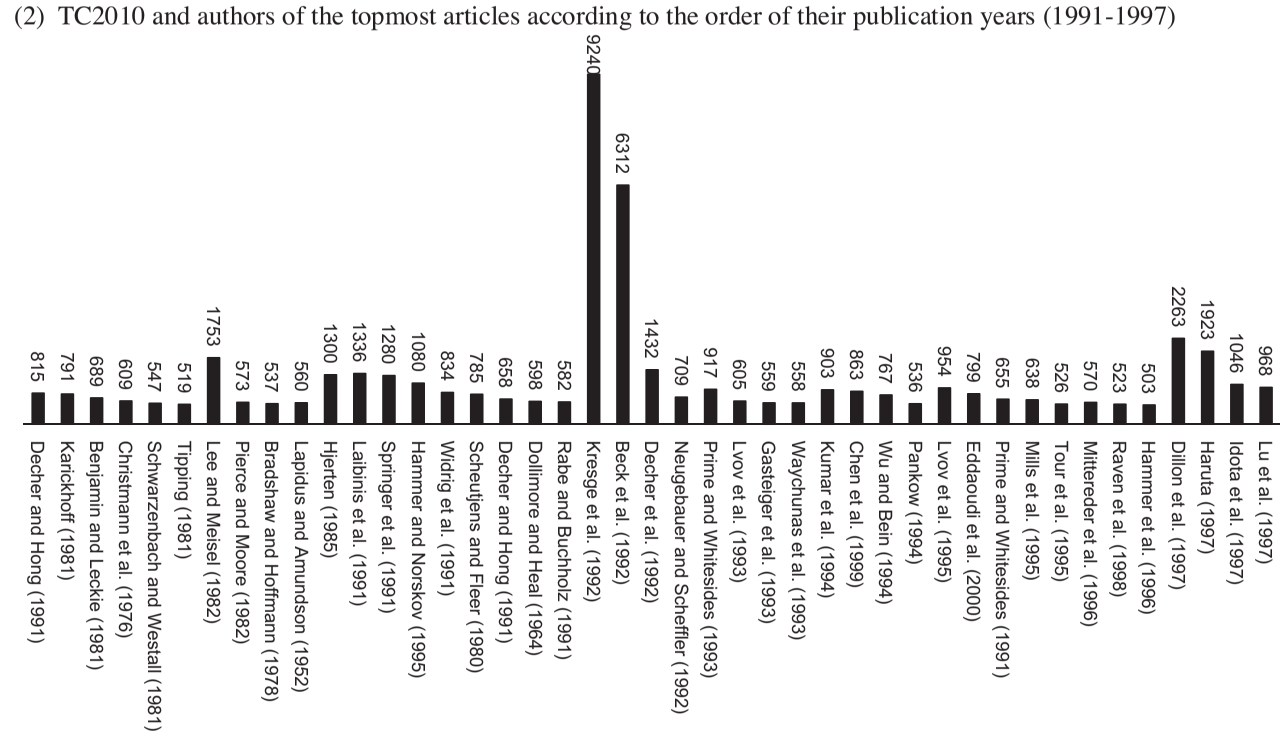

Fig. 3.2. TC2010 and authors of the topmost articles according to the order of their publication years (1991–1997).

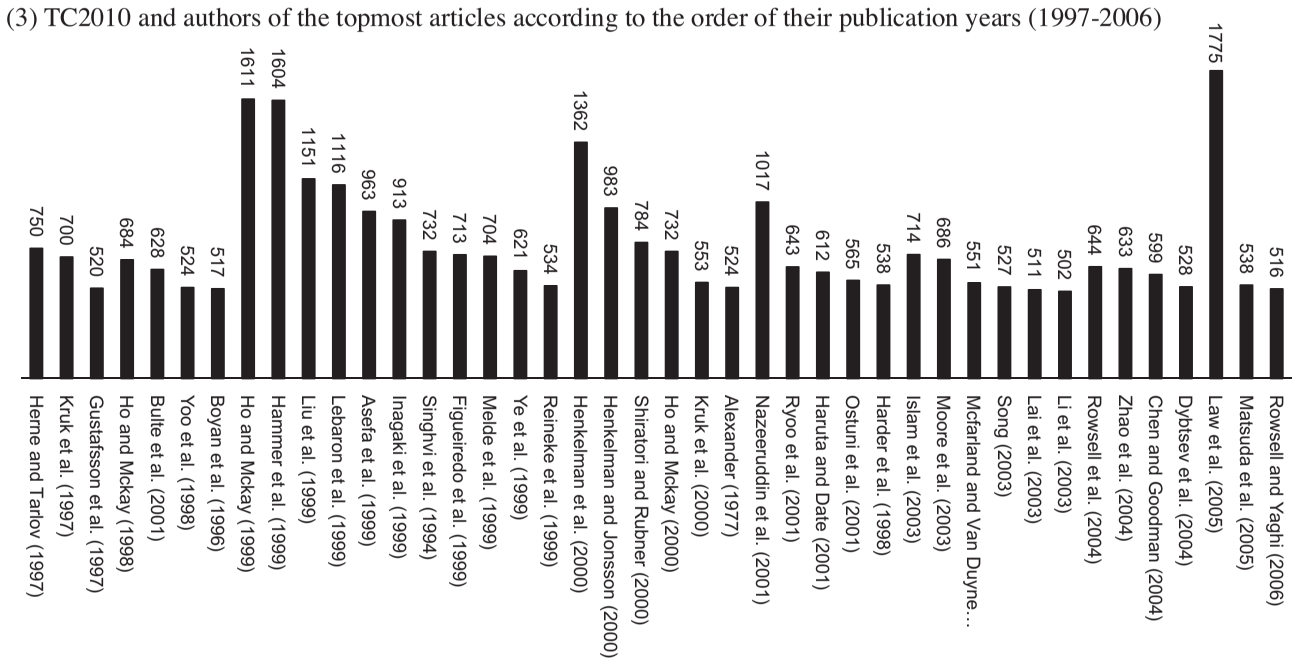

Fig. 3.3. TC2010 and authors of the topmost articles according to the order of their publication years (1997–2006).

high impact factors, similar to the subject area of anesthetics [12]. Note: the leading journals attracted the topmost publications, which in turn maintained the high impact factor of these journals [23]. In addition, articles with TC2011 > 1000 could also be found in journals with lower impact factors such as *Thin Solid Films* with IF = 1.909, *Applied Clay Science* with IF = 2.303, *Journal of the Electrochemical Society* with IF = 2.42, *Process Biochemistry* with IF = 2.648, *Journal of Chemical Physics* with IF = 2.92, and *Catalysis Today* with IF = 2.993. Note that the impact factor from JCR in 2010 from the *Journal of Physical Chemistry* was not available, because the *Journal of Physical Chemistry* was split into *Journal of Physical Chemistry A* and *Journal of Physical Chemistry B* in 1997, and then beginning in 2007, the latter underwent a further split, which included the *Journal of Physical Chemistry C*.

Similarly, some others journals, such as the *Journal of Chromatography* (2 articles), were also split into two or more journals, owing to the ever-growing amount of research in their subject areas.

Table 1
Characteristics of top eight journals with the most frequently cited articles.

Journal	TP (%)	Impact factor	Web of science category (position by impact factor/total journals)
Journal of the American Chemical Society	21 (17)	9.023	Multidisciplinary chemistry (11/147)
Science	9 (7.1)	31.777	Multidisciplinary sciences (2/59)
Nature	8 (6.3)	36.104	Multidisciplinary sciences (1/59)
Journal of Chemical Physics	6 (4.8)	2.921	Atomic, molecular and chemical physics (7/33)
Journal of Physical Chemistry	5 (4)	N/A	N/A
Langmuir	4 (3.2)	4.269	Multidisciplinary chemistry (24/147); physical chemistry (29/127); multidisciplinary materials science (26/225)
Journal of Colloid and Interface Science	4 (3.2)	3.068	Physical chemistry (40/127)
Surface Science	4 (3.2)	2.011	Multidisciplinary chemistry (11/147)

TP: total number of top cited articles; N/A: not available.

Within the total 35 Web of Science categories, 24 categories (69%) published 0–5 topmost articles, six categories (17%) published 6–10 articles, three categories (9.0%) published 11–20 articles, and two categories (6.0%) published more than 30 articles. The three top categories include physical chemistry, with 32 articles, multidisciplinary chemistry, with 31 articles, and multidisciplinary sciences with 20 articles; these three had a majority of the total top-cited articles, with the very high percentage of 60%. Others were multidisciplinary materials science and condensed matter physics, both with 13 topmost articles; environmental sciences with nine articles; chemical engineering, applied physics, environmental engineering, and analytical chemistry all with seven articles; atomic, molecular and chemical physics with six articles; and water resources, polymer science, and nanoscience and nanotechnology with four articles. In addition, three categories had four articles; five categories had two articles; and 13 categories had one article.

3.3. Authors, institutions, and countries/territories

Each person listed as an author of an article has made an independent material contribution to the manuscript [24]. The results of author analysis have identified those researchers who have made significant contributions. Among the 363 authors contributing to 126 top-cited articles, 321 authors (88%) published one topmost article; 29 authors (8.0%) published two topmost articles; 10 authors (2.8%) published three topmost articles; and only three authors published four or more of the topmost articles.

Table 2 lists the most productive authors with three or more articles. Whitesides (Harvard University, USA) published the most articles (8 articles) on systems using self-assembled organic monolayers, but he had no articles as either the first author or as the responding author. The most cited article among Whitesides' eight articles was titled "comparison of the structures and wetting properties of self-assembled monolayers of normal-alkanethiols on the coinage metal-surfaces, Cu, Ag, Au" (TC2011 = 1336) in *Journal of the American Chemical Society*. In 2nd place, Yaghi (Arizona State University, USA) published five articles and was the corresponding author of all five articles. The most popular article of Yaghi was "selective binding and removal of guests in a microporous metal–organic framework" (TC2011 = 799) in *Nature*. Decher (University of Mainz, Germany) who finished 3rd in the list had four articles, in three of which Decher collaborated with the author finishing 12th, Hong from the University of Mainz, on buildup of ultrathin multilayer films by a self-assembly process, and he published a series of related articles. The series of articles contained three articles, and the most heavily cited article was "buildup of ultrathin multilayer films by a self-assembly process: III. Consecutively alternating adsorption of anionic and cationic polyelectrolytes on charged surfaces" (TC2011 = 1432) in *Thin Solid Films*. The author in 4th place, Karickhoff (U.S. Environmental Protection Agency, USA), and the author in 5th place, Hammer (Aalborg University, Denmark; Technical University of Denmark, Denmark) published three top articles, in which they were first author as well as corresponding author. Of Karickhoff's three articles his most frequently cited was "sorption of hydrophobic pollutants on natural sediments" (TC2011 = 1713) in 1979 in *Water Research*. Hammer collaborated with the 11th position Norskov from the Technical University of Denmark and published three articles, the most cited of which was "improved adsorption energetics within density-functional theory using revised Perdew–Burke–Ernzerhof functionals" (TC2011 = 1604) in *Physical Review B*. Subsequently, the

Table 2
Thirteen highly productive authors of three or more topmost articles.

Author	Institution	Rank (TP)	Rank (FP)	Rank (RP)
Whitesides, G.M.	Harvard University, USA	1 (8)	N/A	10 (1)
Yaghi, O.M.	Arizona State University, USA; University of Michigan, USA	2 (5)	14 (1)	1 (5)
Decher, G.	University of Mainz, Germany	3 (4)	1 (3)	2 (3)
Karickhoff, S.W.	U.S. Environmental Protection Agency, USA	4 (3)	1 (3)	2 (3)
Hammer, B.	Aalborg University, Denmark; Technical University of Denmark, Denmark	4 (3)	1 (3)	2 (3)
Ho, Y.S.	Hong Kong University Science & Technology, Hong Kong	4 (3)	1 (3)	N/A
Brunauer, S.	George Washington University, USA	4 (3)	5 (2)	N/A
Kruk, M.	Kent State University, USA	4 (3)	5 (2)	N/A
Jaroniec, M.	Kent State University, USA	4 (3)	N/A	10 (1)
Mckay, G.	Hong Kong University Science & Technology, Hong Kong	4 (3)	N/A	2 (3)
Norskov, J.K.	Technical University of Denmark, Denmark	4 (3)	N/A	N/A
Hong, J.D.	University of Mainz, Germany	4 (3)	N/A	N/A
Jonsson, H.	University of Washington, USA	4 (3)	N/A	N/A

TP: total publications; FP: first author publications; RP: corresponding author publications; N/A: not available.

author in 6th position, Ho collaborated with the 10th position author, McKay from Hong Kong University Science and Technology, China, on the pseudo-second order model for the kinetics of sorption, and published three articles where Ho was assigned as the first author and McKay was assigned as the corresponding author. The most cited article was titled, "pseudo-second order model for sorption processes" (TC2011 = 1611) in *Process Biochemistry*. The author in 7th place, Brunauer had three articles, and one of them was the most highly cited article (TC2011 = 9922), which presented the well known BET adsorption isotherm. The author in 8th position, Kruk collaborated with the 9th position, Jaroniec, both from Kent State University in the USA, and published three articles. Among them, the most cited article was "application of large pore MCM-41 molecular sieves to improve pore size analysis using nitrogen adsorption measurements" in *Langmuir*. Jonsson (University of Washington, USA) published three articles, but was not recognized as the first author nor as one of the corresponding authors. Two of Jonsson's articles were assigned to Henkelman (University of Washington, USA) as the first author, and Jonsson's most cited article was titled "a climbing image nudged elastic band method for finding saddle points and minimum energy paths" in *Journal of Chemical Physics*. These clues show that top authors collaborate to publish top-cited articles, which in turn maintain the high rankings of these authors.

Twenty-four articles were excluded, because they did not have any author address information in the Web of Science; the 102 articles that specified addresses were further analyzed regarding institutions, and countries/territories. Altogether, 102 articles originated from 107 institutions in 17 countries/territories. The top 14 institutions appear in Table 3, with Harvard University of the USA (8 articles), Massachusetts Institute of Technology of the USA (6 articles), and University of Washington of the USA (5 articles) leading the list.

Of the total articles, 64 articles (63%) came from independent institutions, 38 articles (37%) from inter-institutional collaborations, and 14 articles (14%) from national collaborations. It was reported that collaboration was more likely to happen among small institutions than among large countries [25]. The inter-institutional collaboration rate was observed to be large in certain fields, such as 62% of global climate change [26], 53% of atmospheric simulation [27], 44% of solid waste research [28], and 53% of acupuncture research [29]; in contrast, inter-institutional collaboration rate was smaller in some medical fields, such as 12% of 100 top-cited articles in general surgical journals [15], and 8% of 100 ophthalmology class citations [10]. For example, the Massachusetts Institute of Technology, Kent State University, Stanford University, Technical University of Denmark, and Pennsylvania State University had no independent articles, while Arizona State University, University of Mainz, U.S. Environmental Protection Agency, Hong Kong University Science and Technology, University of Michigan, and the University of California Berkeley had no collaborative articles. The distribution of institutions hinged on their individual frequently-cited scientists. For example, Whitesides from Harvard University in the USA, who had eight frequently-cited articles, played an important role in the ranking no. 1 ranking of Harvard University (8 articles); the 4th position of the University of Mainz in Germany (4 articles) was mainly due to Decher and Hong who published three articles together; three articles published by Karickhoff at the U.S. Environmental Protection Agency (U.S. EPA) could be the main reason for the high position of the U.S. EPA (3 articles); and the 6th position of Hong Kong University of Science and Technology (HKU) is attributable to Ho and McKay who had three articles together from HKU.

The 126 articles were published by 363 authors from 107 institutions in 17 countries/territories. Top articles usually originated from a small field centered in a few countries, for example, 100 top-cited articles in general surgical journals were produced by six countries [15]; top 100 most frequently cited articles in anesthetic journals originated from nine countries [12]; the 100 ophthalmology classic citation articles originated from 10 countries [10]. Only 14 articles (14%) were internationally collaborative and they were contributed by just two countries, while the other 88 articles (86%) were independent articles contributed by only one country. The collaboration rate (14%) in the citation classics was similar with that of other areas, such as 14% biosorption technology for water treatment [30], 16% of desalination research [31], 18% of financial crisis research [32], and 14% of acupuncture research [29].

Collaboration played an important role in enhancing the impact of articles in some previous studies [25,33,34]. Some results suggested that highly cited papers typically involve more collaborative research than the general norm [19]. However, collaboration was not obvious for the top-cited articles in the adsorption field. The characteristics of these 17 countries/territories are illustrated in Table 4. The leading country was the USA (62 articles), accounting for 61%, followed distantly by Germany (11 articles), Japan (10 articles), France, China, and the UK (4 articles). As for the 14 internationally collaborative articles, nine were contributed by the USA; and as for non-collaborative independent articles, more than a half were published by the USA. USA took the lead with an overwhelming majority, which is paralleled by the reports of citation classics in general surgical (78%) [15], anesthetic journals (70%) [12], ophthalmology journals (86%) [10], and urology and subspeciality journals (76%) [13]. That most top-cited publications originated from the United States is explained in part by the large size of the American scientific publications [35]. There is some evidence

Table 3
Characteristics of the most cited 14 institutions.

Institution	Rank (TP)	Rank (SP)	Rank (CP)	Rank (FP)	Rank (RP)
Harvard University, USA	1 (8)	1 (4)	2 (4)	1 (6)	N/A
Massachusetts Institute of Technology, USA	2 (6)	N/A	1 (5)	2 (3)	6 (2)
University of Washington, USA	3 (5)	5 (2)	3 (3)	2 (3)	2 (3)
Arizona State University, USA	4 (4)	5 (2)	N/A	2 (3)	6 (2)
University of Mainz, Germany	4 (4)	2 (3)	N/A	2 (3)	1 (4)
U.S. Environmental Protection Agency, USA	6 (3)	2 (3)	N/A	2 (3)	2 (3)
Hong Kong University Science & Technology, Hong Kong	6 (3)	2 (3)	N/A	2 (3)	2 (3)
University of Michigan, USA	6 (3)	5 (2)	N/A	2 (3)	2 (3)
University of California Berkeley, USA	6 (3)	5 (2)	N/A	2 (3)	14 (1)
Kent State University, USA	6 (3)	N/A	3 (3)	10 (2)	N/A
Stanford University, USA	6 (3)	N/A	6 (2)	10 (2)	N/A
Technical University of Denmark, Denmark	6 (3)	N/A	3 (3)	N/A	6 (2)
Pennsylvania State University, USA	6 (3)	N/A	6 (2)	N/A	N/A

TP: total publications; SP: single country publications; CP: collaborative publications; FP: first author publications; RP: corresponding author publications; N/A: not available.

Table 4
Characteristics of the 17 contributing countries/territories.

Country/ territory	Rank (TP)	Rank (SP)	Rank (CP)	Rank (FP)	Rank (RP)
USA	1 (62)	1 (53)	1 (9)	1 (58)	1 (37)
Germany	2 (11)	2 (9)	4 (2)	2 (10)	2 (9)
Japan	3 (10)	3 (6)	2 (4)	3 (7)	3 (4)
UK	4 (4)	4 (4)	N/A	4 (4)	9 (2)
China	4 (4)	5 (3)	7 (1)	4 (4)	3 (4)
France	4 (4)	5 (3)	7 (1)	4 (4)	5 (3)
Netherlands	7 (3)	5 (3)	N/A	7 (3)	5 (3)
Switzerland	7 (3)	8 (2)	7 (1)	8 (2)	5 (3)
Denmark	7 (3)	9 (1)	4 (2)	8 (2)	5 (3)
South Korea	7 (3)	N/A	3 (3)	8 (2)	9 (2)
Canada	11 (2)	9 (1)	7 (1)	11 (1)	11 (1)
Russia	11 (2)	N/A	4 (2)	11 (1)	N/A
Sweden	13 (1)	9 (1)	N/A	11 (1)	11 (1)
Singapore	13 (1)	9 (1)	N/A	11 (1)	11 (1)
Portugal	13 (1)	9 (1)	N/A	11 (1)	11 (1)
Taiwan	13 (1)	N/A	7 (1)	11 (1)	N/A
Israel	13 (1)	N/A	7 (1)	N/A	N/A

TP: total publications; SP: single country publications; CP: collaborative publications; FP: first author publications; RP: corresponding author publications; N/A: not available.

that USA authors tend to quote articles from USA journals more than other countries [36]. Reviewers from the United States and outside the United States evaluate non-US papers similarly and are likely to evaluate papers submitted by US authors more favorably [37]. In particular, all of the top articles from the UK, Netherlands, Singapore, Sweden, and Portugal were independent articles, while the articles from Russia, Taiwan, Israel, and South Korea were all internationally collaborative articles. Furthermore, the scientists played decisive roles in the distribution of countries with small size in top adsorption production. Except for the seven countries with only one article, the other examples can be illustrated in the following way: Ho and McKay from Hong Kong University of Science and Technology contributed three articles to China. The 7th position Denmark was mainly attributed to two scientists, Hammer and Norskov.

3.4. Citation life cycles of articles with the highest TC2011

The articles with the highest TC2011 can be considered the most popular articles in the last 110 years. Some scientists previously studied the citation life cycles of highly cited articles [17–19]. The citation lives of the top six articles (TC2011 > 2000) are shown in Fig. 4.

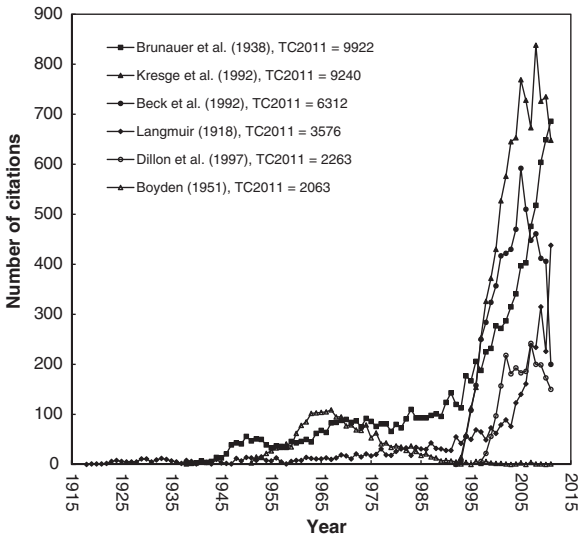

Fig. 4. Citation life cycles of the top six articles (TC2010 > 2000).

Three of these six articles were published after 1990 within a relatively short time span for citations, while the other three were published in 1918, 1938, and 1951. In general, only the two early articles by Brunauer et al. in 1938 and Langmuir in 1918 saw continually increasing trends in all years since publication, while the others' citation rates climbed initially to a peak and then decreased; this is especially evident for the article by Boyden, for which citation rate rose from 3 in 1951 to 109 in 1967 and decreased to only one in 2011. The citations per year of the article by Brunauer et al. [5] rose rapidly to 56 in 1950, with a growth rate of 4.6 citations per year, then grew overall with fluctuations to an average of 89 citations per year during 1971–1990, and then increased sharply from 143 in 1991 to 686 in 2011 with a growth rate of 27 citations per year and average of 324 citations per year. The annual citations of another early article by Langmuir climbed slowly since 1918 and started to grow faster in the 20th century till 2009 with 315 citations, and then fell to 220 in 2010, but increased to 438 in 2011. Boyden [38] studied the adsorption of proteins on erythrocytes treated with tannic acid and the subsequent hemagglutination of antiprotein sera. The other three more recent articles by Kresge et al. in 1992, Beck et al. in 1992 and Dillon et al. in 1997 experienced faster citation increases, especially the two articles published in 1992. The article by Kresge et al. [39] had the highest citation rate increase, increasing by 34 citations per year, from one citation in 1992 to 648 in 2011 with an average value of 462 throughout the period from publication to 2011. Kresge et al. [39] discovered a new family of mesoporous molecular sieves designated as M41S. The report by Kresge et al. [39] stimulated recent work on ordered materials with uniform mesoporosity [40]. The citations of the article by Beck et al. [41] rocketed dramatically from zero in 1992 to a peak value of 592 citations in 2005 with a growth rate of 46 citations per year, but then decreased somewhat, to 200, in 2011. Beck et al. [41] described the synthesis, characterization, and proposed mechanism of formation of a new family of silicate/aluminosilicate mesoporous molecular sieves designated as M41S and MCM-41, one member of the M41S family. The articles by Kresge et al. [39] and Beck et al. [41] were both contributed by research teams at Mobil Oil Company. The annual citations of another article by Dillon et al. [42] kept growing with the growth rate of 42 citations during 1997–2002, but it decreased in 2011. Dillon et al. [42] showed that hydrogen condenses inside of single-walled nanotubes under conditions that do not induce adsorption in a standard mesoporous activated carbon.

The lifetime citations curves were different among these six frequently-cited articles, reflecting possible differences in the cognitive function of the articles. Aversa [17] identified two basic citation patterns: delayed rise – slow decline and early rise – rapid decline. Both of them show general evidence of aging. Interestingly, based on the patterns of the three newer articles and one earlier article by Brunauer et al. [5], there are signs of aging: delayed rise – slow decline. Cano and Lind [18] described two distinct citation patterns of citation classics, five in medicine and five in biochemistry: Type A, a relatively fast accumulation of citations in the early life of a paper; and Type B, a period of initial increase or constant rate of growth in the initial stage, and quite a steady growth from the sixth year after publication. Citations of papers by Brunauer et al./Langmuir showed sustained growth with no declines during a 74-year/94-year period in agreement with the increasing trends of the classical pattern. Thus Brunauer et al. [5] and Langmuir [4] continue to be frequently cited in recent years for the BET and Langmuir isotherms. Researchers are inclined to cite the original paper to show their respect to the authors who presented a novel idea for scientific research and also to show that

they have read the original literature in detail including the papers published a long time ago. It is also believed that the citation curves of highly cited papers follow a typical pattern of rise and decline [19]. Longitudinal citation patterns were found to be highly varied [43]; there were rises and declines and also a sustained growth in citation of notable articles in the adsorption field.

3.5. Citation life cycle of articles with the highest C2011

A single-year citation analysis and review of the top articles can describe the characteristics and high points for that year. TC2011, an accumulative number may reach a large value as long as the time span is long enough. Although some recent articles, for example, those published in 2010, had great potential, they did not have a high TC2011. Therefore, it is necessary to study the citations of an article cited within every single year to interpret the research focus in that year. The number of authors of the article, the number of authors cited, institutions cited, countries or territories cited, journals cited, citations per year, country/territory, C2011, TC2011, and self citations of the top five articles with C2011 greater than 300 are all shown in Table 5. In terms of the citations per year, the article by Kresge et al. [39] has the highest value, 486 citations per year on average. These five articles were all independent articles without international collaboration; and four out of five originated from the USA, and one from China. The detailed figures of cited units (such as authors, or institutions) were listed to reveal more of the characteristics that influence the frequently-cited articles. In general, more citations mean that more authors, institutions, and countries/territories were influenced by the article; for example, the article by Brunauer et al. [5], which has the greatest total citations, was cited by the most authors (20,703), institutions (4001), countries/territories (117), web of science categories (140), and journals (1749). However, it sometimes turns out that an article is cited very frequently yet does not influence as many countries/territories and categories as would have been expected; examples are the articles by Law et al. [45], and by Ho and McKay [46]. The most popular categories to cite the work of Brunauer et al. [5] were physical chemistry (30%), materials science multidisciplinary (16%), and multidisciplinary chemistry (13%). The article by Kresge et al. [39], mainly influenced physical chemistry category (54%), materials science multidisciplinary (37%), and multidisciplinary chemistry (25%). The categories of authors that most frequently cited the work of Langmuir were physical chemistry (22%) and chemical engineering (21%). As for the paper by Law et al. [45], the largest categories were multidisciplinary materials science (59%), applied physics (38%), nanoscience–nanotechnology (36%) and physical chemistry (36). The scientific work of Ho and McKay [46] mainly influenced three categories: the environmental sciences, chemical engineering, and environmental engineering, each of which accounted for more than 30% of the total. Van Raan [44] reported that higher rates of self-citation in highly-cited articles do not significantly increase the impact. Here, the low self-citation rates of seminal articles in the adsorption field are another line of evidence that self-citation makes only a small contribution to the impact of a paper.

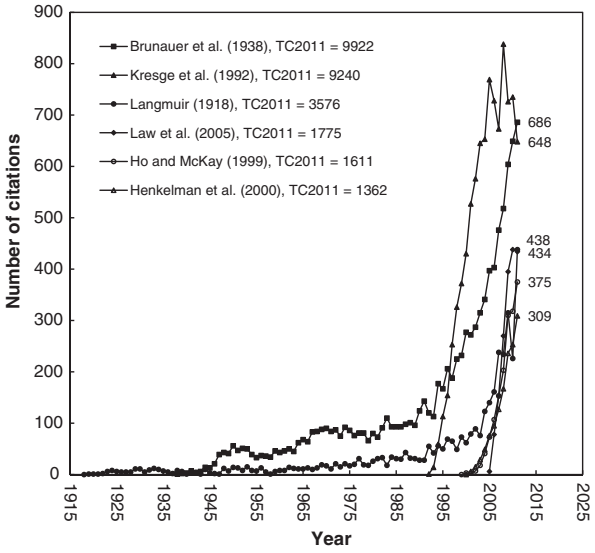

Fig. 5. Citation life cycles of the top six articles (C2010 > 300).

Fig. 5 shows the citation history of the highest six articles for which C2010 > 300. As expected, these articles all had high annual citation growth rates, and thus great vitality. As evidenced by two early articles, by Brunauer et al. in 1938 and Langmuir in 1918, plus four articles that emerged after 1991, the two famous isotherms, BET and Langmuir, have had a strong and lengthy influence on the adsorption field. Three of the articles, Brunauer et al. [5], Kresge et al. [39], and Langmuir [4], overlap in Figs. 3-1–3-3 and 4, which correlates with the facts that TC2011 > 2000, and C2011 > 300. Except for the two famous articles related to well known isotherms, another article by Kresge et al. [39] influenced a great number of scientists. Three other articles, Law et al. in 2005, Ho and McKay in 1999, and Henkelman in 2000, had C2010 > 300, but TC2010 < 2000. In comparison with the six articles in Fig. 5, these latter three did not have enough time to accumulate citations, but all of them have rocketed upwards since their publication. Citations of the article by Law et al. [45] had the highest initial growth rate, 71 citations per year, with an average figure of 256 per year; the article by Ho and McKay [46] had the second highest initial growth rate of 31 citations per year and a mean of 124; the article by Henkelman et al. (2000) had the third highest initial growth rate of 28 citations per year with a mean of 113. Law et al. [45] introduced a version of the dye-sensitized solar cell in which the traditional nanoparticle film is replaced by crystalline ZnO nanowires. Ho and McKay [46] reviewed the use of sorbents and biosorbents to treat polluted aqueous effluents containing dyes, organics, or metal ions, and proposed the pseudo-second order kinetic model which provides the best correlation for all of the systems studied. Since the introduction of a pseudo-second-order

Table 5
Characteristics of top five articles (C2010 > 300).

Top articles	NA	AU	IN	CT	SA	NJ	C/Y	Journal (IF)	Country	C2011 (SC)	TC2011 (SC)
Brunauer et al. [5]	3	20,703	4001	117	140	1749	134	Journal of the American Chemical Society (9.023)	USA	686 (0)	9922 (49)
Kresge et al. [39]	5	15,000	2628	86	94	923	462	Nature (36.104)	USA	648 (0)	9240 (22)
Langmuir [4]	1	7377	1947	98	119	953	38	Journal of the American Chemical Society (9.023)	USA	438 (0)	3576 (5)
Law et al. [45]	5	5019	1009	56	53	312	254	Nature Materials (29.92)	USA	434 (2)	1775 (19)
Ho and McKay [46]	2	3572	948	71	73	285	124	Process Biochemistry (2.648)	China	375 (0)	1611 (34)

NA: number of authors in a paper; AU: number of authors cited; IN: number of institutions cited; CT: number of countries/territories cited; SA: number of subject areas cited; NJ: number of journals cited; C/Y: citations/year; C2011: total citation in 2011; TC2011: total citations from publication to 2011; SC: self-citations.

model for the description of adsorption kinetics in 1999, it has been widely applied to the adsorption of pollutants from aqueous solutions [47,48]. Henkelman et al. [49] presented a modification of the nudged elastic band method for finding minimum energy paths.

4. Conclusions

This article has analyzed the following characteristics: publication year, journals and Web of Science categories, authors, institutions, countries/territories, life citation cycle curves, and characteristics of articles with exceptionally high citation rates, TC2011 and C2011. Firstly, the 126 top articles were cited an average total of 1014 times (ranging from 502 to 9922 total citations), based on results for the last 89 years from 1918 to 2006, with four fifths of the articles published after 1970. Secondly, these papers were published in 55 journals, led by the *Journal of the American Chemical Society*, and followed by *Science* and *Nature*. Physical chemistry, multidisciplinary chemistry, and multidisciplinary sciences led the 35 Web of Science categories, comprising 60% of the total articles. Thirdly, 13 authors are affiliated with three or more such articles, while 107 institutions from 17 countries/territories contributed to the articles. Harvard University, Massachusetts Institute of Technology, and University of Washington were the three most productive institutions, and the USA led the list of countries/territories, accounting for 61% of citations. Collaboration among top authors is quite probable, in contrast to inter-institutional collaboration and international collaboration, which are less common. Moreover, the lifetime citations curves of some articles had trends of increase and decline over the years, while others have increased annually since publication. The extent of influence of exemplary papers on the authors, institutions, countries/territories, journals, and categories among the readership were not necessarily proportional to the number of citations. Finally, the BET and Langmuir isotherms introduced in two early classical articles have been frequently cited during the time period under investigation and still have a strong influence. Two top articles by a research team from Mobil Oil Company described a new family of materials, M41S. The articles related to the pseudo-second-order model of adsorption kinetics, and the modified nudged elastic band method have experienced a high growth rate of citations.

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