An analysis of research activity in department of chemical engineering in USA

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Abstract

A bibliometric analysis was carried out to identify the research activities related to the department of chemical engineering (CE) in the United States of America from 2002 to 2010 and to improve the understanding of research trends in the same period, based on the online version of Science Citation Index Expanded (SCI-EXPANDED), the Thomson Reuters Web of Science. Articles published by CE researchers were evaluated, basing on the distribution of journals and the collaborative relations. Research tendency was investigated by statistically analyzing the distribution of words in article title, author keywords, and KeyWords Plus in different periods and the research behavior of the top institutes were studied according to journals and author keywords. Results showed that research activities in CE have been more involved in interdisciplinary projects. Areas related to nanoscale science, biochem, as well as energy & environmental had an increasing trend during the recent 9 years.

Keywords: Bibliometric, Web of Science, USA, Chemical Engineering, Research Trends

1. Introduction

Chemical Engineering (CE) is a relative young branch of engineering which developed along with the change of modern industry. The historical origins of academic CE can be dated back to George E. Davis with his series of lectures later titled "a handbook of chemical engineering" in 1887 [1]. Since then, CE gradually enriched itself to be recognized as the "universal" engineering discipline. The core concepts of unit operations [2] are the theme of early CE researches, which were mainly incited by the petrochemical industry. As the concept "macromolecule" proposed by Staudinger, the progress in polymer science [3] and its mass production in the 1940s have created a new area in chemistry and pharmaceutical industry [4]. On the other hand, the pioneering work of Damköhler [5] introduced the process diffusion and heat transfer in CE, which led to developments in principle of momentum transport, energy transport, and quality transport in chemical reaction engineering. The new knowledge not only promotes further researches in materials-oriented CE, but also lays foundations for the appearance of simulation and modeling [6]. Today, CE became a multidisciplinary and economically important field [7]. Especially in multidisciplinary areas of polymers, catalysis, electronic material synthesis, biological science and engineering, pharmacology, nanoscience and computing science, basic science research and engineering application have interpenetrated and these topics are gradually becoming the critical issues in CE [4]. However, changes in this field are rapid that make it hard to keep track of the latest CE developments. In this study, the Departments of Chemical Engineering in the United Stated of America are chosen as the research object to indicate recent research activities and new trends, for the reason that US is a good representation of the global academic CE field.

The bibliometric method has been widely applied as an approach to analyze scientific production and research trends [8]. The number of bibliometric analysis of CE subjects has, however, been relatively limited. Previous related studies include Peters and van Raan [7,9,10] who are the first to apply bibliometric methods to the field of CE. They used "co-author analysis" and "co-word analysis" to identify research groups and topics with their changes in time [7,9] and studied the bibliometric characteristics of top-scientists in CE [10]. These results were then discussed with experts to prove their reliability and consistency. Citation analysis has also been applied [11,12]

to assess the flow of information and knowledge in CE with regard to geographical origins, journals, research fronts and interdisciplinary relationships. Yin [13] concluded Southeast Asian CE research activities from 1996-2008 through bibliometric analysis of top journal articles and keywords. However, most of the previous studies have unavoidable defects that the original data was selected only in several journals or categories to represent global research trends related to a certain topic [14]. Moreover, all the bibliometric methods in those studies are depending on citations, author keywords or publication information which may lead to certain bias in analyzing developmental trends or the future orientation in CE.

In this study, we aimed to systematically use a more comprehensive method of bibliometric research and analysis to provide useful information on several aspects such as preference of journals, research collaboration situations, research hotspots and focus of research institutes that related to department of CE in USA. Using the Thomson Reuters Web of Science database guarantees an all-around representation of the discipline as CE. A method of "word cluster analysis" [8,15] was used to reduce the data bias, by taking the distributions of words not only in the article title, author keywords, but also words in the abstract, and KeyWords Plus in different periods.

2. Date Sources and Methodology

The data were based on the online version of Science Citation Index Expanded (SCI-EXPANDED), the Thomson Reuters Web of Science. According to Journal Citation Reports (JCR), it indexes 8,005 major journals with citation references across 174 scientific disciplines in 2010. The online version of SCI-EXPANDED was confined with address "chem same engn same USA" and year published "2002-2010", to compile a bibliography of all articles published by researchers in the department of CE in USA. There were no other limitations on the subject categories or topics of papers, because the focus of the study pertains to the journal publication behavior of CE researchers rather than publications that fall within the area of CE.

The records were downloaded into spreadsheet software, and additional coding was manually performed using Microsoft® Excel [version 2007] to obtain analysis results according to: distribution of outputs in journals, publication outputs of source country, source institute, article title, abstract, author keywords and KeyWords Plus. Articles' affiliations originating from England, Scotland, Northern Ireland, and Wales were reclassified as being from the United Kingdom (UK). During author keywords analysis, keywords were defined as comma-separated items of one or more words. The words in titles and abstracts were separated, and then conjunctions and prepositions such as "and", "of", "in", and "on" were discarded, as they were meaningless for research trend analysis. All keywords, both those reported by authors and those assigned by Web of Science, as well as words in the titles and abstracts, were identified and separated into 3 three-year periods (2002-2004, 2005-2008, and 2008-2010), and then their ranks and frequencies were calculated in order to thoroughly analyze the variations of trends in wording and topics [8,15,16].

3. Results and Discussions

3.1. Overall Characteristics of Publication Output

In this study, 48,100 journal articles were found published during 2002-2010 by CE researchers in USA. The annual publication output experienced a steady growth of 5.1% each year, which indicated that the field of CE has come to a mature stage. Meanwhile, the average number of authors per article rose from 3.7 authors per article in 2002 to 4.7 in 2010. But the average article length had reduced slightly, from 9.6 pages in 2002 to 8.7 pages per article in 2010.

Articles published covered a wide range of 2,155 journals. Table 1 shows the bibliometric results of the top 20 journals that CE researchers in USA preferred to publish. *Industrial & Engineering Chemistry Research*, *AIChE Journal*, and *Chemical Engineering Science* were the most prestigious broad-based chemical engineering journals within the international chemical engineering field [13], while *Langmuir*, *Journal of Physical Chemistry B*, and *Chemistry of Materials* were high-ranked journals in basic chemistry and material science fields.

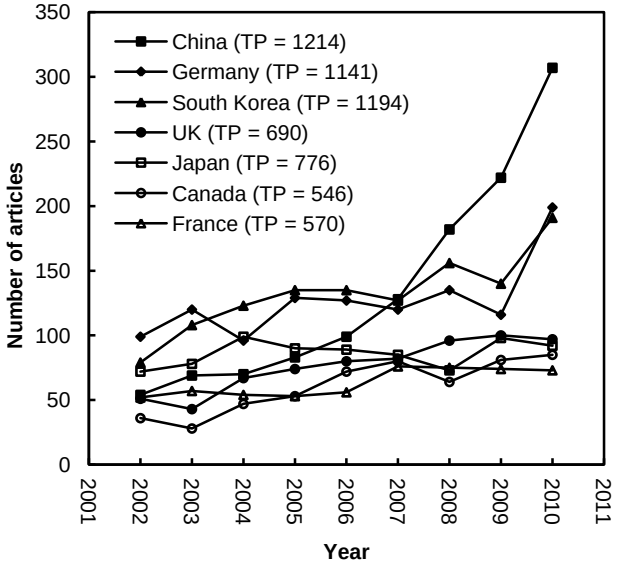
Table 1. The top 20 journals with the number of articles, impact factor, JCR category of journals.

Rank	Journal	TP (%)	IF	JCR subject category (Rank/No. journals)
1	Langmuir	2,017 (4.2)	4.268	multidisciplinary chemistry (24/144) physical chemistry (29/127) multidisciplinary materials science (26/222)
2	Industrial & Engineering Chemistry Research	1,741 (3.6)	2.071	chemical engineering (30/134)
3	Macromolecules	1,589 (3.3)	4.837	polymer science (5/79)
4	Journal of Physical Chemistry B	1,233 (2.6)	3.603	physical chemistry (32/127)
5	Journal of Chemical Physics	1,156 (2.4)	2.920	atomic, molecular & chemical physics (6/32)
6	Journal of the American Chemical Society	1,141 (2.4)	9.019	multidisciplinary chemistry (11/144)
7	Applied Physics Letters	795 (1.7)	3.820	applied physics (14/116)
8	Journal of the Electrochemical Society	779 (1.6)	2.420	electrochemistry (12/26) coatings & films materials science (1/18)
9	AIChE Journal	727 (1.5)	2.030	chemical engineering (32/134)
10	Biotechnology and Bioengineering	715 (1.5)	3.700	biotechnology & applied microbiology (34/160)
11	Journal of Physical Chemistry C	704 (1.5)	4.520	physical chemistry (27/127) nanoscience & nanotechnology (14/63) multidisciplinary materials science (22/222)
12	Polymer	607 (1.3)	3.828	polymer science (9/79)
13	Chemical Engineering Science	552 (1.1)	2.379	chemical engineering (22/134)
14	Chemistry of Materials	545 (1.1)	6.397	physical chemistry (15/127) multidisciplinary materials science (12/222)
15	Journal of Membrane Science	537 (1.1)	3.673	chemical engineering (8/134) polymer science (10/79)
16	Physical Review E	500 (1.0)	2.352	fluids & plasmas physics (8/31) mathematical physics (4/54)
17	Journal of Colloid and Interface Science	477 (1.0)	3.066	physical chemistry (40/127)
18	Journal of Catalysis	469 (1.0)	5.415	physical chemistry (17/127) chemical engineering (4/134)
19	Journal of Applied Physics	463 (1.0)	2.064	applied physics (33/116)
20	Environmental Science & Technology	460 (1.0)	4.825	environmental engineering (2/45) environmental sciences (9/192)

TP: the number of total articles; % share in their total articles; IF: impact factor of the journal in 2010.

There were also journals concerning applied science, such as *Applied Physics Letters*, *Journal of Applied Physics*, and *Environmental Science & Technology*, but the number of publications in them did not rank as high as the journals in fundamental sciences and chemical engineering, which revealed the preference of CE researchers in US. As for the distribution of subjects, the total 20 journals were listed in 15 subject categories included physical chemistry (6 journals), chemical engineering (5 journals), multidisciplinary materials science (3 journals), polymer science (3 journals), multidisciplinary chemistry (2 journals), applied physics (2 journals) and other 9 categories with one journal. The wide range of subject categories indicates that the mainstream of research is no longer restricted to the typical CE area. Because the basic principles in CE, such as the principle of transport phenomena and reactive engineering, can be applied to various research directions and situations, there have been increasing collaborations between CE and other disciplines.

Figure 1. Comparison of growth trends of the top seven productive countries collaborating with US.



Of 48,100 articles published in the recent 9 years in USA, 25% of them were internationally collaborative publications. Figure 1 is the comparison of the collaborative publication trends of the top seven countries. China ranked first and exhibited astonishing publication increases by a factor of 32% from 2006 to 2010. It was not surprising since more than 10 years ago, China has experienced a double-digit annual growth in its total scientific publishing and US has maintained its position as China's top R&D partner [17]. In the area of CE, interregional collaborations between China-US have also been strengthened, For example, China-USA workshop on chemical engineering was held annually since 2005. It was also worthy of note that South Korea ranked second in total publication among all other countries. It is consistent with Korean government's efforts to increase human resources and expenditure in R&D, within which physics, chemistry and biology are mainstream collaborative subjects [18].

3.2. Topics Indicated by Words Analysis

An innovative method was used in this study to seek out hot topics and to keep track of important development of science and programs in CE. It was "word cluster analysis" of selected topics in the combination of author keywords, article titles, KeyWords Plus, and abstracts [8,19]. By screening high frequency words that appeared in the four sources, one can scientifically select out right words for topic description and trend analysis.

Bibliometric method concerning author keywords analysis in a certain period could be found in recent years [20], whereas author keywords used to summarize research trend is more infrequent [21]. Table 2 reveals the top 20 words among 46,322 author keywords counted in this study. The top 20 results not only included the traditional CE subject area such as "adsorption", "rheology", and "kinetics" but also demonstrated high productivity in relative new topics and methodologies such as nanomaterials ("nanoparticles", "self-assembly", and "nanocomposites"), "tissue engineering", and "carbon dioxide". There were also some emerging new words. For example, the rank and percentage of "carbon nanotubes" sharply increased from #208 (0.21%) in 2002-2004 to #21 (0.90%) in 2008-2010. "Graphene" did not appear in author keywords before 2007, but leapt into #70 in 2008-2010. "Density functional theory", "biodiesel", and "molecular dynamics method" were in the same category. However, the use of "photopolymerization", "mass transfer", and "polystyrene" decreased. Although author keywords present intact words that authors want to transmit [22], it has its own deficiency that only 22,390 of all 48,100 articles

had its own author keywords in this study. Some high impact journals, for instance *Science* and *Nature* have no author keywords.

Table 2. Top 20 frequency words in author keywords during 2002-2010 and 3 three-year periods.

Author keywords	TP	02-10 R (%)	02-04 R (%)	05-07 R (%)	08-10 R (%)
adsorption	328	1 (1.5)	3 (1.4)	5 (1.1)	2 (1.7)
diffusion	322	2 (1.4)	1 (1.7)	2 (1.3)	3 (1.4)
nanoparticles	318	3 (1.4)	28 (0.53)	3 (1.3)	1 (2.1)
modeling	287	4 (1.3)	2 (1.5)	1 (1.5)	6 (1.0)
kinetics	251	5 (1.1)	4 (1.4)	4 (1.2)	14 (0.89)
tissue engineering	217	6 (1.0)	5 (1.2)	6 (1.0)	21 (0.75)
drug delivery	217	6 (1.0)	11 (0.74)	15 (0.73)	5 (1.3)
self-assembly	205	8 (0.92)	37 (0.48)	13 (0.76)	4 (1.3)
oxidation	201	9 (0.90)	7 (0.86)	12 (0.80)	8 (1.0)
nanocomposites	193	10 (0.86)	15 (0.69)	9 (0.86)	11 (1.0)
hydrogen	187	11 (0.84)	25 (0.57)	9 (0.86)	9 (1.0)
platinum	185	12 (0.83)	11 (0.74)	17 (0.69)	9 (1.0)
mechanical properties	174	13 (0.78)	8 (0.81)	19 (0.68)	17 (0.84)
hydrogel	173	14 (0.77)	48 (0.43)	7 (0.93)	16 (0.87)
rheology	170	15 (0.76)	6 (0.89)	17 (0.69)	22 (0.73)
optimization	165	16 (0.74)	10 (0.77)	23 (0.61)	18 (0.81)
carbon dioxide	164	17 (0.73)	13 (0.72)	7 (0.93)	31 (0.59)
simulation	158	18 (0.71)	14 (0.70)	16 (0.71)	23 (0.71)
microstructure	156	19 (0.70)	9 (0.79)	11 (0.82)	37 (0.55)
carbon nanotubes	151	20 (0.67)	208 (0.21)	13 (0.76)	13 (0.90)

TP: the number of total articles; R (%): the rank and percentage of word in article titles in total articles which has author keywords.

The title of an article, however, is a necessity and always includes the information that the author would most like to express to the readers. In this study, the most frequently used words in article titles for all periods were "synthesis", "carbon", and "properties". In addition, quite different from author keywords, "surface", "polymer", and "molecular" ranked top 10 in title words. It also revealed a high increase in words "fuel", "nanoparticles" and "nanotubes", which may indicate new focus areas in CE. Authors might choose their title-words to attract a more general or a particular audience [10]. Thus, title words might not indicate the content of the paper correctly.

The KeyWords Plus supplies additional search terms extracted from the titles of articles cited by authors in their bibliographies and footnotes, thus to extent title word and author keywords indexing [23]. The 46,547 articles in all were found to include 64,830 KeyWords Plus information. Among them, "model", "adsorption" and "growth" ranked at the top of the list and their ranking did not fluctuate distinctly. The use of words "biomass", "drug-delivery" and topics related to nanoscience such as "nanoparticles" and "carbon nanotubes" experienced an increasing growth in 2002-2010. There were some new words in top 20 that were not included either in author keywords or in title word, such as "film", "temperature", and "in-vitro".

Zhang et al. [24] used the analysis of single words in abstracts to make specific inferences about the scientific publication and identify the subjective focus firstly. "Surface", "model", and "temperature" were the most frequently used single words in abstract during 2002-2010. Compared to title word and KeyWords Plus, word in abstract helps less in the determinations of topics because words are usually for general description or judgments.

Since author keywords, article title, KeyWords Plus, and word in abstract all have their own advantages and disadvantages, the "word cluster analysis" was applied to improve the bias. It has been successfully used to analyze the research hotspot in the field of environmental science [8]. According to the results of the distribution of the four separated

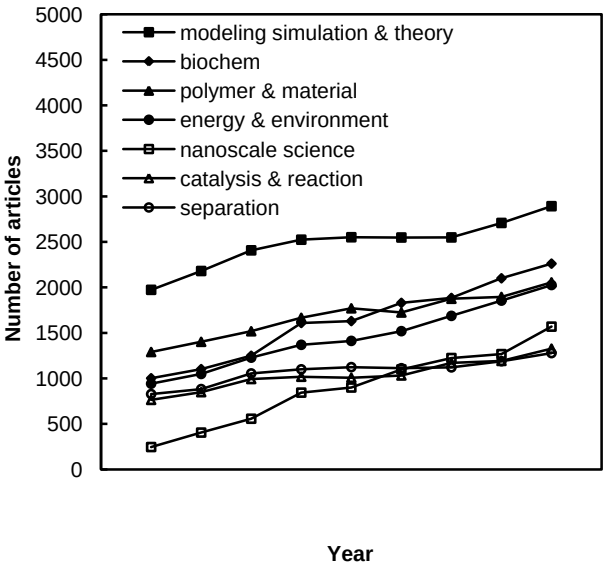
types of keywords above, several words that frequently appeared were chosen to depict related topics and to evaluate research trends (Table 3).

Table 3. The words chosen to describe the research area during the searching process in SCI.

Research areas	Words
nanoscale science	Nanoparticle(s), nanotube(s), nanoscale, nanocomposite(s), nanowire(s), nanostructure(s)
biochem	biological, tissue(s), protein(s), DNA
modeling simulation & theory	model(s), modeling, simulation(s), prediction, optimal(ity), optimization, non-linear, linear
catalysis & reaction	catalyst, catalysis, oxidation, hydrogen
separation	Membrane(s), supercritical, chromatography, chromatographic, (bio)separation(s), osmosis
polymer & material	Polymer(s), polymerization, copolymer(s), polymeric, self-assembly, material(s)
energy & environment	Energy, battery, batteries, fuel, CO_2 (carbon/carbon dioxide) Capture & Sequestration, solar, environment(s), environmental, green

Figure 2 reveals the publication trends of articles related to seven CE typical topics: "nanoscale science", "biochem", "modeling simulation & theory", "catalysis & reaction", "separation", "polymer & material" and "energy & Environment". An obvious rise can be seen in the number of articles related to nanoscale science. Nanomaterial not only has wide range of products such as dendrimers [3], metal nanoparticles, and carbon [30], but also enjoys extended applications in drug delivery [27], catalysis [28], and water purification [29]. Among them, the topic related to graphene [25,26] has risen dramatically since 2004. A journal article of Li et al. [26] has been highly cited recently, which reported that chemically converted graphene can readily form stable aqueous colloids through electrostatic stabilization. It makes possible to provide graphene in scalable amount and indicates potential applications in membranes, electrodes and other usage [31]. The research areas of energy & environment also have a high growth pace, with various research achievements such as the promising type of direct oxidation of hydrocarbons in a solid-oxide fuel cell (SOFC), as an alternative to hydrogen-based fuel cell [33]. The rapid development in biochem is also reflected by some highly cited articles. Dubertret et al. encapsulated quantum dots in phospholipid micelles to increase its biocompatibility, allowing lineage-tracing experiments in embryogenesis [32]. Interdisciplinary research fields, such as CE, always combine new materials and methodologies from various areas for problem-solving. For example, there is always mutual promotion between the technologies of nanotubes and molecular biology [34]. In addition, great attention has been given to the possible environment & health problems caused by nanomaterials [35]. Thus, the topics in one field may also include keywords used in other field.

Figure 2. Comparison of the growth trends of seven research areas related to CE.



3.3. Scientific Production of the Top 20 Universities

The distribution analysis of different institutions' publications were based on journal articles in which the address or affiliation of at

least one author were provided. The top 20 institutions were ranked by the number of total publications, with other statistics including the rank and percentage of the total publications, the first author and the corresponding author articles, as well as proportion of the inter-institutionally collaborated articles among the total articles for each institute (%C) (Table 4). All the top 20 universities' CE department had published more than 800 articles in 2002-2010, and the top three, Massachusetts Institute of Technology (MIT), California Institute of Technology (Caltech), and University of Minnesota at Twin Cities-stood out against others. Since MIT was the first to introduce a chemical engineering curriculum in 1888 [1], it has always been among the leaders in CE with some highly cited articles. The bibliometric result also reveals that different institutes have different strong points and preference on journals and subject matter. MIT, with journals most published in *Langmuir, Macromolecules*, *Biomaterials* and top 3 author keywords "drug delivery", "tissue engineering", "biocompatibility" showed its focus on biomaterials for tissue engineering and drug delivery. It was true that MIT has contributed a lot to the development of drug delivery vehicles [27], cell motility & adhesion [36], and construction of 3D tissues [37]. Its research on communicating nanoparticle systems has also made tumor targeting easier and delivery of drugs more efficient [38]. Caltech, on the other hands, presented a different preference, with top 3 author keywords "directed evolution", "protein engineering", and "protein design". It may indicate its high position in fields related to biology, such as exploring the framework for ABC Transporter in *E. coli* [39] and core structure of nitrogenase [40]. University of Minnesota-Twin Cities showed that its most popular journal was *Macromolecules*, *Physical review B, Journal of physical chemistry B* and top 3 author keywords "rhodium", "catalytic partial oxidation", and "block copolymers". It identified with its strength in the traditional chemical field [41].

Table 4. The top 20 most productive institutes of USA in the department of CE, including the ranking and respective percentages of publications, first author, and corresponding author publications.

Institute	TP	TP R (%)	FP R (%)	RP R (%)	C%
Massachusetts Institute of Technology (MIT)	2,012	1 (4.2)	1 (2.9)	1 (2.8)	60
California Institute of Technology	1,678	2 (3.5)	3 (2.4)	3 (2.4)	53
University of Minnesota-Twin Cities	1,657	3 (3.4)	2 (2.5)	2 (2.4)	52
Georgia Institute of Technology	1,395	4 (2.9)	4 (2.1)	4 (2.1)	54
University of California-Berkeley	1,360	5 (2.8)	5 (2.0)	5 (1.9)	63
University of California-Davis	1,216	6 (2.5)	11 (1.5)	13 (1.4)	72
University of Michigan-Ann Arbor	1,186	7 (2.5)	6 (1.7)	6 (1.7)	55
University of Illinois-Urbana-Champaign	1,077	8 (2.2)	9 (1.6)	9 (1.5)	54
University of Wisconsin-Madison	1,046	9 (2.2)	8 (1.6)	8 (1.6)	51
University of Florida	1,028	10 (2.1)	7 (1.6)	7 (1.6)	59
University of Texas-Austin	1,009	11 (2.1)	12 (1.5)	11 (1.5)	58
University of California-Santa Barbara	1,007	12 (2.1)	13 (1.4)	12 (1.5)	65
Princeton University	989	13 (2.1)	17 (1.4)	16 (1.3)	61
North Carolina State University, Raleigh	976	14 (2)	15 (1.4)	15 (1.4)	62
University of Delaware	926	15 (1.9)	16 (1.4)	17 (1.3)	55
Carnegie Mellon University	920	16 (1.9)	18 (1.3)	18 (1.3)	60
Northwestern University	915	17 (1.9)	14 (1.4)	14 (1.4)	52
Stanford University	891	18 (1.9)	19 (1.3)	20 (1.2)	65
University of Colorado Boulder	888	19 (1.8)	10 (1.5)	10 (1.5)	46
Texas A&M University-College Station	866	20 (1.8)	20 (1.2)	19 (1.3)	54

TP, total articles; TPR, total articles rank; FPR, first author article rank; RPR, corresponding author article rank; % share in their total articles; %C percentage of inter-institutionally collaborative articles in total institute articles.

4. Conclusions

Bibliometric analysis was used in this study for determining the publication activities among CE researchers in the United States of America from 2002 to 2010. The annual publication output experienced a steady growth of 5.1% to a sum total of 48,100 articles. The top 20 published journals were presented to show the preference in top-ranked broad-based CE, basic chemistry and physics science journals among US researches. Researches were not restricted to typical CE topics but also aimed at interdisciplinary targets. As for academic collaboration, China rose to be US' primary collaborative partner since 2007. The distributions of words were analyzed with results of the top rank in author keywords, word in titles, KeyWords Plus and word in abstracts. A method of "word cluster analysis" was conducted to show that the publication of nanoscience had grown quickly, as well as the areas of biochem and energy & environment. MIT, California Institute of Technology and University of Minnesota-Twin Cities ranked at the top in their publications in CE department and showed different preferences in research topics.

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