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Catalysis by nanoparticles: the main features and trends

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Abstract
Catalysis by nanoparticles is an important segment of contemporary nanotechnology. Abundant relevant information is scattered an over enormously big number of sources, only a part of which formally regards to catalysis and/or nanotechnology and nanoscience. With the CAPlus database, the scope of the field and its main thematic features and trends are discussed for the period 1990–2017. The findings match up expert opinion on catalysis as the core area of nanotechnology and nanoscience.

Keywords Nanotechnology · Nanoparticles · Catalysis · Catalysts · CAPlus · SciFinder

Catalysis is the increase in the rate of a chemical reaction due to intermediate participating of tiny amounts of an additional substance, called a catalyst, which does not belong to the starting materials or final products of the reaction, and is able to act repeatedly many times without consuming in the reaction course [1]. Catalysis plays essentially important role in global scientific and technological progress in chemistry, chemical engineering, life sciences, and related disciplines. At the turn of millennium, catalysis was responsible for more than USD 3.5 trillion in goods and services of the global gross domestic product annually [2]. Originatingd inside physical chemistry, catalysis is a well-shaped unique discipline nowadays known as the science of catalysis or catalysis science [3].

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Normally, catalysis is classified as either homogeneous, when the reactions with all their participants proceed in a single phase, or heterogeneous, when at least two phases are involved. In the past quarter of century, progress of nanoscience and nanotechnology [4–6] led to emergence of nanocatalysis [7–10] generally understood as *catalysis by nanoparticle*s and in some aspects filling the conceptual gap between homogeneous and heterogeneous catalysis [11, 12]. Overall, the nanocatalysis is a new subject domain [10, 13, 14] relevant to both science of catalysis and nanoscience and nanotechnology [7, 15]. The field dynamics is very high, and timely recognition of its main features and trends is a challenge.

A reasonable approach to tackling the problem is a thematic analysis based on the Chemical Abstracts Plus (CAPlus) database [16] on the SciFinder platform [17] from the Chemical Abstracts Service (CAS). The CAPlus is specialized in chemistry, chemical technology and a number of related disciplines and, in contrast to the Web of Science (WoS) and Scopus databases, covers patents which are essentially significant for technology. Information in the CAPlus is multi-dimensionally indexed with subject glossaries and headings [16]. Altogether, these allow performing thematic analysis of subject domains.

The present work reports results of the CAPlus-based analysis for catalysis by nanoparticles for the period 1990-2017. The information search was performed in May 2018. The query *concepts catalysis and nanoparticles present anywhere in the reference* gave ~ 105,500 documents and the query *catalysis by nanoparticles* with two concepts being closely associated (SI, §1 and Table S1) ~ 57,600 ones. Both datasets featured 88% of non-patent and 12% of patent publications. The latter dataset was analyzed. Its non-patent segment contained 90% of journal articles, 5% of general reviews, 0.6% of dissertations together with other types' documents (SI, Table S2).

In 1990–2015, growth of annual amount of both non-patent and patent literature in the field, clear visible from the turn of millennium, was exponent-like (Fig. 1), with the domination of journal articles written mostly in English (SI, Table S3). The

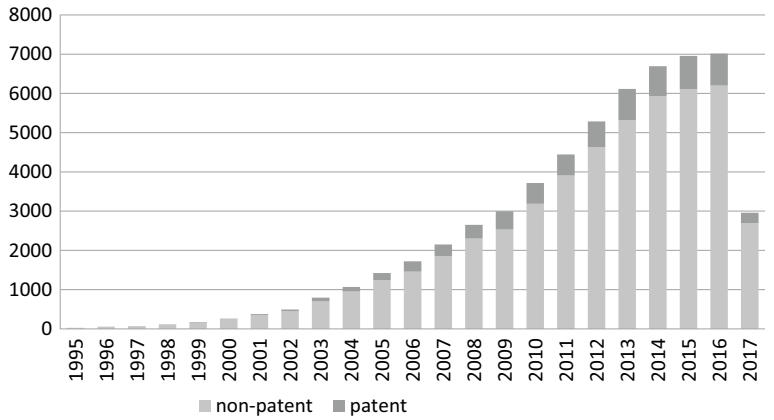

Fig. 1 Annual amounts of publications in 1990–2017 (data for 2016 and 2017 are incomplete due to postponed indexing in the database)

most productive countries are China, the United States and Japan (SI, Table S4). Amongst organizations, Chinese ones are the most visible especially with patents; organizations having at least 50 patents include also Japanese and French ones (SI, Table S5). The non-patent publications are scattered over numerous journals, the uppermost is *RSC Advances* established only in 2011. Of 50 most active titles, only 11 are specialized in catalysis and only 6 in nanoscience and nanotechnology (SI, Table S6). For the top 6 journals, a noticeable growth of amount of articles on catalysis by nanoparticles began only in the 2010s (Fig. 2). Amongst the most active patent offices, Chinese ones are the out-of-reach leaders followed by the International Patent System (PCT) and United States Patent Office (SI, Tables S7–S9).

Analysis based on CAS indexing revealed noticeable thematic diversity of publications on catalysis by nanoparticles. Notably, the distribution of publications over CA Categories indicates that this diversity, reflected by the number of assigned Categories, steadily grows; within the Categories, the most abundant, besides trivial *Catalysts*, are *Materials and products*, *Processes and apparatus*, and *Gas, liquid, and solid phenomena* (Fig. 3). Amongst the assigned CA Sections [16], the one related to *energy* is the uppermost (Fig. 4). Note that there are 80 thematic Sections in the CAPlus, each addressing a broad category of scientific inquiry. A document may be assigned to more than one Section with a section cross-reference. Within the most frequent CA Concept Headings characterizing the general subject matter of publications, those related to *surface* properties and *particle size* are leading (SI, Tables S10 and S11).

The most frequent terms within CA Categories are as follows (Category/terms; trivial terms catalysis, catalysts and nanoparticles omitted): Catalysis/oxidation, photolysis and hydrogenation catalysts; Particle phenomena/particle size and its distribution; Surface phenomena/surface area and structure, adsorption; Materials and products/platinum, palladium, hydrogen; Power and fuel topics/fuel cells

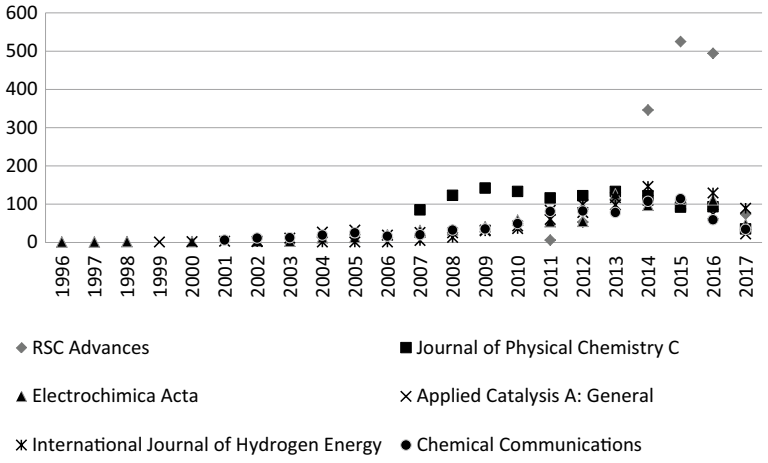

Fig. 2 Publications in the most active journals (data for 2016 and 2017 are incomplete due to postponed indexing in the database)

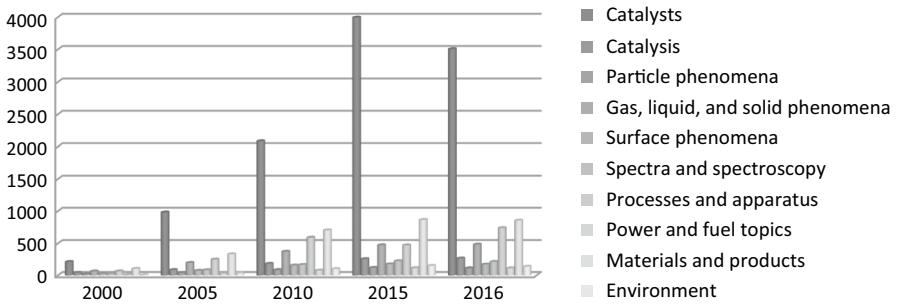

Fig. 3 Distribution of publications over CA Categories (data for 2016 are incomplete due to postponed indexing in the database)

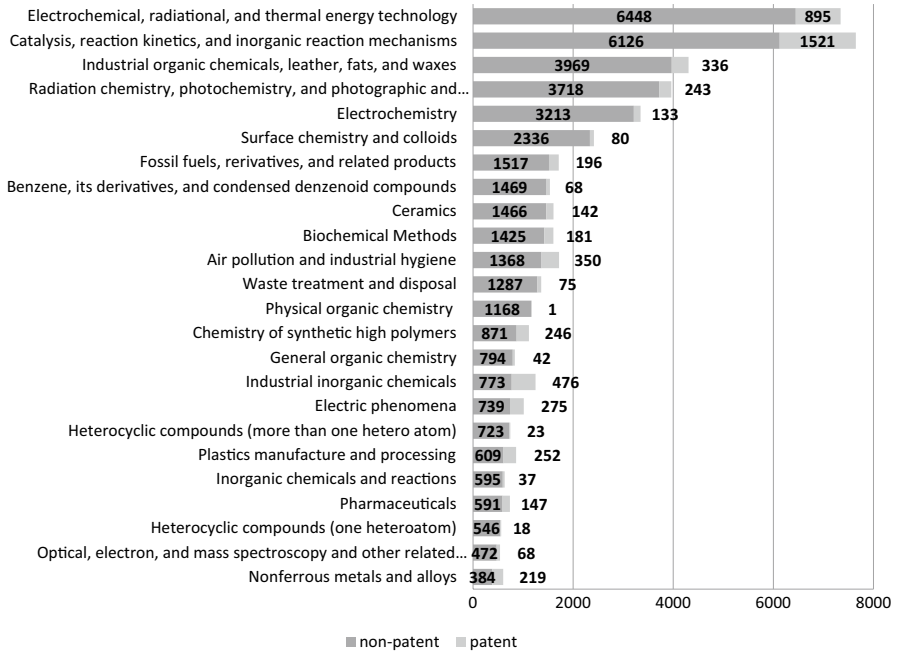

Fig. 4 Distribution of publications over CA Sections

and their anodes; proton exchange membrane fuel cell; Processes and apparatus/adsorption, calcination, fuel cells; Environment/green chemistry, recycling, air pollution control; Spectra and spectroscopy/XPS, XRD, UV–vis. The most frequent supplementary terms (authors' terminology) are headed by oxidation (SI, Tables S12-S20).

The most frequent substances for both the whole dataset and Category Catalysts are platinum, palladium, gold, nickel, silver, and iron supported on titania, carbon, silica, and alumina (Fig. 5; SI, Tables S21 and S22).

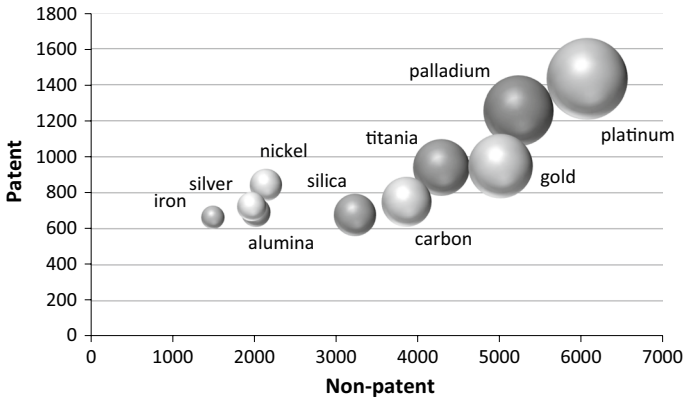

Fig. 5 Ten most frequent substances within Category Catalysts

The most cited journal articles and patents on catalysis by nanoparticles (SI, Tables S23 and S24) reflect the wide diversity of both sources and subjects. Their thematic array belongs to the aforementioned Categories. The articles appeared in such top journals as *Nature*, *Science*, *Chemical Reviews*, *Coordination Chemistry Reviews*, *Angewandte Chemie International Edition*, *Journal of the American Chemical Society*, etc. Together with very high citation score, this confirms the significance of the field for contemporary science and technology. The patents are mostly focused on the synthesis/manufacturing of nanoparticles for a variety of applications. As usual, their citation score is much more less than for journal articles.

Shortly after the turn of millennium, it was suggested that catalysis is the core area of nanotechnology and nanoscience [7, 15]. The findings of this work match up the suggestion. Overall, one can conclude that high global research and innovative activity in catalysis by nanoparticles is extremely diverse. This activity is facilitated by development of both synthetic approaches to nanoparticles and instrumental methods for their precise characterization. The catalysis by nanoparticles is mostly focused on oxidation and hydrogenation (reduction) catalysis, photo- and electrocatalysis. Most massive applications cover fuel cells, recycling, air pollution control and wastewater treatment technologies being important to green chemistry in general sense. The most involved materials include platinum, palladium, gold, nickel, silver, and iron supported on titania, carbon, silica, and alumina, i.e. are relevant to heterogeneous catalysis in the traditional terms. The main instrumental methods cover XPS, XRD, and UV–vis, IR, Raman and (photo) luminescence spectroscopies.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

1. IUPAC Compendium of Chemical Terminology (2006) http://goldbook.iupac.org/pdf/goldbook.pdf. Accessed 07 Nov 2018
2. Filmore D (2002) ACS Today's Chemist at Work. 33. https://pubs.acs.org/subscribe/archive/tcaw/11/i11/pdf/1102industry.pdf. Accessed 11 Nov 2018
3. Davis BH (2008) Development of the science of catalysis. In: Ertl G, Knözinger H, Schuth F, Weitkamp J (eds) Handbook of heterogeneous catalysis. Wiley-VCH, Weinheim, pp 16–37
4. Abbet S, Heiz U (2004) Nanocatalysis. Encyclopedia of nanoscience and nanotechnology. Springer, Berlin, pp 161–177
5. Lavrik OL, Busygina TV, Shaburova NN, Zibareva IV (2015) J Nanopart Res 17:90
6. Youtie J, Iacopetta M, Graham S (2008) J Technol Transf 33:315–329
7. Heiz U, Landman U (2007) Nanocatalysis. Springer, Berlin
8. McIntyre BJ, Salmeron M, Somorjai GA (1994) Science 265:1415–1418
9. Polshettiwar V, Asefa T (2013) Nanocatalysis. Synthesis and applications. Wiley, Hoboken
10. Zibareva IV, Vedyagin AA, Bukhtiyarov VI (2014) Kinet Catal 55:1–11
11. Coperet C, Chabanas M, Petroff Saint-Arroman R, Basset JM (2003) Angew Chem Int Ed 42:156–181
12. Phan NTS, Van Der Sluys M, Jones CW (2006) Adv Synth Catal 348:609–679
13. Schloegl R, Abd Hamid SB (2004) Angew Chem Int Ed 43:1628–1637
14. Olveira S, Forster SP, Seeger S (2014) J Nanotechnol 2014:324089
15. Grunes J, Zhu J, Somorjai GA (2003) Chem Comm 24:2257–2260
16. CAS Products Fact Sheet. https://www.cas.org/support/documentation/references. Accessed Nov 07, 2018
17. Ridley DD (2009) Information retrieval: SciFinder. Wiley, Chichester